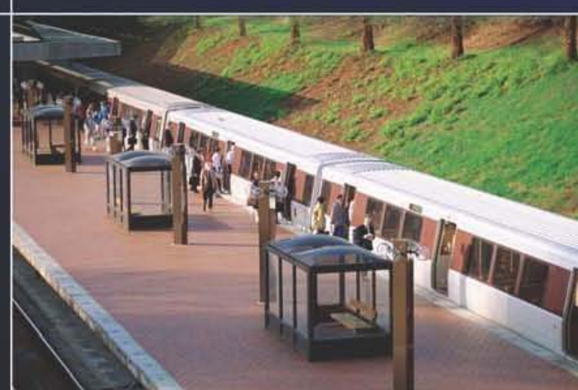
Transportation's Role in Reducing U.S. Greenhouse Gas Emissions

Volume 2: Technical Report

Report to Congress

U.S. Department of Transportation



U.S. Department of Transportation

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About the Center for Climate Change and Environmental Forecasting

The U.S Department of Transportation (DOT) Center for Climate Change and Environmental Forecasting is the focal point in the DOT of technical expertise on transportation and climate change. Through strategic research, policy analysis, partnerships, and outreach, the Center creates comprehensive and multimodal approaches to reduce transportation-related greenhouse gases and to mitigate the effects of global climate change on the transportation network. The Center was formally authorized as the Office of Climate Change and Environment in the Energy Independence and Security Act of 2007.

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1.0 Introduction

Transportation's Role in Reducing U.S. Greenhouse Gas Emissions is a report to Congress from the U.S. Department of Transportation (DOT) on the potential of transportation strategies to contribute to greenhouse gas reductions. Transportation has a significant impact on national greenhouse gas emissions, and transportation can be part of the nation's solution to the climate change challenge. The Energy Independence and Security Act (December 2007) called upon DOT, in consultation with the U.S. Environmental Protection Agency (EPA) and the U.S. Global Change Research Program (USGCRP), to conduct a study of the impact of the Nation's transportation system on climate change and strategies to mitigate the effects by reducing greenhouse gas emissions from transportation. The study is also to consider fuel savings and air pollution reduction from these measures. This report responds to that directive.

Volume 1: Synthesis Report provides an overview of transportation's contribution to greenhouse gas emissions (GHG), analyzes the effectiveness of various strategies available to reduce GHGs from the transportation sector, discusses the role of DOT planning and funding programs in providing a framework for strategic action on climate change, and concludes with five policy actions that Congress may wish to consider. **Volume 2: Technical Report** provides the technical basis for the summary material and recommendations in Volume 1.

This volume, Volume 2, contains detailed technical discussions of the four groups of strategies that can contribute to reducing the carbon footprint of the transportation sector. Each group of strategies is evaluated based on a set of factors including magnitude of GHG reduction, timing of impacts, cost, cobenefits (including fuel savings and air quality), implications for other DOT goals, impacts on infrastructure financing, and feasibility and implementation considerations.

Following this introduction:

- **Section 2.0 – Low Carbon Fuels** discusses the potential of alternative fuels to reduce the carbon content of fuels. This review includes information on ethanol, biodiesel, natural gas, liquefied petroleum gas, synthetic fuels, alternative aviation fuels, hydrogen, and electricity.

- **Section 3.0 – Vehicle Fuel Efficiency** investigates potential technological advances that can lower GHG emissions through improved efficiency of on-road vehicles (including light and heavy-duty vehicles), as well as other modes of transportation, namely air, rail, and commercial marine. The evaluation considers technologies that are currently available or close to commercialization, as well as more advanced strategies that may not be available for a decade or more.

- **Section 4.0 – System Efficiency** discusses a diverse set of strategies focused on ways to optimize the use of the transportation network by improving the efficiency of transportation operations. System efficiency strategies discussed in this report include: Highway operations and management strategies, truck operations and management strategies, improvements to the efficiency of rail and marine freight systems, aviation operations practices, and improvements in materials and methods that reduce GHG emissions generated during the construction and maintenance of transportation infrastructure.

- **Section 5.0 – Strategies to Carbon-Intensive Travel Activity** discusses strategies to reduce greenhouse gas emissions by influencing travelers' activity patterns in order to reduce total travel, shift travel to more efficient modes, or take other actions that reduce energy use and GHG emissions associated with personal travel. Travel behavior strategies discussed in this section include: Pricing, improvements to transit and nonmotorized modes, land use and parking management strategies, commuter/worksite trip reduction programs, and other public information programs.

The reader is directed to Volume 1 for an overview of transportation and climate change in the U.S., and a discussion of the policy options that Congress may want to consider to promote greenhouse gas reductions from this sector, based on the technical analysis presented in this volume.

2.0 Low-Carbon Fuels

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■ 2.1 Summary

Overview of Low-Carbon Fuel Options

Fuels used for transportation in the United States are almost entirely derived from liquid fossil fuel. Petroleum-based fuels make up about 97 percent of transportation energy use, and refined petroleum products such as gasoline, jet fuel, and diesel make up more than 90 percent of this consumption. In particular, petroleum-based gasoline represents about 60 percent of all energy consumption in the transportation sector, followed by distillates (diesel) at 22 percent, and jet fuel at 11 percent (U.S. DOE, 2009a). An additional three percent is used in for the form of residual fuel oil, mostly for marine applications.

The current dominance of petroleum-based fuels reflects the inherent advantages of liquid fuels for transportation, with their high energy densities allowing for extended vehicle range on limited storage. Gasoline and diesel in particular also benefit from their firmly established production and distribution infrastructures, resulting in price advantages and creating significant barriers to entry for most alternatives.

Nevertheless, there are many alternative liquid and nonliquid fuels in various stages of development that can be used to reduce the GHG emissions associated with conventional petroleum-based fuels. The following provides a brief overview of the alternative fuels that could be used to replace conventional gasoline, diesel, and marine distillate in the transportation sector. The potential use of each fuel by mode is summarized in Table 2.1.

Table 2.1 Potential Alternative Fuel Applications by Mode

	On-Road	Rail	Marine	Aviation
Ethanol	●	○	○	○
Biodiesel	●	◐	◐	○
Hydrogen	●	◐	◐	○
Electricity	●	●	○	○
LPG	●	○	◐	○
Synthetic Fuels	●	●	◐	○
Natural Gas	●	◐	◐	○
Alternative Aviation Fuels	n/a	n/a	n/a	●

○ = Little experience or potential; ◐ = Some experience and potential; ● = Significant experience and potential.

- **Ethanol (Section 2.2) –** There are many renewable feedstocks that can be used to produce ethanol. Blends of gasoline with up to 10 percent ethanol are commonly utilized by existing gasoline vehicles, while blends between 10 percent (E10) and 85 percent (E85) ethanol require flex-fuel vehicles (FFV). Flex-fuel systems can operate on fuel blends from 0 to 85 percent ethanol, and are available for a number of light-duty vehicles. Heavy-duty transit buses designed to operate exclusively on E94 with 6 percent additives have been demonstrated in Europe but currently are not available in the United States.

- **Biodiesel (Section 2.3) –** Biodiesel is an alternative fuel that can be produced from renewable feedstock or waste oils and greases. There also is some long-term potential for algae as a biodiesel feedstock. Blends with up to 20 percent biodiesel content with the remainder conventional diesel (B20) can be used in most diesel on-road vehicles without modification, although higher percentage blends may be used with minor changes to fittings and other vehicle components. Biodiesel also has the potential for use in rail and marine applications, but has not been extensively tested in railroad engines or larger marine vessels.

- **Natural Gas (Section 2.4) –** For on-road vehicles, liquefied natural gas (LNG) is primarily an option for medium- and heavy-duty trucks and transit buses, while compressed natural gas (CNG) has been used in both light and heavy applications. Light-duty natural gas vehicles are commonly converted from conventional gasoline vehicles, and may be capable of operating on either fuel (bifuel configuration), or dedicated to natural gas use. LNG can potentially be used in rail applications and marine engines.

- **Liquefied Petroleum Gas (Section 2.5) –** Also known as propane, liquefied petroleum gas (LPG) can be used in light-duty vehicles as well as medium- and heavy-duty trucks and buses. LPG vehicles may be found in dedicated as well as bifuel configurations, and is the most prevalent alternative fuel in use in the United States today. LPG has been used in marine applications to replace smaller gasoline-powered vessels.

- **Synthetic Fuels (Section 2.6) –** Synthetic Fischer-Tropsch (FT) diesel can be derived from natural gas, coal, and biomass. FT diesel can be substituted directly for conventional (petroleum-derived) diesel in on-road vehicles, locomotives, and marine vessels without modification to the vehicle engine or fueling infrastructure. Other synthetic fuels (such as biobutanol, biogasoline, and FT diesel from biomass) can be produced by conversion of cellulosic biomass via biochemical and thermochemical processes into alcohols and hydrocarbon equivalent replacement fuels.

- **Alternative Aviation Fuels (Section 2.7) –** Aircraft engines require fuels with specific characteristics due to the range of operating conditions and safety requirements, limiting alternative aviation fuel options for commercial air passenger and freight transport. Most aviation fuel research has focused on two general classes of alternative fuels, biofuels and synthetic fuels. Synthetic jet fuels are derived through use of the Fischer-Tropsch process. Alternatively, jet fuel can be created from the hydrotreating of animal fats, plant oils, and algae.

- **Hydrogen (Section 2.8) –** Hydrogen can be burned directly in an internal combustion engine, although most researchers focus on its use in fuel cells. Hydrogen fuel cells utilize an electrochemical process to create an electric current that can be used to power a vehicle. Fuel cell applications have focused on light-duty vehicles, although niche applications include forklifts, airport tugs, and auxiliary power for certain heavy-duty vehicles. Locomotives equipped with hydrogen fuel cells also are being developed.

- **Electricity (Section 2.9) –** For on-road vehicles, electricity can be used to power light-duty vehicles and certain medium- and heavy-duty truck applications. Plug-in hybrid electric vehicles also utilize electricity stored on-board in combination with fuel combustion. Electricity-powered transport also is used for various rail transit options, including trolleys, subways, light rail, and some commuter and intercity rail applications. Magnetic levitation (maglev) trains also utilize electricity.

In addition, an alternative fuel that is gaining some traction in heavy duty vehicles is dimethyl ether (DME), which is a substitute for diesel fuel (with a low pressure fuel system) and is produced from wood waste. Much work currently is underway in the areas of evaluating the effectiveness and costs of various alternative fuels in reducing greenhouse gas emissions. For instance, in May 2009 the U.S. Environmental Protection Agency (EPA) published a draft analysis of life-cycle emissions from renewable fuels (U.S.

EPA, 2009a) in conjunction with its Notice of Proposed Rulemaking (NPRM) for a revised renewable fuel standard (U.S. EPA, 2009b) and will incorporate information gathered during a public comment period into this analysis. This Report to Congress provides information from analyses available at the time of writing (through June 2009). As EPA's renewable fuel standard rulemaking was ongoing at the time of writing, this report to Congress does not include analysis of biofuels, at EPA's request. Readers are instead referred to EPA's renewable fuels website, which includes draft life cycle analysis of the greenhouse gas impacts of renewable fuels: http://www.epa.gov/OMS/renewablefuels/.

Renewable Fuels

Some low-carbon fuels are also renewable fuels, and therefore may be desirable from a standpoint of energy security and sustainability as well as reducing greenhouse gas emissions. Renewable fuels are defined by the EPA as fuels produced from plant or animal products or waste, rather than from fossil fuels (U.S. EPA, 2009b). Ethanol and biodiesel are examples of renewable fuels, and certain synthetic fuels that utilize biological feedstock may also be considered renewable. In addition, electricity generation and hydrogen reformation can potentially be accomplished using renewable sources.

The 2005 Energy Policy Act established a Renewable Fuel Standard (RFS1) mandating targeted levels of renewable fuel use in the United States. The 2007 Energy Independence and Security Act (EISA) expanded upon the renewable fuel targets established under RFS1. In May 2009, the EPA issued a Notice of Proposed Rulemaking to implement the mandated changes to RFS1 (U.S. EPA, 2009b). In addition to conventional biofuels such as corn-based ethanol, the revised RFS (RFS2) establishes three new categories for renewable fuels: advanced biofuel, biomass-based diesel, and cellulosic biofuel. The life-cycle reduction targets for each fuel type are expressed in terms of the following percentage reductions in GHG emissions relative to conventional petroleum fuels:[1]

- **Conventional –** 20 percent;
- **Biomass-based diesel –** 50 percent;
- **Advanced –** 50 percent; and
- **Cellulosic –** 60 percent.

The RFS2 also mandates new specific volume standards for these fuels, requiring 16 billion gallons of cellulosic biofuel, 21 billion gallons of advanced biofuel, and 36 billion gallons of total renewable fuel be produced in 2022 (volume requirements for biomass-based diesel are to be determined by EPA through a future rulemaking, but will total at least 1 billion gallons by 2012). In addition, the RFS2 alters the criteria of renewable fuel feedstock, requiring crops used in renewable fuel be produced on land cleared or cultivated before

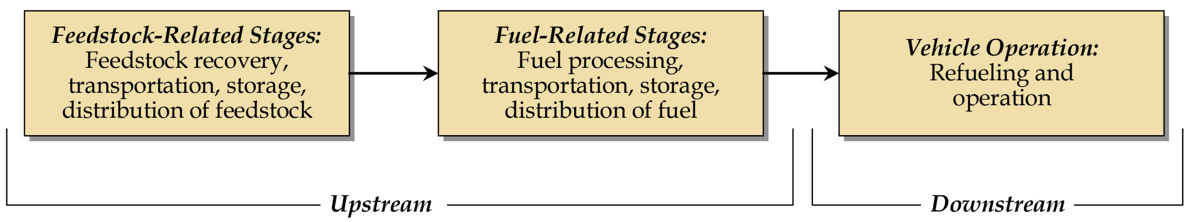
[1] EPA has the authority to adjust the life-cycle thresholds downward by up to 10 percent for each fuel category.

the enactment of the EISA, with this criteria applicable to both domestic and foreign producers of renewable fuels.

Life-Cycle Analyses

The life-cycle greenhouse gas impacts of a fuel – not just emissions from the vehicle itself – must be considered when evaluating low-carbon fuel options. The GHG emissions resulting from vehicle operation (i.e., "tailpipe" emissions) are only a part of the total life-cycle emissions associated with transportation fuel use. As depicted in Figure 2.1, a life-cycle analysis takes into account the GHGs associated with the extraction, processing, distribution, and dispensing of the fuels (Winebrake et al., 2001).

Figure 2.1 Life-Cycle of a Transportation Fuel



Note: "Upstream" also is known as "well-to-pump" and "downstream" as "pump-to-wheel," with the full cycle known as "well-to-wheel." Vehicle operation includes tailpipe emissions from combustion of the fuel in the vehicle's engine, as well as any emissions associated with refueling the vehicle.

The analysis contained in this report considers "well-to-wheel" emissions, which includes all three stages shown in Figure 2.1. Fuel combustion is responsible for about 80 percent of the life-cycle GHG emissions for petroleum fuels, while the processes from feedstock extraction through fuel delivery (well-to-pump) account for about 20 percent. Some GHG emissions also are associated with vehicle manufacture and disposal; these would add about 10 percent to the emissions total but are not included in this analysis, which focuses only on fuels.[2]

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[2] Certain advanced technology vehicles require higher energy intensity materials, entailing a slight increase in manufacturing emissions (increasing from about 26 g GHG per mile traveled for conventional vehicles to about 30g per mile for fuel cells and battery electrics – Heywood et al., 2008).

The proportion of GHG use associated with vehicle operation versus fuels production and transport can vary significantly by the type of fuel. For example, hydrogen fuel cells and electric vehicles have no operating emissions since there is no fuel combustion in the vehicle.

Summary of Impacts

Ethanol benefits vary substantially depending upon the feedstock used to produce the fuel and the production pathway. For instance, using low carbon energy sources to process the feedstock into fuel produces lower greenhouse gas emissions than high carbon energy sources. Cellulosic ethanol, such as ethanol from switchgrass, shows much greater GHG benefits than first generation biofuels. Cellulosic ethanol is produced from the structural material that comprises much of the mass of plants. As EPA's renewable fuel standard rulemaking was ongoing at the time of writing, this report to Congress does not include analysis of biofuels, at EPA's request. Readers are instead referred to EPA's renewable fuels website, which includes draft life cycle analysis of the greenhouse gas impacts of renewable fuels: http://www.epa.gov/OMS/renewablefuels/.

Biodiesel provides the potential for GHG reductions in heavy-duty vehicles, and a blend with conventional diesel of up to 20 percent biodiesel (B20) is compatible with existing engines and infrastructure. Biodiesel can be used in light and heavy duty road vehicles and marine vessels, although further research is required on material compatibility issues for rail applications. For more information, readers are referred to EPA's renewable fuels website, which includes draft life cycle analysis of the greenhouse gas impacts of renewable fuels: http://www.epa.gov/OMS/renewablefuels/.

Natural gas is a clean-burning fossil fuel that has a well-established pipeline system for distribution and provides moderate life-cycle GHG reductions relative to light-duty gasoline vehicles (about 15 percent compared to gasoline vehicles, roughly equivalent to diesel vehicle benefits). A GHG reduction of 7 to 13 mmt per year (0.3 to 0.6 percent of transportation emissions in 2030) is estimated assuming a 3 to 6 percent LDV market share for compressed natural gas (CNG) in 2030. The relatively low potential benefit is not constrained so much by natural gas supplies as by the ability to move natural gas away from other end uses such as electricity production and residential heating. Natural gas would not provide significant GHG benefits in heavy-duty vehicles (HDV) or the off-road sector, since it would primarily displace diesel fuel rather than gasoline.

CNG vehicles have a proven performance and safety record, although range penalties can be significant. CNG also is one of the few alternative fuels available that offers potentially lower fuel costs relative to conventional fuels, with the break-even point estimated to be about $2.50 per gallon of gasoline (pretax). Preferred applications for CNG vehicles are fleets with high mileage and centralized refueling. Primary barriers to implementation include the limited number of CNG vehicle offerings, limited refueling infrastructure, and incremental vehicle costs. Incremental vehicle costs at full production volumes are estimated at $3,000, although current conversion of conventional vehicles is much higher. Considering fuel cost savings, CNG vehicles are estimated to result in a net cost savings of -$130 per tonne, based on AEO fuel cost projections. Due to the high global warming potential of methane – the primary component of natural gas – it is important to minimize leaks during distribution, storage, and dispensing, which could offset GHG reductions for use.

Along with electricity and hydrogen, natural gas is "fungible," with multiple end use options. In addition to transportation and home heating, natural gas has a substantial role in the energy sector producing electricity. To the extent that multiple end use options are available, replacing coal power with natural gas offers substantially greater GHG reduction potential (about 50 percent) than its use in transportation (about 15 percent). Increased demand for natural gas resulting from carbon limits placed on electrical generating units may limit CNG and LNG availability for transport, although a detailed analysis of such impacts is beyond the scope of this assessment.

Liquefied petroleum gas (LPG), also referred to as propane, is commonly used in fleet vehicles in the United States, and benefits from a relatively well-established fueling infrastructure. Potential GHG reductions are about 17 percent relative to conventional gasoline vehicles. LPG is produced as a byproduct of petroleum and natural gas processing, and as such, the ability to expand LPG supplies is highly constrained, with little potential for significant expansion in the transportation sector. While a limited number of original equipment manufacturer (OEM) engines are available for heavy-duty vehicles, LDV owners must have their vehicles converted for LPG use at this time. Moderate cobenefits associated with LPG use relative to gasoline are expected. Barriers to expanded use of LPG include higher incremental fuel costs, expensive retrofits, and significant limitations on LPG production and sales volumes for vehicle use; GHG reduction potential is estimated to be less than 0.5 mmt CO_2e annually.

Many of the **synthetic fuel** options available may actually increase life-cycle GHG emissions, although biomass feedstock should result in substantial reductions. Synthetic fuels lend themselves to easy adoption, however, requiring little to no modification of vehicles and infrastructure. Most of these fuels also promise significant reductions in other pollutants relative to conventional fuels.

Alternative aviation fuels can be used without significant modification in aircraft. While point of use GHG emissions may be reduced slightly (two to four percent) for synthetic jet fuels, life-cycle emissions can increase substantially depending upon the feedstock used in the process. In order for biomass jet fuels to meet stringent commercial aviation fuel standards, these fuels need to be refined with a hydrotreating process. The costs for this additional processing and feedstock prices will determine the cost competitiveness of these fuels. Synthetic jet fuels have been estimated to cost about $75 to $80 per barrel of oil equivalent.

Along with battery electric vehicles, **hydrogen fuel cell vehicles (HFCV)** offer the greatest long-term GHG reduction potential, but only if the hydrogen is produced by low carbon pathways, such as electrolysis using renewables, coal with carbon sequestration, biomass reforming, or nuclear power sources. Net GHG and other emissions vary substantially depending on hydrogen production pathways, as well as hydrogen delivery and storage approaches and may even increase emissions relative to conventional vehicles under worst case conditions; because HFCVs are more than twice as efficient as gasoline internal combustion vehicles, however, the overall well-to-wheels GHG emissions can be significantly lower than other options. For example, estimates suggest the potential for a 51 percent reduction per vehicle in 2030 and 80 percent in 2050, assuming that increasingly cleaner sources of energy are utilized for hydrogen production. Although market penetration estimates and production pathways are *highly* uncertain, illustrative GHG reductions are estimated at 52 to 74 mmt CO_2e annually in the medium term (2.3 to 3.2 percent of transportation emissions in 2030) assuming 18 percent penetration of the light-duty vehicle market and production through natural gas reformation, and 390 to 470 mmt CO_2e annually in the long term (18 to 22 percent of transportation emissions in 2050) assuming 60 percent market penetration and advanced, low carbon production pathways by this time.

While the vehicles themselves have the potential to provide excellent performance, substantial uncertainties exist regarding their long-term fuel storage capacity, fuel cell stack life, and commercialized cost. At high production volumes incremental HFCV costs could be between $1,500 and $5,000 compared to conventional vehicles, although near-term costs are estimated to be $10,000 or more (see Section 2.8). Cost for fuel cell vehicles have dropped significantly between 2002 and 2008 and future year hydrogen fuel costs could even be lower than gasoline, on a cents per-mile traveled basis. However, development of a widespread, cost-effective fuel production and distribution infrastructure will be challenging, most likely requiring the development of entirely new centralized production facilities and dedicated pipelines for transport. No other vehicle technology/fuel combination evaluated in this study must overcome such significant barriers in vehicle technology, fuel production, and distribution simultaneously. Accordingly, the transition costs associated with widescale deployment of hydrogen within the transportation sector may be higher than most other options.

The government costs for both vehicle and infrastructure have been estimated to be roughly $1 to $6 billion per year, or $55 billion over 15 years to enable HFCVs to be competitive in the 2023 timeframe (Greene et al., 2008; NRC, 2008). Regardless of cost, there remains controversy over the likelihood of overcoming the challenges to widespread deployment of HFCVs, including hydrogen production, delivery, storage, and fuel cell performance. Even under aggressive development and deployment scenarios, HFCVs are unlikely to have a significant impact on GHG emissions for the next decade in the United States, and other technologies are expected to be more prevalent during that period (Meyer and Winebrake, 2009). National policies to restrict GHG emissions and encourage the development of fuel-cell vehicles and hydrogen production and infrastructure will be necessary to achieve significant market penetration, even in the long term.

Electricity is available for use as a transportation fuel, but the associated vehicle technology has not advanced enough for battery electric vehicles (BEV) to become commercially competitive at this time. The GHG benefits of these vehicles are strongly based on the type of electricity grid generation used to charge them, but scenarios assuming a move to increasingly cleaner electricity generation sources suggest a potential for up to a 68 to 80 percent GHG reduction per vehicle in 2030, or 78 to 87 percent in 2050. Although market penetration estimates also are *highly* uncertain for BEVs, illustrative market penetration scenarios would result in anywhere from 47 to 55 mmt CO_2e annually in the medium term (2.2 to 2.5 percent of transportation emissions in 2030), and between 570 and 640 mmt CO_2e annually in the long term (26 to 30 percent of emissions in 2050), assuming favorable consumer acceptance. These estimates assume a maximum BEV market penetration of approximately 5 percent of the light-duty vehicle stock in 2030 and 56 percent in 2050, with the emissions range reflecting the uncertainty associated with the source mix used for battery charging.

Advancements in battery technology, especially with regards to cost, could make BEVs viable in the medium to long term, and a shift in grid generation to a greater proportion of renewable sources could allow BEVs to significantly reduce GHG emissions from the transportation sector. Plug-in hybrid electric vehicle (PHEV) technology (see Section 3.2.4) may serve as a step on the path to significant BEV market share in the long term, facilitating battery and other vehicle developments for enhanced BEV performance. Consumer response will likely decisively impact the future of BEVs, with limited operation range (less than 200 miles between charges) providing a significant constraint on acceptability. While even in the long-term BEVs are estimated to be substantially more expensive than conventional vehicles (between $6,000 and $10,000 depending upon the range of the vehicle), low nighttime charge rates would result in operation costs per mile that are about 75 percent lower than for a gasoline vehicle, potentially yielding a net savings over the life of the vehicle.

The Rebound Effect

Benefits from technology strategies may be somewhat offset due to the "rebound effect." This effect can be characterized as the extent to which any fuel cost savings (and corresponding GHG reductions) from alternative fuels are offset by increased travel, because travel is made cheaper per-mile due to reduced fuel costs. (Conversely, a fuel that is more expensive per-mile could have the effect of reducing VMT and therefore providing further GHG benefits.) The National Highway and Traffic Safety Administration (NHTSA), used a 10 percent rebound effect in its analysis of fuel savings and other benefits from higher CAFE standards for MY 2012-2016 vehicles. Recognizing the uncertainty surrounding the 10 percent estimate, the agency analyzed the sensitivity of its benefits estimates to a range of values for the rebound effect from 5 percent to 15 percent (NHTSA, 2009). (For more detail on the rebound effect, see Appendix A.)

The impact of the rebound effect is fairly straightforward to demonstrate in the case of strategies that improve the efficiency of existing gasoline or diesel vehicles, as demonstrated in Section 3.0. For alternative fuel strategies, it is more complicated to estimate as the effects will depend upon the relative cost per mile of the different fuels compared to gasoline. Some of the fuel strategies evaluated in this report will increase the cost per mile, while others are likely to decrease it. (It is the cost per mile, and not any up-front capital cost or savings, which affects consumer behavior with respect to VMT.) Therefore, it is difficult to make blanket characterizations of how the rebound effect might affect the GHG benefits estimated in this section.

Policy Implications

Low-carbon fuels suffer from the "chicken-and-egg" dilemma – consumers are not likely to buy alternative fuel vehicles in the absence of an extensive distribution network, nor will manufacturers have the incentive to develop or offer such vehicles in mass if consumers are not demanding the fuel. Low-carbon fuel policies will have to address this dilemma to increase the use of these fuels. Policies should address the various barriers faced: encouraging the purchase of flex fuel or other alternative fuel vehicles, expanding distribution networks for low-carbon fuels, and research and development to advance these fuels (and vehicles that can use them) into a commercially viable product.

A carbon fuel standard mandates that fuel suppliers meet, on average, minimum percentage requirements for reductions in greenhouse gas emissions compared to conventional fuels (e.g., gasoline, diesel). A carbon fuel standard allows fuel suppliers to determine how to most cost-effectively meet the standard through any combination of fuel strategies. This fuel-neutral approach rewards lowest carbon results without choosing winners and losers in the development of improved fuels and technologies. By providing certainty over future demand for low-carbon fuels, it also encourages vehicle manufacturers to design vehicles that support the use of such fuels (such as bi-fuel or flex-fuel vehicles capable of running on both gasoline and ethanol).

California's low-carbon fuel standard provides one model for this approach. In January 2007, Governor Schwarzenegger called for the establishment of a Low-Carbon Fuel Standard (LCFS) by Executive Order (CEC, 2009). In response, the California Air Resources Board (CARB) adopted a resolution to implement the new standard on April 23, 2009 (CARB, 2009a). The CARB standard will reduce GHG emissions from the transportation sector by about 16 mmt in 2020 by lowering the carbon content of transportation fuels used in California. This reduction by 2020 represents a 10 percent reduction of the total GHG emission from the statewide mix of transportation fuel. The LCFS will contribute to the State's efforts of reducing GHG emissions to 1990 levels by 2020 (CARB, 2009b). Eleven Northeast and Mid-Atlantic states intend to establish a regional LCFS initiative as well (Connecticut Department of Environmental Protection et al., 2008).

The LCFS is imposed on transportation fuel providers in the State, establishes performance standards that fuel providers must meet each year beginning in 2011, and uses market mechanisms to spur the steady introduction of lower carbon fuels. The carbon intensity of a fuel, expressed in terms of grams of CO_2 equivalent per megajoule, is established by determining the sum of GHG emissions associated with the production, transportation, and consumption of a fuel. The carbon intensity of all fuels is tracked through a system of "credits" and "deficits." Credits are generated from fuels with lower carbon intensity than the standard. Deficits result from the use of fuels with higher carbon intensity than the standard. The regulation is performance-based and provides flexibility for fuel providers to comply with the standard through different approaches:

1. Supply a mix of fuels above and below the standard that, on average, equal the required carbon intensity;

2. Supply only fuels that have lower carbon intensity than the standard (blend low carbon ethanol in gasoline, or renewable diesel fuel in diesel fuel);

3. Purchase credits generated by other fuel providers to offset any accumulated deficits from their own production; or

4. Bank excess credits generated in a previous year and use those credits when needed.

An alternative approach to a carbon fuel standard is provided by EPA's Renewable Fuel Standard, which establishes target percentages of certain types of defined renewable fuels, along with life-cycle GHG reduction criteria for each fuel type. This approach has the advantage of encouraging the advancement of promising fuel technologies and providing certainty for fuel producers and vehicle manufacturers regarding a market for particular fuels.

Tax credits or differential fuel tax rates can be used to encourage consumers to purchase vehicles that are capable of utilizing low-carbon fuels. Tax credits already are offered for ethanol to encourage its use, currently at about 47 cents per gallon. A complication for low-carbon fuel policies is the need to take into account the full fuel-cycle GHG implications of different fuel strategies. Some strategies are likely to have significantly better performance from a life-cycle perspective than others, due to the relative energy intensiveness of different forms of agricultural production or other processes needed in the fuel production process. Incentives and tax rates based on the life-cycle GHG released from the fuel provide a level playing field for all fuels and encourage the use of those fuels with the greatest GHG reductions.

Support also may be needed, whether regulatory or via incentives, to encourage the development of alternative fuel distribution networks. One strategy is to begin to invest in such networks in limited geographic areas in order to demonstrate feasibility and consumer acceptance of the fuel. For example, initiatives have been undertaken in California and in the Northeast United States to develop a hydrogen refueling infrastructure. Partnerships with public and private vehicle fleet operators to use vehicles that can make use of these fuels can help to create initial demand for the fuel and begin to recover investment costs before there is widespread consumer demand.

For fuels that appear to be at or near viability, requirements or incentives could be placed on vehicle manufacturers to design vehicles to support the fuel. For example, today's gasoline vehicles can be designed to use ethanol blends at up to 85 percent at only modest additional cost. Introducing such vehicles today would allow for faster adoption of the fuel in the future, if production constraints can be overcome.

A general GHG performance standard for vehicles is another potential option as an alternative (or in addition to) a low-carbon or renewable fuel standard. This approach directly measures GHG emissions per mile from vehicles rather than measuring GHG emissions by a fuel efficiency or fuel carbon content proxy. A GHG emissions standard would allow fuel producers and vehicle manufacturers to develop the most cost-effective combinations of vehicle and fuel technology to reduce GHG emissions. GHG performance standards for vehicles have been proposed in California, along with a low-carbon fuel standard. To be effective, a GHG performance standard must reflect the life-cycle emissions associated with the fuel, not just the emissions produced by the vehicle in operation.

Ultimately, significant additional research and development is needed to make many of these low-carbon fuels commercially viable. Additional funding could be provided to advance research to make new feedstocks commercially viable, such as cellulosic ethanol- and algae-based biodiesel. Major advances are needed for hydrogen fuel cell technology as well as for battery technology in order to make these fuel sources practical for consumers as well as cost-competitive with current fuels and vehicles. The U.S. government already is funding research on renewable fuel sources, for example, through the Department of Energy's FreedomCAR and Vehicle Technologies Program (U.S. DOE, 2006).

It is clearly desirable to avoid contradictory or overlapping policies. However, multiple policy levers may still be needed to assist vehicle and fuel producers in focusing research, development, and production resources on complementary technologies and to provide consistent incentives to consumers. Whenever possible the government should strive to set "technology-neutral" policies that allow markets to select the most cost/effective GHG reduction technologies, while recognizing that in practice this may be difficult, especially with respect to fuel technologies. In particular, the level of coordination required between vehicle manufacturers, fuel and feedstock producers, and providers of distribution infrastructure suggest that multiple policy levers may be necessary, sometimes focusing on particular technologies.

Summary Evaluation

Table 2.2 summarizes the strategies discussed in this section and presents an assessment of each strategy's effectiveness, cost-effectiveness, and cobenefits, as well as a summary of key Federal policy initiatives that would be needed to implement the strategy beyond current levels. A similar summary is provided in Section 3 for other vehicle technologies, including advanced internal combustion engines, hybrids, and plug-in hybrids.

The factors presented in the table are rated according to the following metrics:

- **GHG Reduction Effectiveness** – Low = < 0.5% of transportation GHG emissions in 2030 (12 mmt CO_2e; Moderate = 0.5 to 2.5% (12 to 60 mmt CO_2e); High = > 2.5% (60 mmt CO_2e).

- **Costs (net included cost per tonne)** – Cost-effectiveness measured as net included cost per tonne of CO_2e reduced. A positive number represents increased costs, while a negative number represents a net savings. High Cost = > $200 per tonne CO_2e reduced; Moderate Cost = $20 to $200 CO_2e reduced; Low Cost = < $20/tonne CO_2e reduced; Net Savings = < $0/tonne CO_2e reduced.[3] "Net included cost" includes both fuel production and distribution costs and vehicle costs, and is calculated as the cost increment relative to the cost of conventional fuels and vehicles (gasoline for light-duty vehicles, diesel for heavy-duty vehicles), net of taxes. See Appendix A for details on the calculation of costs.

- **Cobenefits** – Plus (+) = significant positive cobenefits; Minus (-) = significant negative cobenefits; Plus/minus (+/-) = both significant positive and negative cobenefits; Zero (0) = modest or negligible cobenefits. Cobenefits may include air pollutant emission reductions, consumer benefits, or other factors. The cobenefits rating does not include gasoline savings or related national security benefits, since all strategies analyzed in this report will reduce gasoline consumption.

Cost-effectiveness includes direct implementation costs as well as costs or savings associated with fuel use changes incurred by vehicle owners/operators.

Table 2.2 Low-Carbon Fuel Strategies
Summary Evaluation

Strategy	GHG Reduction Effectiveness (2030)	Net Included Cost per Tonne	Cobenefits	Key Federal Policy Options
2.2 *Ethanol*				
E85 Flex-fuel Vehicles (Cellulosic Ethanol)	n/a	n/a	n/a	Research and development support for cost-effective cellulosic ethanol production. Assistance with fuel distribution infrastructure expansion.
2.3 *Biodiesel*				
B20 in On-road Heavy-Duty Vehicles	n/a	n/a	n/a	Research and development support for cost-effective production of advanced feedstocks such as algae.
2.4 *Natural Gas*				
CNG in Dedicated Light-Duty Vehicles	Low to Moderate 0.3-0.6%	Net Savings	+	Determine most cost-effective dispatch of natural gas across alternative end uses. Assistance with fueling station expansion Incentives for purchase of dedicated, OEM CNG vehicles for fleets.
2.5 *Liquefied Petroleum Gas (LPG)*				
LPG in Dedicated Light and Heavy-Duty Vehicles	Low <0.1%	Not calculated	+	Incentives for niche applications such as fleet vehicles.
2.6 *Synthetic Fuels*				
FT fuels, biobutanol, biomass and coal to liquids, HDRD	Uncertain/ varies	Uncertain/ varies	+	Research assistance to determine viability of CCS with certain production pathways.
2.7 *Alternative Aviation Fuels*				
Synthetic and biomass-derived	Uncertain/ varies	Uncertain/ varies	+	Support for additional research and development. Demonstration programs / partnerships Policies and incentives to support commercialization and deployment of fuels.
2.8 *Hydrogen*				
Hydrogen Fuel Cell Light-Duty Vehicles	High 2.3-3.2% (2030) 18-22% (2050)	Net Savings to Moderate Cost	+/-	Continued research and development support for HFCV efficiency, stack life, on-board storage, and hydrogen production pathway options. Continued demonstration project support In the longer term, extensive support for delivery infrastructure development.
2.9 *Electricity*				
Battery Electric Light-Duty Vehicles	High 2.2-2.5% (2030) 26-30% (2050)	Net Savings	+/-	Continued research and development support for BEV battery efficiency and durability. In the longer term, extensive public charging station network development. Policies to support low-GHG electricity grid

Cobenefits and Implications for Other Transportation Goals and Objectives

The following provides a brief evaluation of fuel strategies in general terms with respect to the five goals identified in the U.S. DOT's Strategic Plan, as well as against additional planning factors cited in the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) of 2005. More detailed information on cobenefits and feasibility-related issues, particularly emissions and safety impacts, is provided in the respective section for each fuel.

- **Safety** – Several of the fuel strategies evaluated in this section have different safety considerations relative to conventional fuels, and require additional safety enhancements associated with fueling infrastructure, emergency responder requirements, as well as the vehicles themselves. Fuels with unique safety considerations include ethanol, natural gas, and hydrogen. Other strategies such as biodiesel and certain synthetic fuels are not expected to present significant safety concerns compared to gasoline and diesel.

- **Reduced Congestion/Increased Mobility –** The fuel strategies investigated in this section may result in different operating costs per unit of travel. To the extent that total miles traveled varies as a result, mobility may be impacted. Beyond that, these options are not expected to change the number of vehicles in operation or the overall mobility of the associated transportation system.

- **Global Connectivity –** The fuel strategies evaluated here are not expected to impact network operations or global connectivity.

- **Environmental Stewardship –** Many alternative fuels also reduce other air pollutants, including volatile organic compounds (VOC), oxides of nitrogen (NO_x), particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_x), and air toxics. However, these reductions will vary by fuel as well as the operating characteristics of an engine. In some cases increased emissions are expected relative to conventional fuels. The location of emissions (i.e., proximity to population) will also affect their relative health impacts. Strategies involving electric batteries should consider additional waste disposal/recycling requirements. Table 2.3 compares the emission reductions of the alternative fuels discussed in this section compared to conventional gasoline or diesel, given current fuel production and engine technologies.

- **Security** – With the exception of certain synthetic fuels, which may increase oil or natural gas imports, all of the fuel options discussed in this section result in decreased fossil fuel use, which in turn reduces reliance on foreign oil. As such, these strategies support economic and national security.

- **Economic Vitality** – Many of the fuel strategies discussed in this section will increase vehicle ownership costs, due to increased fuel costs per mile and/or increased vehicle costs; however, others may reduce net ownership costs. The relative costs and benefits will vary for each option depending on incremental vehicle costs and fuel prices. Increased domestic fuel production will provide additional employment opportunities. Finally, many of these options will require increased vehicle manufacturing capacity to meet increased demand, which also will increase employment opportunities.

- **Efficient System Management and Operation –** Certain fuel options may affect the management and operation of the transportation system. To the extent that access to alternative fuels may be limited, system operation may be constrained to certain regions or refueling locations. Such concerns will be most prevalent during transition periods, before full build out of new infrastructure capacity.

- **System Preservation –** The fuel options are assumed to have negligible impact on preservation of the existing infrastructure.

Table 2.3 Relative Life-Cycle Emissions of Alternative Fuels (Percent Change versus Conventional Gasoline)

Pollutant	Conventional Gasoline Emissions (g/mi)	CNG	LPG	Gaseous Hydrogen[b]	Battery Electric Vehicle[c]
VOC	0.316	-45%	-35%	-92%	-91%
CO	3.817	0%	0%	-98%	-98%
NO_x	0.379	-20%	-14%	-59%	-11%
PM_{10}	0.083	-9%	-47%	23%	416%
$PM_{2.5}$	0.036	-20%	-38%	36%	220%
SO_x	0.126	+11%	-14%	N/A	494%

Source: GREET Model Version 1.8b, with default assumptions for current vehicle technologies. Relative emissions will vary depending upon vehicle emission controls as well as fuel extraction and production methods. Relative emissions may change in future years as these various technologies evolve in different ways.

[b] Assuming distributed natural gas reforming, the current primary production pathway; these values do not represent future technologies or other production pathways or feedstocks. Refer to Section 2.8 for detailed hydrogen production pathways.

[c] Assuming current grid-average electricity generation mix. Future scenarios will differ considerably depending upon grid mix and when vehicles are charged. See Section 3.2.4 for a detailed analysis of electricity dispatch impacts.

Effects on Infrastructure Funding

The revenue effects of alternative fuels will depend upon taxation policy. Since 2006, Federal policy has been to tax alternative fuels on an energy-equivalent basis to gasoline (FHWA, 2008).[4] This means that policies focused solely on increasing the use of lower-carbon fuels should not have a significant revenue impact on the Highway Trust Fund. On the other hand, current tax policies may have implications for general fund revenue; for example, ethanol receives a substantial tax credit which reduces general fund revenues, but a tariff is levied on imported ethanol which could potentially generate revenue. The long-term finance implications of a shift to hydrogen or electricity will depend on tax policy for these fuels; current Federal policy does not tax these fuels for transportation purposes, and therefore any shift to these fuels will result in lost revenues to the Highway Trust Fund under the current finance structure.

[4] Ethanol users actually pay slightly more per gallon of gasoline equivalent even though ethanol is taxed less on a volumetric basis (Vol. 2 Sec. 2.2).

2.2 Ethanol

Overview

Ethanol is a biodegradable liquid fuel that is made from the fermented sugars of renewable feedstock, typically corn in the U.S. Ethanol is the most widely used alternative fuel and is commonly blended with conventional gasoline to help reduce carbon monoxide (CO) and reduce engine knocking in light-duty vehicles.

Ethanol can be derived from starch- and sugar-based feedstock or from cellulosic feedstock. Ethanol is almost always blended with conventional gasoline in varying amounts. The two commonly available blends are E10 and E85. E10 is composed of 10 percent ethanol and 90 percent gasoline (commonly known as gasohol), while E85 is 85 percent ethanol and 15 percent gasoline. Ethanol concentrations above 85 percent are not used in order to avoid cold-starting problems. E10 is sold in fueling stations located in all 50 states and accounts for about one-third of all gasoline consumed in the United States. E10 is required for sale statewide in Missouri and Minnesota, and will be required in Florida beginning in 2010. Montana and Oregon also will adopt E10 mandates contingent upon local production volumes (AFDC, 2009a). All but a few states also offer E85, with over 1,906 fueling stations across the United States as of June 2009 (U.S. DOE, 2009b). High concentration fuel blends (more than 10 percent) require flex-fuel vehicles (FFV) which can run on conventional gasoline or any ethanol blend volume up to 85 percent.[5]

The combustion of a gallon of pure ethanol produces about two-thirds as much energy as a gallon of gasoline, so more gallons of fuel are required to travel the same distance when using ethanol blends as a transportation fuel. Depending on the availability of fuel and the size of the vehicle fuel tank, this lower energy density may create a disincentive for consumers towards the purchase of E85.

Most FFVs are light-duty vehicles (about 80 percent), automatically adjusting their combustion process to account for the amount of ethanol in the fuel. There are over six

[5] The U.S. Department of Energy is funding the National Renewable Energy Laboratory (NREL) and Oak Ridge National Laboratory (ORNL), among others, to conduct a series of studies on the effects of intermediate ethanol blends on vehicles and other engines. The first report from this work (West et al., 2008) investigated the effect of E15 and E20, which found that fuel economy losses correlated with energy density of the fuels and that regulated tailpipe emissions remained largely unaffected. In April 2009, the U.S. Environmental Protection Agency issued a request for comments on an ethanol industry petition asking the Agency to permit an increase in the amount of ethanol in gasoline to 15 percent.

million FFVs on the roads in the United States today, and sales continue to be strong with 870,000 new FFVs sold in 2007 compared to 15.1 million new car and truck sales total (U.S. DOE, 2009a). However, only a small fraction of these vehicles use E85 predominantly[6] due to a number of obstacles such as limited E85 distribution and infrastructure, lack of owner awareness of their vehicle's E85 capability, and the lower energy density, which makes it difficult for consumers to know the price point at which E85 becomes more cost-effective than gasoline. FFVs are available for purchase from every major automotive manufacturer at no incremental cost to the consumer compared to dedicated gasoline models (AFDC, 2009A). If incremental manufacturing costs were passed along to the consumer, price increases for FFVs would be approximately $150 per vehicle (Greene, 2007).

FFVs suffer a slight fuel economy penalty relative to vehicles optimized to operate on a particular fuel. Ethanol's higher octane level compared to gasoline would allow for increased compression ratios on a vehicle designed to operate solely on E85, providing for about a 10 percent improvement in fuel economy compared to comparable gasoline engines, and even more relative to FFVs (Greene and Schafer, 2003). This analysis assumes utilization of FFV rather than optimized E85 technology due to the former's advantages with respect to consumer acceptance and convenience.

The vast majority of domestically produced ethanol used by FFVs is derived from starch- and sugar-based feedstock such as corn, sugar cane, sugar beets, grain sorghum, and potatoes, with more than 90 percent of current production from corn. Large-scale ethanol production from these feedstocks is economical using biochemical conversion technologies to extract and ferment sugar or to break down starches into simple sugars for fermentation. Because of impacts on land use and food supplies, there are limits to the use of corn and other crops to produce ethanol for transportation. The Government Accountability Office (GAO, 2007) estimated that sustainable production of ethanol from corn is capped at 15 billion gallons per year due to water constraints for irrigation.[7] Additional corn ethanol production may be possible with increased yields from fields and improved conversion efficiencies.

In the long run, cellulosic feedstocks have the greatest potential for increasing fuel ethanol production. Cellulosic ethanol is derived from cellulose and hemicellulose that forms the structure of plant stalks, leaves, and woody material. Feedstock include agricultural residues, forestry residues, and fast-growing grasses (such as switchgrass and miscanthus), or trees (like poplar and willow). Compared to starch- and sugar-based feedstock, cellulosic feedstocks have many advantages: they are abundant, can be grown on marginally productive land not suitable for other crops, and do not divert crops from food use. However, there are limitations on the amount of crop residue that can be removed from land while still preventing land erosion and sustaining soil organic carbon.

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6 Roughly 300,000 in 2006.

7 The growth and production of one gasoline equivalent gallon of corn-based requires roughly 2,700 gallons of water (NGA, no date).

It also is more difficult to chemically convert cellulosic feedstock into sugars. The U.S. DOE and other government and industry groups are actively supporting research to develop economically viable processes to convert cellulosic materials into ethanol.

The technology for starch- and sugar-based ethanol production is well-established, although improvements in efficiency and yields continue to be made.[8] Ethanol can be produced at dry mills or wet mills. Dry mills are optimized for ethanol production, while wet mills are designed primarily to produce corn sweeteners but generate ethanol as a coproduct. Both types of plants produce animal feed and other coproducts as well. Between 2000 and 2007, the number of ethanol production facilities in the United States more than doubled, and production capacity tripled, with most of the growth from dry-mill plants. In 2008, the ethanol industry included 172 operating plants with a production capacity of 10.6 billion gallons, with an additional 23 plants with 1.7 billion gallons of capacity idled (Urbanchuk, 2009).

One cellulosic commercial plant is operating in Georgia, and several more are under construction. The DOE currently is providing about $500 million to support several small-scale cellulosic biorefinery projects to demonstrate use of a range of cellulosic feedstock such as corn stover and other agriculture residues (e.g., wheat straw, rice straw), wood wastes, municipal solid wastes and energy crops such as switchgrass (U.S. DOE, 2007a, 2008a).

For corn-based ethanol, the majority of feedstock production is in the Midwest, which also is where most ethanol plants are located. In 2005, 98 percent of corn ethanol feedstock was shipped to production plants by truck (USDA, 2007). Thus far, the established infrastructure for food crop distribution has been able to accommodate the transport of starch- and sugar-based ethanol feedstock to production facilities. While most ethanol feedstock resources and ethanol plants are in the Midwest, transportation fuel consumption is highest along the East and West Coasts. Ethanol is generally blended at the local wholesale terminal for use as E10 or E85, with high concentrations of ethanol shipped from the point of production (National Commission on Energy Policy, 2009). In 2005, rail accounted for 60 percent of ethanol shipments and truck for 30 percent (USDA, 2007).

[8] Brazil, the world's second-largest ethanol producer behind the United States and the largest consumer of ethanol for transportation, uses sugar cane as a feedstock. While sugar cane has significantly higher production yields than corn or cellulose, it is not expected to become a major source for domestic ethanol production in the United States since there are limited areas where sugar cane can be grown, and its primary use is for food purposes.

Tax and tariff policy also can affect the market price of ethanol. The Food, Conservation, and Energy Security Act of 2008 reduced a previous ethanol credit from 51 to 45 cents per gallon of ethanol blended, which became effective January 1, 2009 (U.S. DOE, 2009a). Additionally, some producers may qualify for the Small Agri-Biodiesel Producer Tax Credit, which provides a credit of 10 cents per gallon to a producer for the first 15 million gallons produced each year (IRS, 2009).

The latest Farm Bill included a new cellulosic ethanol producer's tax credit of $1.01 per gallon through 2012. The United States also has an import tariff of 2.5 percent on foreign ethanol as well as a secondary tariff of 54 cents per gallon of ethanol imported from non-Caribbean Basin countries, which is in effect through 2010 (U.S. DOE, 2009a); this may provide a disincentive to the use of less expensive sugar cane ethanol imported from Brazil.

Biodiesel from Algae[a]

Algae has long-term potential as a biodiesel feedstock that can be produced on marginal land or in brackish water not suitable for production of other crops. Although an earlier NREL project on algal biofuels that began in 1978 was discontinued in 1996 to focus on ethanol, there has recently been a revival of interest in algae as a biodiesel feedstock due to the many positive characteristics of algae as a feedstock. Growing algae requires land, sunlight, water, carbon dioxide, and macro- and micro-nutrients. CO_2 waste streams from other industrial processes or fossil fuel combustion emissions could be used as feed for algae, serving a beneficial purpose while reducing emission releases. Other benefits of algae production include use of a renewable feedstock that does not impact current U.S. food resources, and ability to use land or water resources that would otherwise be non-productive (e.g., desert land, saline water, waste water).

Since algae is renewable on a continuous basis (i.e., no harvesting/planting cycle), the potential for algal oil production is sizable compared to other renewable crops on a per-acre basis, estimated to provide between 30 and 100 times more biomass per acre than conventional agricultural feedstocks (NGA, no date). However, there are significant challenges to overcome. Three main areas identified for research include (1) selection and breeding of algae strains for continuous high-level oil production, (2) cultivation facility design and operation (including efficient harvesting and oil extraction technologies and finding uses for remaining algae components) and (3) cost-effective fuel production from extracted oil.

[a] This section draws heavily from Pienkos (2007)

2.3 Biodiesel

Overview

Biodiesel is a nontoxic and biodegradable liquid fuel that is made from renewable feedstock such as new and used vegetable oils and animal fats. Biodiesel's properties are similar to petroleum diesel, but it is generally cleaner burning with notably lower PM and SO_x emissions (Radich, 2004). Given the very small number of light-duty diesel vehicles in operation in the United States, the following analysis assumes biodiesel use in medium- and heavy-duty vehicles, although similar benefits would accrue in light-duty applications as well.

Biodiesel can be blended with petroleum diesel in any percentage, with B20 (20 percent biodiesel and 80 percent petroleum diesel) commonly discussed in the literature. However, although some engine manufacturers have approved the use of biodiesel blends of 20 percent or higher, most manufacturers have not officially approved the use of blend levels above B5 (National Biodiesel Board, 2009). Use of higher biodiesel concentrations, especially above B20, may require minor vehicle modifications (e.g., for fuel system seals) as biodiesel is a stronger solvent than gasoline (Congressional Research Service, 2005). For this reason blends of B20 and lower are the most common focus in biodiesel research and testing. As of June 2004, 628 refueling stations offered B20 or higher blends of biodiesel for sale in the United States (U.S. DOE, 2009b).

Some marine applications also are using biodiesel. In 2006, the National Oceanic and Atmospheric Administration (NOAA) implemented the Green Ship Initiative, which converted all research vessels in the Great Lakes region to B100 biodiesel derived from soy. The conversion included propulsion and auxiliary diesel engines for generating electricity. NOAA documented higher lubricity and cleaner injectors with the use of biodiesel compared with marine distillate.

The majority of current U.S. biodiesel production (90 percent) comes from soybean oil, although many other feedstock can be used, including other plant oils such as canola, cottonseed, peanut oil, and rapeseed oil; waste vegetable oils (yellow grease); and animal fat (beef tallow, pork lard). Like corn for ethanol, biodiesel demand for these feedstock competes with food use. Algae also has long-term potential as a biodiesel feedstock, although algae production processes are still in the research and development phase (see sidebar on page 2-45).

The production process for biodiesel is straightforward with relatively low start up costs (NGA, no date). The ease of start up, along with increasing demand, has resulted in rapid growth in the U.S. biodiesel industry in recent years, with production tripling from 2004 to

2005, tripling again from 2005 to 2006, and doubling from 2006 to 2007 to 491 million gallons (predominantly from soy).[9] U.S. biodiesel currently is produced at 148 plants, with production capacities ranging from one million to 25 million gallons per year (AFDC, 2009a). As of June 2009, there were 628 biodiesel refueling stations in the United States (U.S. DOE, 2009b).

The increase in biodiesel production also has been promoted by targeted government initiatives, including a $1 per gallon fuel blender subsidy for virgin-oil biodiesel (e.g., soy oil), and 50 cents per gallon for waste-derived biodiesel (e.g., "yellow greases"). An additional agricultural subsidy from the USDA's Commodity Credit Corporation program provides soybean feedstock production credits of about $1.46 per gallon. B20 also has been designated as an alternative fuel available for fleet credits under EPAct (Lutsey, 2008, pages 73-74). Future demand for biodiesel also may be driven by EPA's RFS targets, and certain states have mandated biodiesel purchasing quotas for their public fleets (NGA, no date).

■ 2.4 Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG)

Overview

Natural gas is a mixture of hydrocarbons, primarily methane, but also contains ethane and propane and small amounts of other gases, including hydrogen sulfide and water vapor. Natural gas is primarily produced from gas wells and as a byproduct of crude oil production. Supplemental sources provide much smaller amounts of natural gas, including synthetic gas, biogas recovered from landfills and other resources (see sidebar on page 2-53), and coal-derived gas.

> **Natural Gas**
>
> *Benefits*: **Low - Moderate**:
> - 15% reduction per vehicle
> - 2.5-5% potential market penetration (LDV) in 2030
>
> *Net Included Costs*: **Net Savings**: -$130 per tonne
>
> *Confidence in Estimates*: **Low**
> - Very low existing market penetration; potential market saturation unknown but likely to be limited by competition for supply with other sectors
>
> *Key Cobenefits and Impacts*: **Positive**
> - Potentially lower life-cycle emissions
> - Increased energy security due to primarily domestic production
>
> *Feasibility*: **Moderate**
> - Currently limited by high incremental vehicle costs and limited refueling infrastructure
>
> *Key Policy Options*:
> - Determine most cost-effective dispatch of natural gas across alternative end uses
> - Assistance with fueling station expansion
> - Incentives for purchase of dedicated CNG vehicles for fleets

In order to be contained in a small enough volume to be useful for transportation, natural gas must be compressed (CNG) or liquefied (LNG). Compressed natural gas is typically stored at up to 3,600 pounds per square inch onboard vehicles, while liquefied natural gas must be purified and condensed into liquid by cooling to -260°F. Liquefied natural gas use is almost exclusively in heavy-duty vehicles (U.S. DOE, 2009h) while CNG is utilized in both light- and heavy-duty applications.

CNG has been commercialized to a more significant degree than LNG, with 781 CNG fueling stations nationwide compared to only 36 LNG stations as of June 2009 (U.S. DOE, 2009b). There were approximately 114,000 CNG vehicles operating in the United States in 2007, about two-thirds of which were LDVs, and about 3,000 LNG vehicles, essentially all of which were HDVs (U.S. DOE, 2007c). CNG vehicles are found in dedicated (natural gas only), and bifuel (natural gas or conventional fuel mode) configurations. The majority of CNG LDVs in operation have been converted to CNG use by certified technicians. Only one original equipment manufacturer (OEM) CNG LDV was available in 2008, the Honda Civic GX (Yacobucci, 2008).

In 2006, approximately 43,000 medium- and heavy-duty CNG and LNG vehicles were in operation across the country. OEM natural gas engines are more common in the medium- and heavy-duty market, with four models available for purchase in 2008 for various applications, including refuse haulers, buses, and line-haul trucks. Five certified retrofit kits also were available for these vehicle types as well (NGVAmerica, 2009). The transportation sector currently consumes about 25 billion cubic feet of natural gas per year, or about 0.1 percent of total national consumption of 23 trillion cubic feet.[10]

Biogas

Anaerobic digestion of organic matter produces a mixture of gases consisting primarily of methane and CO_2 called biogas, also known as landfill or digester gas. Sources include sewage sludge, agricultural and industrial wastes, animal by-products, and municipal solid wastes (AFDC, xxxx). Biogas typically has somewhat lower methane content compared to natural gas, which typically is more than 70 percent methane. The remaining content of natural gas is other hydrocarbons, while biogas contains 20 to 50 percent CO_2. Biogas must be treated to increase the proportion of methane and decrease the CO_2 content and other contaminants (Persson et al, 2006).

After purification, the gas must be transported. Although the purified gas can be distributed using the conventional natural gas infrastructure, further technology development and testing is needed before biogas distribution via the natural gas pipeline grid may become common practice.

Purified biogas can substitute for conventional CNG or LNG as a vehicle fuel. An estimated 12,000 vehicles worldwide, mostly in Europe, are fueled with upgraded biogas. Conversion of landfill gas to transportation fuel has the added benefit of reducing landfill methane emissions.

Research and development projects are underway to reduce costs of producing and purifying biogas as well as to evaluate the performance of vehicles using biogas. However, even allowing for cost-effective recovery, processing, and delivery strategies, the ultimate amount of biogas available for transportation use is quite limited. Assuming all of the methane from landfills, wastewater treatment facilities, and composting could be recovered for transportation use, this would translate to only about 2 percent of current gasoline consumption in the U.S. (based on the 2007 EPA Sources and Sinks value of 158.9 Tg CO_2e emissions, equating to ~ 3 billion gge/yr).

For rail transport, LNG is more applicable for long-haul railroad operations because the fuel density is five times greater than CNG, reducing the space requirement and the required frequency of refueling. LNG can be stored in a separate tender car that is constructed as a double walled stainless shell similar in design to a thermos bottle, and can keep the LNG adequately cold for up to 14 days before gas venting is needed. During operation a heat exchanger converts the LNG back to a gaseous state which is piped to the engine. Dual LNG/diesel engines have been developed and used by Burlington Northern Santa Fe (BNSF) for more than a decade, using diesel fuel as an ignition source for LNG combustion, as well as a backup fuel if there is a failure in the LNG fuel supply. It is possible that LNG may be released from storage tanks if pressure exceeds the tank's design strength. Little data available on LNG venting currently is available, though the practice is not required as long as the tank pressure is maintained at a safe level by keeping the fuel at or below -160 C.

[10] AEO 2009, Table 13.

CNG powered rail engines require more frequent fueling and therefore are more appropriate for switch engine applications, limited to rail yard and short-haul operations.

In marine applications, LNG tanker ships have been using boil-off gas as a fuel source since 1964, with a long and positive experience using the gas to run the vessel's steam turbines, as well as in diesel power plants. Since 1982, at least 18 natural gas powered ships, mainly ferries, have been built worldwide that use CNG, LNG or duel CNG/diesel fuel. Most of these vessels use a dual diesel/CNG fuel configuration with excellent maintenance histories. Since 2000, Norwegian shipping lines have been developing increasingly larger vessels that use LNG, including six LNG ferries and four LNG offshore vessels engaged in regular coastal or short sea shipping services. Several large European ship builders currently are designing even larger LNG powered vessels.

Magnitude and Timing of GHG Reductions

Life-Cycle Emissions

The GREET model estimates a 12 percent reduction in life-cycle GHG emissions associated with bifuel CNG use in LDVs, and 15 percent for dedicated CNG vehicles, the latter being roughly comparable to diesel vehicle benefits relative to conventional gasoline vehicles. A 1999 Argonne National Laboratory (ANL) report estimated long-term GHG reductions for CNG (with projected production improvements and modest improvements in vehicle fuel economy) between 21 and 26 percent. A study conducted by the Federal Transit Administration (Clark et al., 2007) estimated that life-cycle GHG emissions for CNG transit buses were approximately equal to those of a comparable diesel bus using ultralow sulfur fuel. Based on these estimates, CNG is evaluated in this section as a potential alternative to gasoline LDVs rather than for heavy-duty diesel applications, since replacing diesel HDVs with CNG HDVs may not result in GHG reductions.[11]

The 1999 ANL report also estimated that, compared to gasoline used in LDVs, methane emissions typically increased by a factor of four for CNG vehicles. Natural gas is largely comprised of methane, which is 25 times more potent as a GHG than CO_2. A substantial portion of the GHGs emitted from the life cycle of natural gas fuels are fugitive emissions of methane that escape during transport, storage, or dispensing of the natural gas. However, net GHG reductions are still projected for natural gas vehicles by the GREET model, which includes estimates of fugitive methane emissions as well as CO_2. Nevertheless, methane's high global warming potential merits special precautions to minimize fugitive losses during all portions of the production and use cycle.

[11] Although not evaluated explicitly in this assessment, LNG (and CNG) may provide an incremental GHG reduction benefit for niche applications in certain gasoline HDV trucks.

Market Penetration

The future market potential for CNG vehicles is highly uncertain. The AEO Reference case only projects a modest increase in the number of CNG LDVs over time, with about 144,000 vehicles (substantially less than one percent of the total vehicle stock) capable of operating on natural gas in 2030.[12] On a Btu basis, CNG's contribution to total LDV fuel consumption is even smaller, less than 0.1 percent in both the near and long term.[13]

CNG vehicles are a proven technology, which could be produced and utilized in substantially greater numbers assuming incremental vehicle costs and refueling infrastructure issues could be adequately addressed. However, the extent to which existing natural gas supplies could be cost-effectively diverted from their primary uses (roughly evenly split between residential/commercial, industrial, and electricity production; NGA, no date), is uncertain. Such a determination would require macroeconomic modeling regarding energy resources at the national and possibly international level.

However, as a conservative point of reference it is assumed that between 2.5 and 5 percent of current natural gas consumption (0.6 to 1.1 trillion cubic feet per year in 2010)[14] could be diverted, or production expanded, for LDV use by 2030 at a minimal cost increase to the consumer. This amount of gas corresponds to up to 7.9 billion gge per year, or roughly 3 percent of light-duty vehicle gasoline use in 2010. Assuming CNG vehicle fuel economy values equal to conventional gasoline vehicles, this level of consumption corresponds to approximately 10 to 19 million CNG vehicles on the road in 2030. This is substantially less than the number of hybrid-electric vehicles (HEV) assumed to be on the road by this time under the AEO Reference case, and should be technically feasible.

Net Impacts

Applying the GREET GHG reduction estimates for dedicated CNG vehicles, this scenario translates to a reduction of approximately 7 to 13 mmt CO_2e in 2030 (Table 2.4). As noted, this scenario is highly speculative, and could be significantly higher or lower depending upon available gas supply, vehicle costs, and infrastructure development status.

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[12] AEO 2009, Supplemental Table 58.

[13] AEO 2009, Supplemental Table 47.

[14] AEO 2009, Table 14.

Table 2.4 LDV Penetration and GHG Reductions Utilizing Five Percent of Natural Gas Supply

Year	Incremental # CNG LDVs (Millions)	Gasoline Saved (Mgal/Year)	GHG Reduction (mmt CO2e/yr)
2030	9.5-19.0	4.0-7.9	7-13

Cost-Effectiveness

The market price of CNG compares quite favorably with that of gasoline in general. The AEO Reference case estimates retail national average CNG prices at $1.76 per gge in 2010, compared to $2.14 for gasoline, including taxes.[15] After taxes and credits, the near-term incremental cost of CNG is estimated to be 33 cents per gallon in 2010.[16] Under these assumptions, CNG obtains a savings relative to gasoline (pretax/credit) when retail gas prices climb above $2.46 per gallon.

A substantial cost savings for CNG is expected to develop in the long run, with CNG prices rising only 16 percent between 2010 and 2030, while gasoline prices are projected to increase by almost 80 percent over this same period.[17] Accordingly, a $1.07 per gallon savings is estimated for CNG relative to gasoline in 2030. Note this assessment assumes that CNG fueling station costs are fully recovered in the fuel sales price.[18]

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[15]See AEO Tables 12 and 13. Cost differentials are volatile, with falling gasoline prices eroding the cost advantage of CNG substantially relative to 2008 fuel prices. The Clean Cities reports also track the price of CNG over the past few years (U.S. DOE 2009g, p. 14). CNG prices tends to track with gasoline and have similar seasonal spikes, in part because some of the supply comes from crude oil refining, and in part, because natural gas experiences peak demand in the summer similar to gasoline. Similar trends are expected for LNG as liquefaction costs are fairly constant over the year, although a much smaller market exists and less price data has been collected for LNG relative to CNG.

[16]Assuming 18.3 cents per gge federal tax, no state tax, and a 50 cent per gge excise tax credit for CNG.

[17]AEO Tables 12 and 13.

[18]Fueling station costs are roughly $500,000 per California Energy Commission (2006). The above CNG prices assume the use of "fast-fill" retail stations. If fueling is performed using home refueling units, an additional cost savings of about 15 cents per gge could be obtained. (http://www.eia.doe.gov/oiaf/archive/aeo08/gas.html) Home refueling requires an additional

(Footnote continued on next page...)

Incremental costs for CNG LDVs range from approximately $3,000 to $6,000 for original equipment manufacturer (OEM) vehicles (NGA, no date), to approximately $15,000 for conversion of an existing gasoline vehicle (NGVA, 2009). Much of the costs to the vehicle owner may be defrayed through tax credits, however. This analysis assumes the use of dedicated OEM vehicles in the medium to long term. In this timeframe, OEM vehicle costs would likely decrease under higher production volume scenarios (NGA, no date). Accordingly, the lower value of $3,000 is assumed for the 2030 assessment.

Table 2.5 summarizes the incremental costs, savings, and emission reduction benefits associated with CNG use as an alternative to gasoline LDVs in 2030, with an estimated cost-effectiveness of -$132/tonne. One estimate was identified in the literature regarding potential cost-effectiveness of CNG vehicles in the medium term (McKinsey, 2009, page 100), at approximately -$50/tonne. These negative cost per tonne values are likely the result of large fuel savings assumed in these analyses.

Table 2.5 CNG per Vehicle Cost and Cost-Effectiveness Ranges by Time Period

Year	Incremental Vehicle Cost	MPGGE[a]	Lifetime Gasoline Saved (Gallons)	Discounted Fuel Savings[b]	Net Discounted Cost/Savings	Average GHG Reduction (Tonnes/Year)	Dollars/ Tonne – Calculated
2030	$3,000	28	6,500	$4,460	-$1,460	0.7	-$132 to -$50

[a] Equal to AEO 2030 conventional gasoline vehicle.

[b] Using pretax AEO gasoline and CNG gge price projections for 2030 (long-term) of $3.43 and $2.36, respectively.

Cobenefits

Natural gas, as either LNG or CNG, is clean-burning and emits somewhat lower levels of particulate matter and ozone precursors compared to gasoline or diesel light-duty vehicles. The GREET model estimates life-cycle reductions for dedicated CNG LDVs relative to conventional gasoline vehicles, as shown in Table 2.6. The differentials may vary, however, depending upon the gasoline vehicle emissions control technology.

$4,500 for the necessary slow-fill equipment (CRS, 2008). This analysis assumes exclusive use of fast-fill retail stations.

Table 2.6 Emissions for Natural Gas (CNG) versus Conventional Gasoline

Pollutant	Percent Change versus Light-Duty Gasoline
VOC	-45%
CO	0%
NO_x	-20%
PM_{10}	-9%
$PM_{2.5}$	-20%
SO_x	+11%

In addition, about 90 percent of all natural gas consumed in the United States is domestically produced, thereby improving energy security relative to current petroleum-based fuels.

Feasibility

As discussed above, CNG LDVs have relatively high incremental vehicle costs and limited fueling infrastructure. In addition, CNG LDVs also have significantly decreased operational range compared to comparable gasoline vehicles, due to the lower energy density of natural gas, even when under pressure. For example, the dedicated CNG Honda Civic can only accommodate a 7.2 gge storage tank, limiting its operating range to 170 miles (Honda, 2009). Operating range can be extended, especially when converting light trucks and SUVs, by increasing tank capacity, but at the cost of lost storage and hauling capacity (NGVAmerica, 2009).

CNG LDVs have excellent safety records on the whole. CNG tanks are made to withstand very high pressures and temperatures to minimize safety problems. The odorant ethyl mercaptan also is added to natural gas to aid in leak detection for CNG, although odorants are not added to LNG. In addition, engine maintenance requirements appear to decline in natural gas engines relative to conventional engines, due to the very clean burning properties of the fuel, which may in turn result in extended engine life.

Despite the acceptance of LNG as a transportation fuel, there are a few safety concerns associated with its use. Some of the potential dangers include cryogenic burns, lung damage, and asphyxiation. LNG also can vaporize to the gaseous phase leading to extremely high pressure buildup; hence, pressure release valves are used to prevent rupturing of tanks and piping systems (Battelle, 2002). Therefore fleet technicians and maintenance personnel must be trained in the use of cryogenic fuel systems. However, between 1980 and 2002 only four vehicle-related LNG accidents were reported in the United States, none involving fatalities (Foss, 2003).

With respect to infrastructure requirements, natural gas is widely used as a fuel throughout the United States, accounting for approximately one-quarter of total energy consumption, but only one-tenth of one percent is used for transportation. Despite the small amount used for transportation, the infrastructure is largely in place to distribute CNG much more widely throughout the United States for vehicle use. Natural gas is transported by 300,000 miles of transmission pipeline throughout the 48 contiguous states with an additional 1.9 million miles of pipeline available for use within utility service areas. There also are hundreds of storage facilities, and over 50 points for importing and exporting natural gas. "fast-fill" CNG fueling stations are found in all but four states, although many of the 775 locations are restricted access for private fleet use. These stations require significant equipment purchases, including large compressors and dispensing equipment to allow for fueling in a matter of minutes.

Given the increase in CNG LDV market penetration evaluated above, a large increase in the number of CNG fueling stations would be required. Assuming the same average number of vehicles could be served by a CNG station as are served at conventional gasoline stations today (roughly 1,900 vehicles per station in the U.S.; Kushner, 2009), this equates to an additional 10,000 CNG stations, requiring sizable investment. In addition, this number is likely to be even higher in order to provide the necessary geographic coverage for nationwide support of 19 million CNG vehicles.

CNG vehicles also may be fueled in private residences or garages using a "slow-fill" process. CNG home fueling appliances are available that can be installed outside or in a garage to fuel a CNG vehicle overnight. With approximately 55 percent of households having natural gas hookups (U.S. DOE, 2009f), this option can help facilitate CNG vehicle market penetration until public refueling infrastructure expansion can take place. Cost is a potential barrier, however.

LNG is less accessible than CNG as there are fewer fueling stations in place, and only a few large-scale liquefaction facilities in operation. Liquefaction can occur either on or off fueling station property. However, liquefaction would either have to be performed at each fueling station or many more large scale liquefaction facilities would need to be built so that LNG could be transported directly to the station by tanker truck.

Some limited expansion of LNG availability may be facilitated by the increase in LNG import capacity in the United States over the last few years. As of 2007, four LNG import terminals were operating in the United States, located in Massachusetts, Maryland, Georgia, and Louisiana, with three additional terminals under development in Texas. The design capacity of these facilities ranges from 725 to 2,600 million cubic feet of gas per day (U.S. DOE, 2007b). However, these facilities are intended for regasification for gas pipeline distribution, and LNG would have to be diverted by tanker truck for transportation use.

Given the limited economical range of tanker truck deliveries, LNG import impacts would likely be limited to areas near these terminals.

One other potential benefit of expanding CNG usage in the short run is that it could facilitate hydrogen use in the future. Natural gas itself is the number one source of commercial hydrogen used in the United States, so natural gas distribution lines could be used to bring natural gas to fueling stations where it could in turn be converted to hydrogen. This could be an early step to help create demand for a hydrogen fuel economy and is being done at a number of the roughly 60 hydrogen fueling stations across the country.

While these projections do not anticipate natural gas vehicles becoming a large component of the overall fleet mix, the potential exists for increases in the short run, primarily among fleet vehicles with centralized fueling and high fuel costs. As discussed above, the price of natural gas is most often comparable to or lower than gasoline; the distribution pipeline is in place; vehicles may be fueled overnight at home; natural gas is produced almost exclusively domestically; and hundreds of fueling stations already exist.

Along with electricity and hydrogen, natural gas is "fungible," with multiple end use options. In addition to transportation and home heating, natural gas has a substantial role in the energy sector producing electricity. In fact, electricity generated using natural gas averages 1.18 pound CO_2 per kilowatt-hour (kWhr), compared to an average value of 2.14 pound per kWhr for coal fired units.[19] Thus, to the extent that multiple end use options are available, replacing coal power with natural gas offers substantially greater GHG reduction potential (about 50 percent) than its use in transportation (about 15 percent). In fact, increased demand for natural gas resulting from carbon limits placed on electrical generating units may limit CNG and LNG availability for transport greatly, although a detailed analysis of such impacts is beyond the scope of this assessment.

[19]Combustion emissions (rather than life cycle), from eGRID2006V2_1_plant.xls.

2.5 Liquefied Petroleum Gas (LPG)

Overview

Liquefied Petroleum Gas

Benefits: **Low**:

- 17% reduction per vehicle
- Minimal market share

Net Included Costs: **Not calculated**

Confidence in Estimates: **High**

- Limited by fuel supply and inherently higher costs

Key Cobenefits and Impacts: **Positive**

- Potentially lower life-cycle emissions

Feasibility: **High**

- Existing distribution infrastructure

Key Policy Options:

- Consider incentives for niche applications such as fleet vehicles

Liquefied petroleum gas (LPG), also known as propane, can be used to replace gasoline and diesel. LPG is the fourth most common vehicle fuel, behind gasoline, diesel, and natural gas,[20] although less than two percent of U.S. consumption of LPG is used for transportation.[21] LPG vehicles are found in both light- and heavy-duty applications, such as service trucks and buses. Like CNG vehicles, LPG vehicles can be designed for dedicated alternative fuel use, or for bifuel configurations which allow for operation on gasoline as well.

Domestic LPG sources are divided fairly evenly between byproducts of crude-oil refining and byproducts of natural gas processing. Domestic LPG demand is not high enough to justify importing oil specifically for the purpose of creating LPG, meaning the supply of LPG is relatively constant throughout the year. Recently, researchers at MIT have demonstrated the ability to make "biopropane," which is LPG made from corn or sugarcane, and have created a startup company that is attempting to scale up the production process of LPG from corn and sugarcane (Bourzac, 2007). In the end however, this production method will likely only be viable as a niche option to produce LPG given the competition for corn feedstock for ethanol production and food and because sugarcane is not a viable large scale feedstock in the United States.

In 2006, there were approximately 94,000 light-duty LPG vehicles in operation in the United States, and about 70,000 medium- and heavy-duty LPG vehicles (U.S. DOE, 2007b). The vast majority of LD LPG vehicles were converted from gasoline cars and trucks, and no light-duty OEM models currently are available for purchase. Several OEM LPG

[20] AEO 2009, Supplemental Tables 47 and 67.

[21] AEO 2009, Table 2.

engines are available for heavy-duty vehicle use, including delivery trucks, school and shuttle buses, and recycling trucks (Propane Council, 2009).

LPG stations can be found throughout the country. There were over 2,200 LPG fueling stations nationwide, as of June 2009, making it the most widely available alternative fuel in the United States today (U.S. DOE, 2009b).

In marine applications LPG-powered vessels have been used as a replacement for relatively small (from 5 to 60 horsepower) gasoline-powered vessels. Due to the lower energy content of LPG, there is a 10 to 15 percent power loss at high-speed especially under load; therefore, it is not an effective alternative fuel for freight movement. Similarly, LPG is not an option for rail modes.

Magnitude and Timing of GHG Reductions

Life-Cycle Emissions

Unlike natural gas, propane does not have a significant direct global warming potential when released into the atmosphere, although it does have indirect impacts.[22] A report by Argonne National Laboratory (ANL, 1999) combined emissions data from three primary studies to determine the effects of LPG on LDV emissions. These results were used in the GREET model for a comparison with LDVs running on gasoline. The analysis found that LPG reduced GHG emissions by 21 to 24 percent (including a methane emissions increase of 10 percent). The cited GHG reductions are for LPG produced from natural gas. For the current industry average LPG supply (60 percent produced from natural gas, 40 percent from crude oil), GREET 1.8b estimates GHG reductions of 17 percent for LPG vehicles compared to gasoline vehicles. As with natural gas vehicles, GHG levels associated with LPG are roughly comparable to those from diesel vehicles; therefore, use of LPG in heavy-duty vehicles is not analyzed as a GHG reduction strategy.

Market Penetration

The EIA's short-term outlook for LPG production predicts fairly constant levels over the next few years. U.S. natural gas liquids production (of which over 95 percent is LPG) is

[22] Indirect global warming potential (GWP) occurs through the affect on terrestrial radiation absorption by influencing the formation and destruction of tropospheric and stratospheric ozone, or by affecting the absorptive characteristics of the atmosphere. Propane is estimated to have an indirect GWP of 3.3 (IPCC, no date). To the extent that LPG vehicle use leads to fugitive propane emissions associated with additional production, storage and/or distribution, some amount of GHG enhancement may be expected. However, the life cycle approach adopted for this analysis only includes direct GWPs.

predicted at approximately 25 billion gge from 2008 through 2010.[23] EIA projects long-term production decreasing in future years, from about 23.9 to 22.1 billion gge per year between 2015 and 2030 (U.S. DOE, 2009a).

Even at these production volumes, however, the potential for LPG to significantly penetrate the transportation market appears limited. First, the price of LPG is typically higher on a gge basis than conventional gasoline, as discussed below. In addition, LPG and gasoline prices are related, since a large portion of LPG is produced from crude-oil refining. Most importantly, the total production capacity for LPG is highly limited because it is a byproduct of crude-oil refining and natural gas processing. This means that allocating more LPG for the transportation sector would necessitate cutting the amount of LPG used in the residential, commercial, and/or petrochemical sector, where alternative supply options may be tightly constrained. While the infrastructure to store and distribute LPG seems to be adequate to allow for expanded use in transportation, the LPG supply cap will ultimately be limiting.

Net Impacts

These facts, combined with the relatively high incremental cost of converting vehicles to LPG use, have inhibited the market penetration potential of LPG in the transportation sector for years despite the incipient commercial infrastructure in place. The AEO Reference case even projects a declining LPG LDV stock over time, falling from approximately 85,000 in 2008 to about 14,000 in 2030 (Supplemental Table 58). The Reference case also assumes very modest increase in medium- and heavy-duty LPG vehicles during this time, from about 66,000 units in 2008 to 75,000 units in 2030 (Supplemental Table 67). The corresponding 2030 fuel consumption levels for 2030 are six million gge for LDVs and 112 million dge for medium- and heavy-duty vehicles in 2030.[24] At these LPG consumption levels GHG emission reductions equate to 230,000 metric tons per year. However, given the limited potential for increased LPG market share, quantitative estimates of GHG reduction potential beyond the AEO baseline, and associated costs and cost-effectiveness, are not presented for LPG LDVs.

Cost-Effectiveness

The market price of LPG is often higher than gasoline on a gge basis. According to the AEO Reference Case, retail LPG prices are estimated to be $2.51 per gge in 2010, and $4.11 in 2030 (Table 12). Netting out taxes (which average 26.3 cents per gallon for LPG and 38.7

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[23]From 1.80 million barrels of LPG per day at 4.45 million BTUs per barrel.

[24]Supplemental Tables 47 and 67, respectively, and assuming 84,300 Btu/gallon of LPG.

cents per gallon for gasoline), the cost differential between the LPG and diesel comes to 50 cents per gge in 2010, and 41 cents per gge in 2030.

The negligible variance in fuel cost increase is to be expected, as the LPG market price tracks very closely with oil and gasoline since much of it is produced as a byproduct of crude-oil refining and it competes with crude-oil-based fuels in the market. The price volatility of the two fuels is comparable, except that LPG also is susceptible to a wintertime price peak. The supply of LPG is relatively constant as it is tied to crude oil and natural gas production. As a result, when wintertime demand increases due to its use as a heating source, there is no way to increase supply, so prices typically spike, as shown in the figure.

Incremental costs for light-duty OEM LPG vehicles ranged from $1,000 to $2,000, when last produced in the early 2000s (Yacobucci, 2005). Light-duty vehicle conversions are significantly more expensive, ranging from $4,000 to $12,000 (AFDC, 2009a). Much of the costs to the vehicle owner may be defrayed through extensive tax credits, however.

Cobenefits

The GREET model estimates reduced emissions for LDV LPG use, for all criteria pollutants, with the largest reductions found for VOC and PM. CO reductions are negligible compared to gasoline, however (Table 2.7).

Table 2.7 Life-Cycle Emissions for Liquid Petroleum Gas versus Conventional Gasoline

Pollutant	Change in Emissions versus Gasoline
VOC	-35%
CO	0%
NO_x	-14%
PM_{10}	-47%
$PM_{2.5}$	-38%
SO_x	-14%

Feasibility

LPG is generally regarded as an exceptionally safe transportation fuel. LPG has the lowest flammability range of all alternative fuels, and LPG tanks are 20 times more puncture resistant than gasoline tanks. Additionally, an odorant, ethyl mercaptan, is typically added to quickly identify tank leaks (AFDC, 2009a). For marine vessel applications, there is a safety concern because LPG is denser than air, and it tends to accumulate in ship hulls in concentrations that could be explosive. There is a similar concern for LPG vehicles in enclosed spaces, which may require additional ventilation systems to avoid pooling of vapors.

While there is a range penalty associated with dedicated LPG vehicles due to the fuel's lower energy density compared to gasoline (~20 percent), increasing tank volumes can be used to offset this limitation to some degree. Vehicle performance is similar to comparable conventional vehicles, while maintenance costs and engine life may be improved due to LPG's clean burning properties (AFDC, 2009a).

Because LPG already is used extensively around the country for numerous purposes, the infrastructure for bulk production, storage, and distribution already is in place. Infrastructure costs related to expanding LPG's use as a transportation fuel would thus primarily be related to expanding the distribution network by converting existing gas stations and building new LPG stations. The conversion from a gas station to an LPG station is straightforward, only requiring the installation of a tank, pump, and metering equipment.

2.6 Synthetic Fuels

There are a number of synthetic fuels in various stages of research and development with potential for use in the transportation sector. Synthetic fuels typically utilize fossil fuels such as coal or natural gas as their feedstock, although biomass sources such as vegetable oils and fats also may be used. Depending on engine type and application, these fuels may be substituted directly for conventional fuels with little to no modification to existing engines or fueling infrastructure. Synthetic jet fuel can be used directly or blended with conventional jet fuel in existing aircraft engines without modification. Synthetic fuels also contain almost no sulfur species or aromatics. Therefore, sulfur emissions from combustion are essentially zero, VOC emissions extremely low, and particulate matter can be reduced 50 to 90 percent. In most cases, however, substantial uncertainty remains regarding the cost and production potential for these fuels.

The following provides a brief overview of several of the more promising synthetic fuels under evaluation today.

Fischer-Tropsch (FT) Fuels

The Fischer-Tropsch (FT) process converts gaseous hydrocarbons into liquid fuel. The gas sources used include natural gas and gasified coal or biomass, each described briefly in the following sections. Use of the FT process to convert natural gas into liquid fuels has been done on a commercial scale for decades in South Africa, and more recently in Europe and Thailand. Most major oil companies have announced plans to investigate gas-to-liquid production of diesel. In the United States, more than 400,000 gallons of natural gas-derived liquid fuels, including diesel and jet fuel, have been produced by Syntroleum at a demonstration plant. DOE supports research and demonstration projects for GTL production and use in vehicles through its Vehicle Technologies Program, which includes the National Renewable Energy Laboratory's work on nonpetroleum-based fuel use in vehicles (U.S. DOE, 2009d).

While natural gas and coal are still fossil fuels, use of these fuels to produce FT diesel may have some advantages over conventional diesel. However, current production methods using conventional fossil fuel feedstock appear to increase life-cycle GHG emissions relative to conventional diesel. For example, one DOE evaluation found that coal-based feedstocks more than doubled GHG emissions per mile for an SUV relative to conventional diesel. Natural gas feedstocks had less impact, but still increased emissions by roughly 20 to 60 percent depending upon the source of gas.

Regardless of the feedstock used, Fischer-Tropsch diesel can be substituted directly for conventional (petroleum-derived) diesel to fuel diesel-powered vehicles without modification to the vehicle engine, distribution infrastructure, and fueling infrastructure. FT fuels also are considered ultralow sulfur.

Biobutanol

Butanol derived from biomass feedstock is referred to as biobutanol. Like ethanol, butanol is suitable for blending with gasoline. The energy content of butanol is higher than ethanol but lower than gasoline. EPA considers gasoline blends with up to 11.5 percent butanol to be operationally similar to pure gasoline (AFDC, 2009a). Testing of higher concentrations of biobutanol in current vehicles has been limited, so it is uncertain what upper limit of biobutanol blend can be used without requiring vehicle modifications. Although butanol is generally being considered as a gasoline blend component, a preliminary study by Argonne National Laboratory (cited at the Green Car Congress web site) has shown that use of butanol as a blending agent in diesel fuel reduces emissions of particulate matter without significantly increasing NO_x.

Biobutanol also does not cause corrosion and water contamination problems as does ethanol, so biobutanol could likely use existing gasoline infrastructure for distribution. Biobutanol would not require new or modified pipelines, blending facilities, storage tanks, or retail dispensing pumps. In addition, relatively minor modifications are required to adapt existing ethanol facilities to produce butanol.

Processes to produce butanol by fermentation of biomass have existed for many years, but these processes have been more expensive than production of petrochemicals. However, there are several efforts currently underway to produce biobutanol more efficiently and economically. Nevertheless, the long-term production potential and costs for biobutanol remain highly uncertain at this early stage of development (Lammers, 2008). Furthermore, production of biobutanol results in significant volumes of acetone as a byproduct, and it is not clear what would be done with this acetone if biobutanol were produced on a large scale (Smith, 2009).

Biomass-to-Liquids (BTL)

Most BTL processes today are either a) gas-to-liquid processes, in which biomass is first converted into a gas, then to a liquid, or b) pyrolysis processes in which biomass is decomposed in the absence of oxygen to produce a liquid oil. In the gas-to-liquid process, biomass is heated with insufficient oxygen for complete combustion, producing synthesis gas (syngas) composed of carbon monoxide and hydrogen. There are a variety of commercial processes that can be used to convert syngas into useful products, including fuels and chemicals, or syngas can be burned to produce electricity. Currently, there are no commercial biomass gas-to-liquids producers in the United States.

Pyrolysis, also known as thermochemical conversion, produces oil that can be burned like fuel oil or refined into fuels and chemicals. Production of energy and chemicals from pyrolysis oil is being done at several commercial facilities, and high-quality hydrocarbon fuels have been produced from pyrolysis oil in demonstration projects, but not on a commercial scale.

BTL technology is relatively immature, with research focusing on improving process efficiency and economics. DOE is working to produce biosyngas suitable for commercial fuel applications.

In addition to compatibility with existing vehicles and fuel infrastructure, other benefits of BTL fuels include use of renewable feedstock, carbon-neutral combustion emissions (return to the atmosphere of carbon dioxide removed from the atmosphere during biomass growth), similar or better vehicle performance compared to conventional fuels, and reduced exhaust emissions of regulated substances.

Coal-to-Liquids (CTL)

As its name implies, CTL technology involves converting coal into liquid fuel, via the FT process (the dominant CTL process) or direct liquefaction. Commercial CTL fuel production already is occurring, and research is underway to improve production efficiency and economics and develop FT CTL projects on a commercial scale. In the Bergius hydrogenation process, a direct liquefaction process, coal is reacted with hydrogen to produce liquids that can then be refined into synthetic fuels.

Both CTL and gas-to-liquid FT diesel processes increase greenhouse gas emissions relative to conventional diesel, but carbon sequestration technologies may be used for mitigation in the future if these technologies are successfully developed. A recent report from the DOE National Energy Technology Laboratory (NETL) concluded that CTL with carbon capture and sequestration (CCS) could result in 5 to 12 percent lower life-cycle GHG emissions compared to conventional diesel. The synthetic fuel is economically competitive with petro-diesel when crude oil prices rise above $86 per barrel. Adding eight percent biomass to the CTL process (with CCS) results in a fuel with 20 percent lower life-cycle GHG emissions, and is economically competitive with conventional diesel at oil prices at or above $93/barrel (Green Car Congress, 2009). However, CCS technologies require additional development and demonstration before this option is considered a viable GHG reduction strategy.

Hydrogenation-Derived Renewable Diesel (HDRD)

Fats or vegetable oils that have been processed in a refinery and used alone or blended with petroleum are known as HDRD, sometimes called a "second-generation biodiesel." It is expected that HDRD, like FT diesel, can substitute directly for conventional diesel without requiring modifications to engines or infrastructure. However, further testing is needed.

Although HDRD research is well advanced and close to full commercialization, HDRD is not yet widely available. A number of companies have commercial trials underway, although long-term costs and production potential remain uncertain. Gasoline can be produced by a similar process, but this process is less developed.

Because the HDRD process uses existing oil refinery capacity, extensive new production facilities are not required. Other benefits include use of renewable resources, carbon-neutral combustion emissions, anticipated compatibility with existing vehicle engines and fuel infrastructure, fuel properties that suggest similar or better vehicle performance compared to conventional diesel, and ultralow sulfur content.

■ 2.7 Alternative Aviation Fuel

The fuel burned in turbo-fan and turbo-prop aircraft engines is unique in that it is kerosene-based fuel.[25] And unlike other transportation modes that can operate on a range of fuels, aircraft engines require fuels with highly specific characteristics, making alternative aviation fuel options for commercial air passenger and freight transport more challenging. Extensive studies are required to evaluate fuel performance, potential safety concerns, international fuel availably, and changes to existing infrastructure (aircraft/engine designs as well as fuel distribution systems). Changes to aviation fuels require industry and user consensus achieved through the standard setting bodies: ASTM International in United States and DefStan in the United Kingdom.

Studies of alternative aviation fuels have been implemented by a large number of government agencies such as the U.S. DOT's Volpe National Transportation Systems Center, the Federal Aviation Administration, U.S. Department of Defense (DOD), and the National Aeronautics and Space Administration (Esler, 2007), as well as the Canadian National Research Council's Institute for Aerospace Research, and the European Commission's Sustainable Way for Alternative Fuel and Energy in Aviation (SWAFEA) program within the Directorate General for Energy and Transportation. Information concerning alternative aviation fuels is shared with diverse stakeholders through programs such as the Commercial Aviation Alternative Fuels Initiative (CAAFI) and the International Civil Aviation Organization (ICAO) that seek environmentally sustainable aviation fuels options that are economically viable.

Most aviation fuel research has focused on four general classes of alternative fuels which include cryogenic fuels (such as liquid hydrogen, methane, LPG, butane, or other petroleum gases), alcohol fuels (for example, ethanol, and methanol), biofuels, and synthetic fuels (Daggett et al., 2006).

Cryogenic and alcohol fuels currently are not viable as replacements for conventional kerosene-based jet fuels as they have low-energy density, requiring more fuel to provide the same performance as conventional jet fuel. A much larger wing would be required for fuel storage, and aircraft engines would have to provide significantly more thrust to compensate for the greater weight of the modified aircraft and associated fuel.

Synthetic jet fuels are derived through use of the Fischer-Tropsch (FT) process described previously. In 2009, ASTM International approved a new specification for commercial use of a 50 percent blend of synthetic jet fuel made from any feedstock including coal, gas or

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[25]While piston propeller aircraft consume aviation gasoline, kerosene-based jet fuel use is approximately 100 times greater than aviation gasoline. As such, only alternatives to kerosene-based fuel are considered herein. (http://www.eia.doe.gov/emeu/states/sep_fuel/html/fuel_av_jf.html).

biomass. Synthetic jet fuel from coal made by SASOL at the Secunda plant in South Africa is being sold for jet aviation applications. Synthetic fuel represents the only currently approved "drop-in" alternative fuel for the commercial aviation industry, in that it can be applied directly to aviation applications without changes to existing aircraft engine or frame design or the existing aviation fuel distribution system (Hileman et al., 2008).

Synthetic fuels are attractive as they have low concentrations of sulfur and aromatics and a slightly higher hydrogen to carbon ratio. Use of these fuels in aviation application provide significant reductions in sulfur and hydrocarbon emissions (Brown et al., 2008). Emissions of particulate matter are reduced 50 to 90 percent while combustion CO_2 emissions can drop by two to four percent (Blackwell, 2007; Chevron, 2006). As noted earlier, however, when life-cycle emissions are taken into consideration CO_2 can increase significantly depending upon the feedstock used in the process.

Alternatively, jet fuel can be created from animal fats, plant oils, sugars, and cellulose; these products are often referred to as hydroprocessed renewable jet (HRJ) fuels and have nearly the same weight, volume, and energy characteristics as petroleum-derived jet fuel. HRJ fuels are seen as attractive for a variety of reasons, one of which being that when life-cycle emissions are taken into consideration they can have a positive effect on greenhouse gas emissions because all of the carbon in the finished fuel originated in the atmosphere as CO_2 which has been absorbed by plants that were turned into oils or fed to animals and converted into fats (Syntroleum, 2009; Green Car Congress, 2007).

The U.S. Department of Defense's Defense Advanced Research Projects Agency (DARPA) in conjunction with the Energy and Environmental Research Center's National Alternative Fuels Center at the University of North Dakota are investigating a variety of affordable alternatives to petroleum-based JP-8, include biofuels derived from agricultural (e.g., soy, palm, canola, and coconut oil, and inedible oils such as jatropha and camelina and animal fats) and aquacultural (i.e., algae) feedstock materials that are noncompetitive with food sources. The goal of the BioFuels – Alternative Feedstocks study is to reduce the military's reliance on nonrenewable and imported sources of oil. DARPA is evaluating the technological feasibility of developing fuels from these alternative feedstocks, as well as the anticipated cost of these fuels (U.S. DOD, 2009). Similar studies currently are being implemented in the private sector by aircraft and engine manufacture such as Boeing, General Electric, and Rolls-Royce as well as many of the major airlines.

In order for bio HRJ fuels to meet stringent commercial aviation fuel standards, these fuels need to be refined in a hydrotreatment process similar to that used for Hydrogenation–Derived Renewable Diesel (HDRD). The higher costs for processing put HRJ fuels at a higher price than HDRD. As jet fuel prices increase in the future HRJ fuels may be a competitive option relative to existing petroleum products. Alternatively, cost impacts can be reduced by blending biojet fuel with conventional jet fuel. In 2009, ASTM International approved specification for 50 percent blend of FT fuel. Specification approval for 50 percent hydrotreated renewable jet fuel is expected in 2010.

2.8 Hydrogen

Overview

Hydrogen gas can be used in two important ways within America's transportation sector. First, it can be burned directly in a hydrogen internal combustion engine (HICE) to power a vehicle; and second, it can be combined chemically with oxygen from the air within a fuel cell to create an electric current which can be used to power a hydrogen fuel cell vehicle (HFCV). HICEs can be used in a conventional configuration or in hybrid configurations (similar to today's gasoline-electric hybrids). A small number of vehicles have also been built that can switch between hydrogen and gasoline, and can operate on gasoline as the need arises due to the lack of a hydrogen fueling infrastructure.

Hydrogen Fuel Cell Vehicles

2030 Benefits: **Moderate-High**:

- 40-55% reduction per vehicle
- 18% potential market penetration (LDV) is high estimate from literature

2050 Benefits: **High**:

- 79-84% reduction per vehicle
- 60% potential market penetration (LDV) is high estimate from literature

Net Included Costs: **Net Savings to Moderate Cost**: -$160 to +$70 per tonne

- Some studies show much higher costs – range of -$200 to +$800 from literature

Confidence in Estimates: **Low**

- Development of both vehicle technology and fuel production/distribution infrastructure are highly uncertain

Key Cobenefits and Impacts: **Mixed/Uncertain**

- Current modeling shows decreases in some pollutants but increases in PM; will depend upon fuel source

Feasibility: **Low-Moderate**

- New distribution infrastructure required

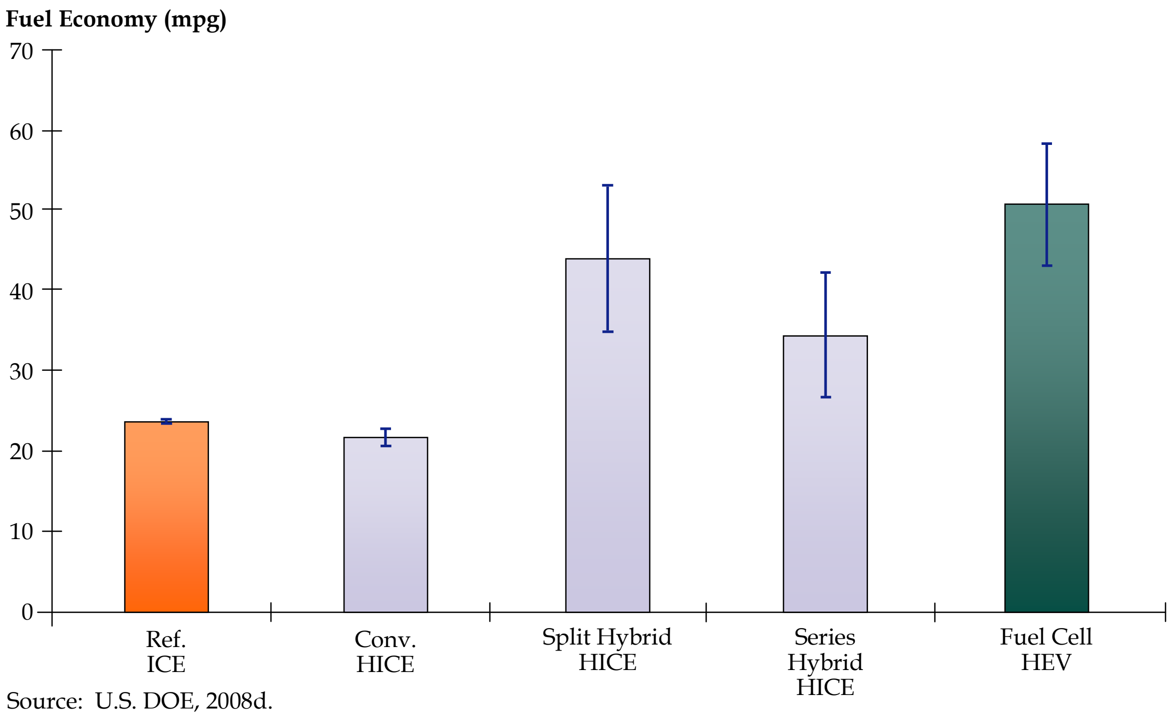
Key Policy Options:

- R&D on fuel cell technology, hydrogen storage technology, and hydrogen production technology (including non-fossil energy sources)

Hydrogen fuel cells show potential for transformative efficiency gains; vehicles have been shown to operate with on-road efficiencies of 40 to 70 percent, i.e., 40 to 70 percent of the energy contained in the fuel is put to useful work (U.S. EPA, 2007; NREL, 2009b). This is substantially higher than the 25 to 30 percent efficiency of most internal combustion engines in use today. Figure 2.2 provides recent test results showing the potential efficiency advantage of HFCVs compared to conventional gasoline internal combustion engine ("Ref ICE") as well as various HICE configurations (conventional, split, and series hybrid). The focus of this report is on HFCVs.

Figure 2.2 Gasoline and Hydrogen Vehicle Fuel Economy

Gasoline-Equivalent



Source: U.S. DOE, 2008d.

Hydrogen fuel cells may be adopted in both light- and heavy-duty applications. Most auto manufacturers are actively researching HFCV transportation technologies and testing prototype passenger vehicles, and several North American cities also are testing fuel cell-powered transit buses. The AEO Reference case estimates approximately 300 HFCVs are on the road in the United States as of 2009 (Table 58). In addition, there were approximately 60 hydrogen fueling stations in the United States in June 2009 (U.S. DOE, 2009b).

Locomotives equipped with fuel cells also are being developed. In 2002, a 3.6 tonne, 17 kW hydrogen fuel cell-powered mining locomotive was demonstrated in Val-d'Or, Quebec, (Sandia National Laboratories, 2002) while in 2007 a demonstration "hydrail" went into service in Kaohsiung, Taiwan (East Japan Railway Company, 2006). Currently, BNSF is working with Vehicle Projects LLC to develop a fuel cell-powered yard locomotive (BNSF, 2008).

Fuel cell applications for the marine sector have been studied for many years, initially by the military and researchers involved in submarine activities. Most of these applications focus on auxiliary power units that generate electricity to meet vessel electrical needs; for example, in the 1980s the U.S. Navy installed a 30 kW fuel cell powered system on the Deep Quest submarine vehicle.

Recently fuel cells also have been considered for propulsion of passenger ferries and tourist boats. This includes the European Union-funded ZEMship, a 100 passenger boat which started operation in the summer of 2008 in Hamburg, Germany. This vessel is equipped with two 50kW fuel cells that provide energy for propulsion. In addition, hydrogen hybrid harbor tugs also are being designed for use in European harbors.

While hydrogen is one of the most abundant elements on Earth, almost all hydrogen is combined with other elements, forming such materials as water and fossil fuels. Several basic processes can be used for production of hydrogen. Hydrogen can be produced at central plants from natural gas via steam reforming, from electrolysis of water using solar energy via photovoltaics, from nuclear energy via thermochemical cracking of water or electrolysis, or from gasification of coal with carbon dioxide sequestration or biomass gasification. At refueling stations, hydrogen can be produced by steam reforming of natural gas, electrolysis of water using grid or renewable electricity, or from steam reforming of bioderived liquids, ethanol, or methanol.

At this time fossil fuels are the primary source of hydrogen production with approximately 99 percent of current consumption by industrial processes at chemical and refining facilities (EIA, 2008). DOE describes these industrial operations as limited in scale and not capable of providing the technology advances and carbon management required for the widespread use of hydrogen as a transportation fuel (U.S. DOE and U.S. DOT, 2006).

Providing a hydrogen fuel production and distribution network to support HFCVs presents several challenges, as discussed in more detail under "feasibility." Large investments are required to establish hydrogen production facilities and a convenient hydrogen distribution system to serve the general public (U.S. EPA, 2007).

Hydrogen can be stored and transported in either liquid or gaseous form. Liquid hydrogen must be cooled to a temperature of -423°F (-253°C) and stored in insulated tanks while gaseous hydrogen is compressed and stored in high-pressure tanks at up to 10,000 pounds per square inch (psi). Research also is being conducted into materials-based storage, i.e., binding hydrogen atoms or molecules tightly in a compound or other storage material. This may allow storage of larger quantities in smaller volumes at low pressure and near room temperature (U.S. DOE, 2008c).

DOE, NREL, and their partners are working to overcome the challenges of incorporating hydrogen into the U.S. energy system through research in the following areas (U.S. DOE, 2009e):

- Hydrogen production technologies that minimize environmental impacts and are cost-competitive with conventional fuels;
- Cost-effective distribution of hydrogen;

- Space- and weight-efficient onboard storage of hydrogen aimed at enabling a vehicle driving range of 300 miles or more;
- Reducing fuel cell cost and size, including improvements to performance and durability; and
- Scaling up from lab-scale technologies to viable commercial-scale operations.

Even allowing for substantial technological advancements toward DOE goals, however, there is a general consensus that a broad scale deployment of fuel cell vehicles in the United States is more than a decade away (NRC, 2008).

Magnitude and Timing of GHG Reductions

Life-Cycle Emissions

Hydrogen FCVs offer dramatic emission reduction potential at the point of use, emitting only water vapor. However, similar to electricity, hydrogen is an energy carrier that can be produced from various feedstock. Therefore total life-cycle emissions must be considered, including the hydrogen feedstock and production pathway when assessing GHG impacts.

A study for Argonne National Laboratory (Wang, 2002) analyzed GHG emissions for 10 hydrogen production and distribution pathways selected to represent the most common production methods as well as some that are likely to be pursued in the future. Pathways evaluated included gaseous and liquid hydrogen produced at central plants and at refueling stations from natural gas reforming, electrolysis of water using solar energy, electrolysis of water using grid electricity, and electrolysis of water using electricity produced from renewable sources.

The Argonne study found that hydrogen use reduces GHG emissions for all fuel pathways except when the fuel is produced by electrolysis from typical grid electricity. It is important to note that gaseous hydrogen reduces GHGs more than liquid hydrogen, except when the liquefaction is accomplished using fully renewable sources of energy. Also, while electrolysis options using the current U.S. grid mix were estimated to actually increase GHG emissions relative to gasoline vehicles, carbon capture and sequestration (CCS) technologies could be adopted in the long run to make these production options viable, although feasibility and cost for CCS have yet to be demonstrated (Newell, 2005). In a 2007 study the California Energy Commission (CEC) examined GHG emissions from various hydrogen pathways, coming to the same general conclusions as the Argonne study.

This analysis utilizes the latest HFCV GHG performance estimates from the 2009 DOE Hydrogen Program in order to generate inputs for the GREET model. GREET is then used to project life-cycle HFCV GHG reductions relative to conventional gasoline LDVs for different time periods. Figures 2.3 and 2.4 illustrate the GREET estimates for both gaseous and liquid hydrogen production options for a variety of pathways, assuming the baseline gasoline and HCV efficiencies shown in Table 2.8.

Figure 2.3 Life-Cycle GHG Emissions for Gaseous Hydrogen Fuel Cell versus Gasoline Vehicle

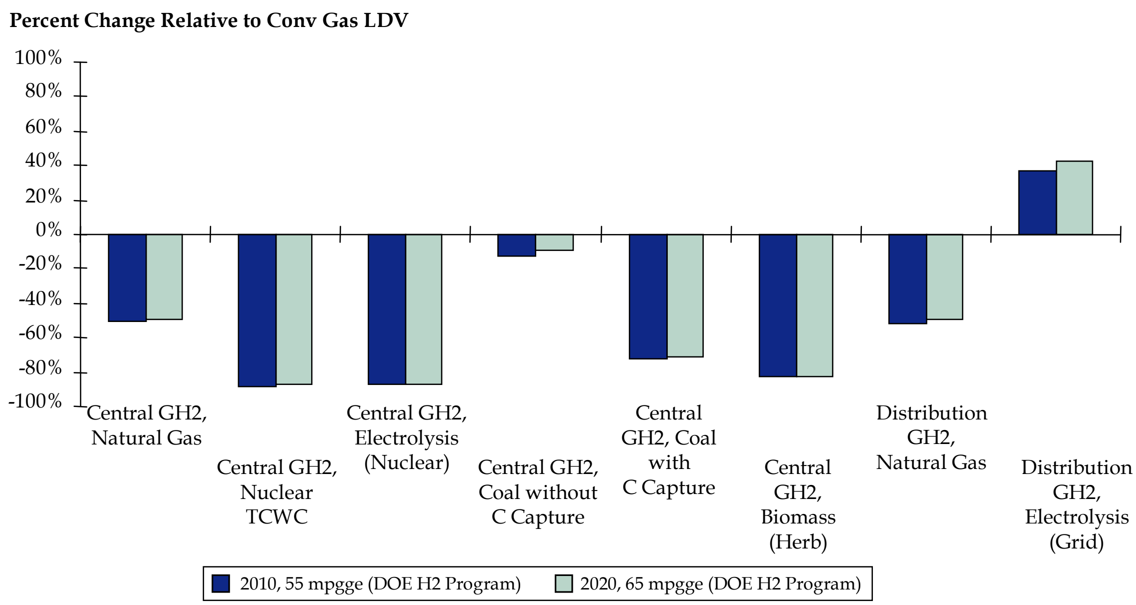


Figure 2.4 Life-Cycle GHG Emissions for Liquid Hydrogen Fuel Cell versus Gasoline Vehicle

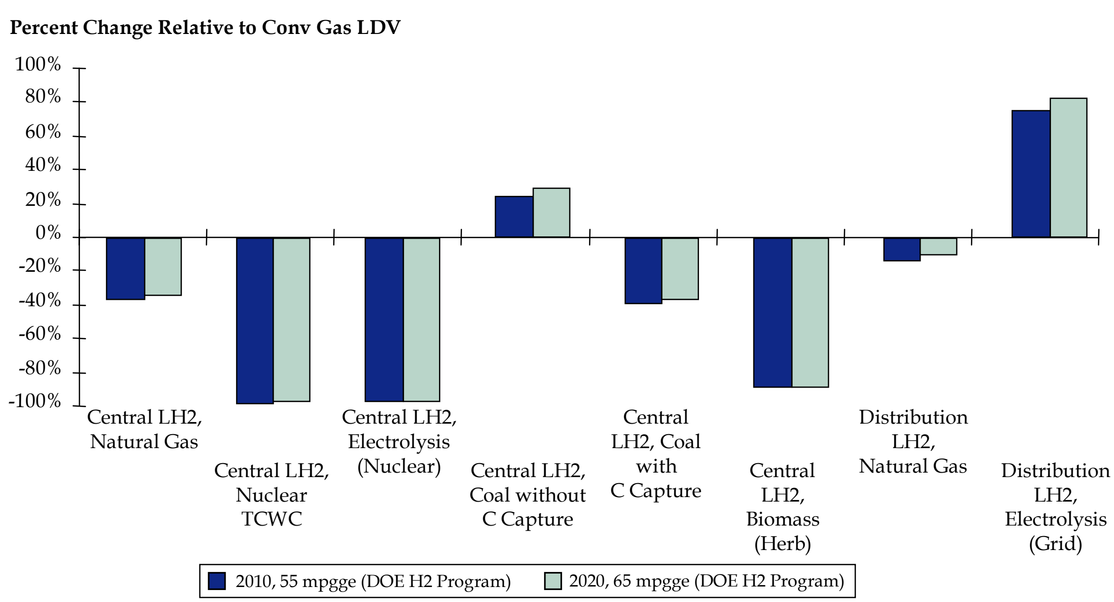


Table 2.8 Conventional Vehicle and HFCV Fuel Efficiencies by Time Period (Gasoline-Equivalent MPG)

Vehicle Technology	2010	2020
Conventional Gasoline (AEO)[a]	22	27
HFCV (DOE)	55 [b]	65 [c]

[a] Average of in-use estimates for cars and light trucks for new vehicle sales (Table 61).
[b] GREET assumption that HFCV mpg is 230 percent of gge in the near–term scenario.
[c] DOE Hydrogen Program 2009.

Several conclusions can be drawn from these figures. First, the efficiency advances in both conventional vehicles and HFCVs tend to minimize the relative differences between the different technologies across time periods. The figures also show that reliance upon grid-average electricity for electrolysis is highly inefficient, generating substantial increases in GHG emissions relative to conventional gasoline vehicles. However, utilizing nuclear (or equivalently, renewable such as wind or solar) energy for electrolysis can almost eliminate GHG emissions.[26] Biomass feedstock and centralized coal with CCS (for gaseous hydrogen) display potential reductions almost as large. However, each of these options is either limited in availability (e.g., nuclear and renewable electricity) or as yet unproven (e.g., coal with CCS – which is also a concern for PHEVs and BEVs). Finally, if liquid hydrogen is used, liquefaction technologies performed to facilitate transportation and/or increase vehicle storage and range, entails substantial efficiency and GHG penalties for the nonrenewable (and nonnuclear) pathways. Nevertheless, hydrogen production using currently available centralized or distributed natural gas reforming still offer sizeable GHG reduction potentials. The life-cycle approach adopted for this analysis only includes direct GWPs; hydrogen also has some indirect GWP.[27]

Market Penetration

While the per-vehicle GHG reduction potential of FCVs can be sizable depending upon the production pathway, obtaining significant GHG reductions for the transportation sector as a whole will entail deployment of millions of FCVs across the country. The 2009 AEO

[26] Emissions associated with power plant construction and maintenance are not included in the GREET estimates.

[27] Hydrogen gas is believed to have an indirect GWP of 5.8, contributing to increased ozone levels and methane enhancement in the troposphere (IPCC, no date). To the extent that HFCV use leads to fugitive hydrogen emissions associated with production, storage and/or distribution, some amount of GHG enhancement may be expected.

Reference case projects that only about 93,000 light-duty HFCVs will be on the road by 2030, consuming 29.7 million gge per year of hydrogen.[28] On the other hand, a report for the National Research Council (NRC) has estimated that the maximum practicable number of hydrogen FCVs that could be on the road by 2020 would be approximately two million, or 0.7 percent of the on-road light-duty fleet, growing to 60 million (18 percent) by 2035 and 200 million (60 percent) by 2050 (NRC, 2008). These values represent the high end of market penetration estimates found in the literature and are used to estimate upper bound GHG reduction potentials.[29]

A 2008 Energy Information Administration study concluded that it is highly unlikely that hydrogen FCVs will have significant impacts on light duty vehicle energy use and GHG emissions by 2030 (EIA, 2008).

Oak Ridge National Laboratory (ORNL) also conducted an analysis on HFCV deployment scenarios to estimate the impact of various policies, oil prices, and technology advancements (Greene et al., 2008). Their main 2025 scenarios ranged from 2 million to 10 million HFCVs deployed. The study reported that there was no consensus on the penetration rate, but that the scenarios were "inclusive of industry expectations." In order to achieve these levels of HFCVs, policy actions are required to offset the higher costs in the short term until economies of scale are realized.

Net Impacts

In order to determine the magnitude of the potential GHG reductions, the hydrogen production pathway must be identified. EIA does not provide production assumptions in AEO 2009, but both NRC (2008) and Greene et al. (2008) assume that distributed natural gas reformation will fuel HFCVs through 2025. There also will be niche areas where excess liquid hydrogen from industrial plants will be delivered to refueling stations. However, the volume will be limited and is not anticipated to increase given the energy intensiveness and costs of trucking over longer distances. By 2025, NRC (2008) and Greene et al. (2008) suggest that coal gasification with carbon capture and storage (CCS) will become economically viable. NRC also includes biomass gasification as a hydrogen pathway in this timeframe. However, modeling by Greene et al. (2008) projects that this pathway will become economically viable a few years later, unless the additional GHGs reductions from biomass gasification are somehow valued (e.g., through carbon credits).

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[28] AEO 2009 Supplemental Tables 58 and 47.

[29] The NRC report was based on a scenario recently developed by DOE through 2025 and extended by the NRC committee to 2050. However, the Council noted that these estimates were based on a "rapid and widespread deployment," and that this is an "optimistic estimate of what might be possible—not a forecast of what is likely or probable." Achieving this scenario, the Council notes, would be challenging and would require "significant continued technical progress, consumer acceptance, and policies to achieve market penetration of HFCVs during the early transition period."

For this assessment distributed natural gas reformation for gaseous hydrogen production is assumed for the medium-term case (with a 40 to 55 percent GHG reduction), while a generic "advanced pathway" case with a 79 to 84 percent GHG reduction is assumed for the long term.[30] Impacts in terms of gasoline saved and GHG reductions are shown in Table 2.9.

Table 2.9 Maximum Potential HFCV Penetration and Benefits by Time Period

	Incremental Market Penetration (Percent)[a]	Incremental Number of HFCVs (Millions)	Gasoline Saved – Mgal/Year[b]		GHG Reduction (mmt CO2e /yr)	
			Minimum	Maximum	Minimum	Maximum
Medium-Term (2030)	18%	60	9,100	13,000	52	74
Long-Term (2050)	60%	200	43,200	52,800	388	474

[a] Incremental to AEO Reference Case – maximum value found in literature.

[b] # vehicles x AEO base gal/mi x 11,500 mi/yr (LDV avg.) x fuel consumption improvement.

Cost-Effectiveness

The cost-effectiveness of HFCVs depends upon both the cost of hydrogen and the incremental cost of vehicle, including the fuel cell and storage components.

Hydrogen Cost

The price of hydrogen transportation fuel is a function of many factors, including the cost of the feedstock, the maturity, and efficiency of the production technology and distribution costs. It is generally accepted that the price of hydrogen fuel will be higher than petroleum fuel on a gge basis in the earliest years of vehicle deployment. However, hydrogen fuel costs will ultimately need to be roughly equivalent to gasoline costs on a per mile traveled basis in order to obtain consumer acceptance without subsidies. Therefore DOE is targeting the cost of hydrogen in 2015 between $2 and $3 per gge as delivered to the pump

[30] In the range of eighty percent is broadly representative of several centralized gaseous hydrogen production pathways including nuclear/renewable electrolysis, coal with CCS, and biomass, as shown in Figure 2.3.

for all the production pathways, in order to make it cost-competitive with gasoline on a cents per mile traveled basis.[31]

There is tremendous uncertainty related to the costs of hydrogen, and DOE presents much of their data in terms of progress toward meeting predefined cost targets. Table 2.10 is taken from the DOE Hydrogen Program's FY 2008 *Annual Progress Report* which indicates the advancement toward the cost goals (Dillich et al., 2008) and an independent panel's estimate for hydrogen costs from natural gas (NREL, 2006). The table also includes EIA's more recent projected prices for gasoline, which projects that retail gasoline will be $3.35 and $3.60 per gallon in the same timeframes as DOE's projections. If DOE's hydrogen cost projections hold true, this would mean that hydrogen fuel is actually less expensive than gasoline on a miles traveled basis (excluding incremental HFCV costs). NRC (2008) estimates that hydrogen will become cost-competitive in 2017 at $5.60 per kg (assuming $2.80 per gallon for gasoline).

Table 2.10 Projected Delivered Cost of Hydrogen ($/GGE[a])

Production Pathway	2014	2016-2020
Onsite electrolysis	$3.70	$3.00
Centralized electrolysis	$4.80	$3.00
Nuclear – electrochemical and thermochemical	$5.00	$4.50
Coal gasification with carbon capture and storage (CCS)[b]	N/A	$3.00
Centralized biomass gasification	$3.30	$2.10
Distributed natural gas	$3.50	$2.75
Gasoline	$3.35	$3.60

Sources: Dillich et al., 2008; AEO March 2009; NREL, 2006.

[a] Does not account for efficiency of the fuel cell (i.e., twice as many miles traveled with hydrogen on a gge basis).

[b] There is still uncertainty surrounding the feasibility of carbon sequestration strategies.

[31] One kg of hydrogen is roughly equal to one gge. DOE's cost targets are based on a gasoline price of $1.26 in 2015 multiplied by the energy efficiency ratio of HFCVs, which is 2.40 relative to a gasoline ICE and 1.66 when compared to a gasoline hybrid electric car (U.S. DOE, 2005). So a kilogram of hydrogen, which is roughly equivalent to a gallon of gasoline, is cost competitive with gasoline when it is $2 to $3 kilogram.

As discussed earlier, the least-cost hydrogen production pathway in the short term is generally believed to be reforming of natural gas at distributed locations. An independent review panel projected a hydrogen cost range of $2.75 to $3.50 per delivered gge, assuming economies of scale are reached with the deployment of 500 new 1,500 kg-sized stations per year, utilized at 70 percent capacity (NREL, 2006). For the cost-effectiveness values reported later in this section, a delivered hydrogen price of $3.50 to $7.00 is assumed for the short term. In the long term, prices of $2.10 to $4.50 are assumed.

Fuel Cell Cost

The raw materials required for catalysts (e.g., platinum) dominate the cost of fuel cells, though recent technology advances are reducing total system costs. Based on its current research and development estimates, DOE estimated that for high-volume production (more than 500,000 units per year), an 80 kW (107 hp) automotive fuel cell stack would cost approximately $73/kW (U.S. DOE, 2008e). Compared with a cost of approximately $54/kW for an equivalent internal combustion engine, the scenario estimates an incremental FCV cost of $1,520 for an 80 kW drivetrain (U.S. DOE, 2008e; NRC, 2008). DOE has set a goal to reduce costs to $30/kW for the fuel cell component (e.g., fuel cell stack and balance of the plant) of the vehicle system.

Developing onboard hydrogen storage to achieve a 300-mile driving range has been one of the greatest technical challenges for HFCVs. NRC (2008) reports that the current cost is $15 per kW for a 5,000 psi compressed hydrogen system, which is most likely representative of short- to mid-term technology. The NRC study utilized a short- to mid-term hydrogen storage cost of $10 per kWh in their model. Other storage solutions, such as solid and chemical hydrides storage solutions, are being explored, but Bandivadekar et al. (2008) reports that none seem likely to offer the combination of cost, simplicity, efficiency, and energy density, without a technology breakthrough. According to these assessments, substantial advances will be required to meet DOE's long-term target cost for onboard storage of $2 per kWh. However, this low cost target is not essential to sizable market penetration by 2040 (Greene et al., 2008).

FCV costs, while likely to remain high relative to conventional vehicles for some time, dropped significantly between 2002 and 2008 (U.S. DOE, 2008e) and are expected to further decrease as market penetration progresses. Current incremental costs for light-duty hydrogen fuel cells are estimated to be approximately 10 times that of a conventional gasoline engine (Yacobucci, 2005), or about $25,000.[32] The following cost assessment assumes that current fuel cell stack life estimates of 2,000 hours are extended to the DOE target of 5,000 hours, and therefore fuel cell replacement will not be required during this period. In addition, these estimates do not account for any potential maintenance savings, which could be substantial with FCVs due to the greatly reduced number of moving parts.

[32]Typical gasoline engine costs are reported between $2,000 and $3,000 (Yacobucci, 2007).

Bandivadekar et al (2008) calculates an incremental FCV cost of $5,300 in 2035, which is assumed for this assessment.

FCV costs are likely to remain high relative to conventional vehicles for some time, but their costs are expected to decrease as market penetration progresses. Incremental costs for light-duty hydrogen fuel cells have been estimated to be approximately 10 times that of a conventional gasoline engine (Yacobucci, 2005), or about $25,000.[33] However, costs have been decreasing rapidly as fuel cell developers and component suppliers have lowered the amount of platinum required and increase power density. A more than 70 percent reduction in fuel cell costs was reported between 2002 and 2008 (U.S. DOE, 2008e). A recent independent study of DOE's cost analysis methodology determined that a range of $60/kW to $80/kW is a valid estimate of the potential manufactured cost for an 80 kW fuel cell system, based on 2008 technology extrapolated to a volume of 500,000 systems per year (NREL, 2009c). In general, cost estimates do not account for any potential maintenance savings, which could be substantial with FCVs due to the greatly reduced number of moving parts. Bandivadekar et al. (2008) calculates an incremental FCV cost of $5,300 in 2035, which is assumed for this assessment, although it is acknowledged that higher volume production would lower the increment.

Another important consideration for FCVs to be competitive is long-term durability, so while costs are being reduced, fuel cell life cannot be compromised. DOE's target is 5,000 hours, which is equivalent to 150,000 miles on a conventional vehicle. Although laboratory testing has achieved 7,300 hours on a small scale, independent road testing of 140 FCVs has achieved a 2,000 hour life thus far, at which point there is a 10 percent degradation of fuel cell performance (Wipke et al., 2009).

If mass-produced, HICE vehicles could serve as a lower cost technology (compared to fuel cell vehicles) to introduce the public to hydrogen, while expanding the demand for hydrogen and its refueling infrastructure systems. The capital cost of a HICE vehicle is expected to be just 25 percent that of a hydrogen fuel cell vehicle (CEPA, 2005).

HFCV Costs and Cost-Effectiveness Ranges

Calculating the cost-effectiveness of HFCVs in reducing GHG emissions is complicated given the number of assumptions needed for such an analysis. Table 2.11 summarizes the per vehicle incremental costs, fuel cost/savings, net present value of total cost/savings, average GHG reductions, and associated cost-effectiveness ranges for HFCVs for the timeframes of interest. Key to the calculated cost-effectiveness ranges are that the projected cost reductions in both the cost of an HFCV and hydrogen production/delivery are achieved. As discussed later, there is a significant learning curve to reach economies of scale, which will require investment in infrastructure and fuel cell development in the

[33] Typical gasoline engine costs are reported between $2,000 and $3,000 (Yacobucci, 2007).

short to mid-term. The general consensus is that, at least in the near term, HFCVs will not be cost-effective.

Table 2.11 HFCV per Vehicle Cost and Cost-Effectiveness Ranges by Time Period

	Incremental Vehicle Dollars	Fuel Savings/ Cost NPV[a]	NPV Cost/ Savings	Average GHG Reduction Tonnes/Year	Dollars/Tonne Calculated	Dollars/Tonne Literature
2020	$10,000	-$3,500 to $4,400	$6,500 to $14,400	2.7	$151 to $333	N/A
2030 to 2050	$1,500 to $5,300	-$11,900 to -$8,300	-$10,300 to -$3,000	3.3	-$199 to -$57	-$194 to $275

[a] Using pretax price projections for 2010 (near-term) and 2030 (long-term) – $3.00 to $7.00 and $2.10 to $4.50 relative to AEO projections for gasoline of $1.75 and $3.43, respectively.

To put the results of Table 2.11 in context, other cost-effectiveness values found in the literature are reported here. For example, Bandivadekar et al. (2008) estimates a cost-effectiveness between $132 and $163 per tonne CO_2e in 2035, assuming a gasoline price of $2.50 per gallon. However, net cost savings are projected at $5 per gallon in this same study, resulting in cost-effectiveness estimates between -$161 and -$194 per tonne. Keith and Farrell (2003) calculated a cost-effectiveness value of $275 per tonne CO_2e for long-term HFCVs. However, that study also estimates that the cost-effectiveness could improve by a factor of 10 with successful development and application of CCS technologies associated with electricity production. Lastly, Fulton (2004) estimated the cost-effectiveness in the range of $200 to $800 per tonne CO_2e in 2030 with the caveat that this calculation will depend on the price of producing hydrogen through low-carbon pathways.

Cobenefits

HFCVs emit no pollutants at the point of service, with life-cycle emissions resulting exclusively from fuel production and transport. Atmospheric emissions from HFCVs are vastly different depending on the production pathway and feedstock. Table 2.12 shows GREET model estimates of life-cycle emissions for gaseous and liquid hydrogen production for two selected pathways: distributed natural gas reforming and centralized nuclear plant production. The life-cycle analysis modeling estimates the emissions of VOC, CO, and NO_x to be less compared to conventional gasoline vehicles. Although PM_{10} increases for gaseous H2, the amount of these pollutants generated is still very small.

These estimates represent current technology for both conventional gasoline vehicles and hydrogen natural gas reformation and are not necessarily representative of relative emissions from future technologies. Nuclear production is included in the table to show a likely high and low range of emissions based on different production pathways.

Table 2.12 Life-Cycle Atmospheric Emissions from HFCVs Compared to Baseline Gasoline Vehicles (Range of Distributed Natural Gas Reforming to Central Nuclear Plant Emissions)

	Gaseous H2		Liquid H2	
Pollutant	Difference from Baseline (g/mile)	Percent Change	Difference from Baseline (g/mile)	Percent Change
VOC	-0.29 to -0.31	-92% to -98%	-0.27 to -0.31	-86% to -99%
CO	-3.75 to -3.80	-98% to -100%	-3.71 to -3.81	-97% to -100%
NO_x	-0.22 to -0.31	-59% to -81%	-0.03 to -0.34	-3%to -90%
PM_{10}	0.02 to 0.015	23% to 18%	0.27 to -0.046	327% to -56%
$PM_{2.5}$	0.02 to0.008	36% to -22%	0.09 to -0.024	221% to -67%

Feasibility

Hydrogen has an excellent industrial safety record, but the public is unfamiliar with hydrogen, and safety perceptions must be proactively addressed. As was done for CNG in the past, hydrogen will require the adoption of national fueling codes and standards, along with the education of the public and emergency personnel. For example, hydrogen is a colorless and odorless gas, so fueling stations will need to be equipped with leak detection devices. DOE is working with organizations to identify the current gaps in the standards development process; facilitate the creation and adoption of model building codes and equipment standards for hydrogen systems; and provide technical resources to harmonize the development of international standards (U.S. DOE, 2008d). Hydrogen also has a very broad flammability range, and its flame is invisible, so special training will be required for emergency responders (CRS, 2007).

Both durability and performance also must be improved before fuel cells can become acceptable from a consumer standpoint. For example, failures such as platinum dissolution into the carbon electrodes or sulfur and CO poisoning of the fuel cells can shorten the life of FCVs.[34] Current fuel cell stack life from on-road vehicle testing is approximately 2,000 hours at which point fuel cell performance is only 90 percent of the original performance (NRC, 2008), which is significantly lower than the 5,000-hour lifespan needed to enter the light-duty vehicle market (Wipke et al., 2007).

Another obstacle is the ability to store a sufficient quantity of hydrogen for adequate (i.e., 300-mile) driving range. The current on-road driving range (corrected for EPA drive cycle) for a FCV test program ranged between 190 and 250 miles (NREL, 2009b). High-pressure hydrogen storage tanks appear to be the most effective solution for onboard hydrogen storage until a more suitable hydrogen storage material is identified.

In addition, the amount of time required to refuel hydrogen vehicles currently is higher than the time required for conventional gasoline refueling on a gge basis. A recent NREL study of 3,700 refueling events showed an average of about 0.8 kg/min was achieved for 350 bar (~5,000 psi) tanks, while only 0.6 kg/min was achieve for 700 bar (~ 10,000 psi) tanks (Wipke et al., 2009).[35] Assuming the average consumer requires a 5 kg fill, waiting six to eight minutes to refuel is not acceptable so refueling rates must be improved. Also, the fill rates for hydrogen are nonlinear and slow down as the tank fills. Refueling rates will likely continue to improve as onboard storage systems evolve to provide longer driving ranges.

In addition to vehicle-related challenges, a critical component to the development of HFCVs will be the development of a widespread hydrogen production and distribution infrastructure. NRC (2008) estimated the government cost for hydrogen vehicle/infrastructure development at $55 billion between 2008 and 2023 to achieve the two million HFCV penetration target by 2020 and 5.6 billion by 2023. Greene et al., (2008) estimated $10 billion in Federal investment is needed to achieve two million HFCVs on the road. There are significant challenges in the development of either a centralized infrastructure (in which hydrogen is reformed at central production facilities and distributed to refueling facilities) or a decentralized infrastructure (in which hydrogen is produced at numerous small-scale facilities located at the point of sale). The options and challenges are discussed in more detail in the sidebar on page 2-87.

Finally, reporting requirements currently exist for production, transport, and dispensing of hydrogen, and will need to be modified or minimized in order to avoid unacceptable administrative burdens associated with large scale use within the transportation sector (NGA, no date).

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[34] Both sulfur and CO are commonly present in hydrogen gas.

[35] An FCV's increased fuel economy roughly doubles their range compared to conventional gasoline vehicles, so small capacity fuel tanks (on a gge basis) do not severely limit operational range.

A 2008 Energy Information Administration study of the potential for hydrogen to reduce petroleum consumption and carbon emissions summarizes the challenges in developing a hydrogen-based transportation system:

> Widespread use of hydrogen fuel cells in LDVs will require significant R&D breakthroughs, including: (1) the development and widespread deployment of economical hydrogen production technologies or processes; (2) the development and production of economical, high-density, on board hydrogen storage that can be drawn on quickly as needed[76]; (3) the widespread development and deployment of an economical hydrogen transportation, distribution, and dispensing network; and (4) the development and large-scale deployment of economical PEM fuel cells and their seamless integration into LDV motors. Moreover, in addition to the economic and technological challenges, public safety concerns about hydrogen in LDVs must be addressed at the consumer, State, and Federal levels, as they have been for compressed natural gas (CNG) vehicles (EIA, 2008).

Development of a Hydrogen Infrastructure

Development of a hydrogen production and distribution infrastructure is a critical challenge in the transition to widespread use of hydrogen as a transportation fuel. There are several options for producing hydrogen for FCVs. One option is to generate the hydrogen at a central production facility, such as a plant which performs natural gas steam reforming, then transport the hydrogen to a distribution network for transfer to refueling facilities. This requires development of a new fuel distribution network. Delivery and dispensing of hydrogen could cost as much as its production and consume significant energy, thereby negating much of the GHG reduction potential (Jones, 2008).

In Jones' aggressive FCV deployment scenario, it was assumed that initially excess hydrogen from current industry production would be trucked to a few select stations, or stations would house small natural-gas reformers. As consumption and geographic coverage increases, increased production volumes would be accomplished via large appliance-type hydrogen production units fueled with natural gas or renewable liquid fuels such as ethanol. In the later transition stage, production would be accomplished at large central production plants using primary feedstock such as natural gas, coal with CO_2 sequestered, and biomass.

Two delivery technologies are feasible for hydrogen produced at centralized locations—pipelines and tanker truck (U.S. DOE and U.S. DOT, 2006). The existing hydrogen pipeline system is only one-third of 1 percent of the natural gas network length (EIA, 2008). Therefore in the short term, long-distance transport of hydrogen via tanker truck is the most likely delivery option. Most hydrogen will need to be transported in liquid form due to the increase in energy density compared to gas. There are currently seven liquid hydrogen plants in the U.S. supplying 760 million gge per day (EIA, 2008).

In the short-term distributed natural gas and on-site electrolysis are advantageous for the transition to hydrogen FCVs because they avoid the need for a new delivery infrastructure. Both small reformers and water electrolysis systems can be built in a modular fashion (i.e., sized for demand) for placement at existing gasoline stations (Jones, 2008). The components at the hydrogen fueling stations would be similar regardless of whether hydrogen is produced on site or at a centralized location. These facilities will require hydrogen storage, compression, and fast delivery systems.

DOE also envisions a transitional approach relying on a distributed fueling infrastructure in high population density areas, such as Southern California and New York City, with expansion to Boston and Washington, D.C. in future years. This distributed approach is less capital intensive, depending on steam reformation of natural gas as the primary source of hydrogen through the mid-term (GAO, 2008). However, for hydrogen to become a widespread transportation fuel, economics will require its production at centralized facilities delivered via a pipeline infrastructure (GAO, 2008).

Development of a Hydrogen Infrastructure (continued)

Reliance on natural gas pipelines may be another way to transport centrally produced hydrogen during the initial stages of hydrogen infrastructure development. However, hydrogen's lower energy density would require higher pressure pumps and compressors, and hydrogen also causes metal embrittlement in conventional natural gas pipes. In addition, seasonal natural gas demand will limit the available capacity for natural gas pipelines to transport hydrogen, requiring the construction of new pipelines key in sustaining year-round delivery. Historic cost data for construction of hydrogen pipelines indicates $1.2 million per transmission mile and $0.3 million per distribution mile, with cost projections in 2017 to be $0.5 million per transmission mile, and similar costs for the distribution lines (EIA, 2008). In order to construct transmission and distribution pipelines of equal length to those of natural gas (295,000 miles of transmission pipeline and 1.9 million miles of distribution lines, per EIA, 2008), the estimated cost is $480 billion to $920 billion depending on construction costs. (It is not clear to what extent, if any, that these cost estimates include right-of-way acquisition.) EIA also reports that costs for developing a hydrogen pipeline will depend on where the pipelines are sited, rights-of-way, operating pressures, and how applicable environmental and safety issues are addressed.

EIA (2008) also reports a great amount of uncertainty regarding how a centralized hydrogen transmission and distribution systems might evolve. Many experts have stated that large-scale penetration of hydrogen powered fuel cell vehicles is unlikely without significant long-term government policies and support due to the economic costs associated with fuel cells as well as hydrogen production, storage, and distribution.

Since all current hydrogen refueling stations are essentially first generation prototypes, current costs for their construction are high (CEC, 2006). Lipman and Weinert (2006) estimate that hydrogen fueling stations will cost between $500,000 to over $5 million for stations that produce and/or dispense between 30 and 1,000 kg of hydrogen per day. For small demand levels, mobile hydrogen units could be possible at a cost of $250,000. Operation and maintenance costs for hydrogen stations are also likely to be as high as or higher than comparable natural gas stations (CEC, 2001). However, it should be noted that many of these refueling stations also make

■ 2.9 Electricity

Overview

Many of the alternative fuels discussed in this section are limited by production potential or infrastructure constraints. In contrast, electricity is widely available in a form that can be used by large numbers of vehicles, and instead is primarily limited by the quantity of electric vehicles on the road. There are a number of vehicle types that use electricity as a power source. Battery Electric vehicles (BEV) and plug-in (grid-connected) hybrid electric vehicles (PHEV) store energy in batteries that are charged from electric outlets. BEVs rely solely on electricity, while PHEVs also rely on hybrid electric power trains for a portion of their operating time to generate their own power from an internal combustion engine or fuel cell. BEVs produce no tailpipe emissions, although there are emissions associated with the extraction, processing, and combustion of the fuels used to generate the electricity at power plants. The emissions from the generation of electricity are dependent on the mix of power sources for the area where the vehicles are charged. This section focuses on BEVs and their associated power source emissions. PHEVs and associated automotive battery technologies (relevant to BEVs as well) are discussed in greater detail in Section 3.2.4.

Electric Vehicles

2030 Benefits: **Moderate**:

- 68-80% reduction per vehicle
- 5% market penetration is high estimate from literature

2050 Benefits: **High**:

- 78-87% reduction per vehicle
- 56% market penetration is high estimate from literature

Net Included Costs: **Net Savings**: -$20 to -$110 per tonne

Confidence in Estimates: **Low**

- Market penetration depends upon advancement of battery/electricity storage technology
- Emissions benefits depend upon future electricity production mix
- BEV efficiency also uncertain

Key Cobenefits and Impacts: **Mostly Positive**

- Pollutant emissions will depend upon fuel source, but tailpipe emissions will be eliminated

Feasibility: **Moderate**

- Modest infrastructure requirements; primary barrier is energy storage technology

Key Policy Options:

- Research and development support for BEV battery efficiency and durability
- Investment in public charging infrastructure
- Investment in nonfossil electricity generation

The primary focus for continued BEV development is the battery. Battery characteristics affect the range, cargo space, power, cost, and weight of a BEV. These characteristics must meet consumer demands for these vehicles to achieve significant market penetration. Batteries must be recharged, often on a daily basis, and this process takes much longer than refueling a similar conventional vehicle, up to 10 hours depending on the battery capacity, state of depletion, and recharging method (reference), although advanced charging techniques can reduce this time significantly (Burke et al., 2007). Electric passenger cars are becoming more attractive with the advancement of new battery technologies that have higher power and energy density than previous prototypes (i.e., greater possible acceleration and more range with less battery mass). Currently, nickel-metal hydride (NiMH) batteries and lithium-ion (Li-ion) batteries are the best options for BEVs and PHEVs. NiMH dominates the current market, although Li-ion batteries may gain market share over time, as discussed in Section 3.2.4.

With the advent of California's Zero Emission Vehicle (ZEV) mandate, an initial attempt was made to develop BEVs for mass market purchases. However, less than 5,000 BEVs were produced across a handful of makes and models before the ZEV requirements were relaxed. For reasons that are still subject to debate, vehicle production was not sustained in the absence of mandates, ceasing by 2003 in the United States. Today, BEVs are not available except in niche markets such as neighborhood electric vehicles, with a maximum speed of 25 mph. (Burke et al., 2007)

Current BEV designs are primarily for LDVs, with estimated ranges typically between 50 and 200 miles between charges (Burke et al., 2007). Like hybrid vehicles, BEVs can recapture some energy by regenerative braking, which can extend operating range to some extent. With additional developments in battery technology BEV range is expected to increase. Beyond a certain point, however, BEV range eventually reaches a point of diminishing returns, as increased battery weight decreases overall vehicle efficiency. Increased battery capacity also increases vehicle costs dramatically. For example, doubling BEV range from 200 to 400 miles might result in battery size and cost increases of 130 percent to compensate for the associated weight increase (Kromer and Heywood, 2007). Considering these factors, one recent study concluded that an upper bound of about 200 miles between charges was a reasonable limit on commercial BEV range for mainstream LDVs in the long run (Bandivadekar et al., 2008), although unforeseen technological advances could change this conclusion.

The electrical energy used to charge a BEV battery can be generated by any source, including renewable, nuclear, natural gas, coal, and petroleum. As such, the resulting GHG emissions per mile associated with BEV operation can vary drastically from region to region and by time of day and year. (See Section 3.2.4 for a discussion of life-cycle GHG emissions associated with battery charging for PHEV operation.) Some BEV designs employ on-board chargers, which allow the battery to be charged directly from a standard 120 V wall outlet. Other designs require the purchase of an off-board charging unit.

While the power source for BEVs is readily available, there is a need to develop a publicly accessible charging infrastructure allowing BEVs to be charged away from users' homes. Public access recharging could substantially extend a BEV's daily range, depending upon trip lengths and available charge time. As of June 2009 there were 451 charging stations in the United States, with almost all of these located in California (U.S. DOE, 2009b).

BEVs also will be available for a limited portion of the heavy-duty vehicle segment in the near future. One opportunity lies with short-haul drayage trucks that move cargo containers within a contained area. These trucks can easily be brought back to their charging station as the battery becomes depleted. Also, time spent idling waiting to load and unload would not require energy consumption (Port of Los Angeles, 2008). Electrification of other HDVs such as school buses also is feasible. Because school buses move along a preplanned route and return to their storage yards and park twice per day, concerns over range could be managed. Buses could be charged both during the day and overnight for their morning and afternoon trips. These vehicles are likely to use lead-acid batteries for the near future. This battery technology is much older than NiMH and Li-ion systems and is fully demonstrated. Batteries of this type are much less expensive than those that would be found in light-duty BEVs and their increased weight is less of a concern for the heavy-duty market. However, BEV use is not considered feasible for most heavy-duty applications, given range requirements (for long-haul trucks), and the limited ability for many applications to charge overnight (Muster, 2000).

Electricity-powered transport also is used for various urban transit options, including trolleys, subways, and light rail. It also is used for intercity rail, although currently only the Northeast Corridor in the United States (between Boston and Washington, D.C.) is electrified. Intercity rail electrification could be used for both passenger and freight trains. Magnetic levitation (maglev) trains utilize electrically powered magnet systems to float the train above the track without the use of wheels. The first commercial maglev trains ran in the 1980s in Birmingham, U.K., providing a low-speed shuttle service between the airport and the railway station. The experimental Japanese maglev train JR-Maglev MLX01 broke the world speed record for ground transportation in 2003, reaching a speed of 361 mph. An 18-mile Maglev system opened in 2004 connecting the Shanghai city center with the city's airport. Currently, a maglev system is being considered to link Los Angeles and Las Vegas and to replace drayage trucks that operate at the ports of Los Angeles and Long Beach. However, maglev trains require the construction of special purpose tracks which are incompatible with existing rail infrastructure.

Magnitude and Timing of Reductions

Life-Cycle Emissions

Because electric vehicles do not burn fuel at the point of service, they do not emit pollutants at the tailpipe. However, the life-cycle emissions for producing and delivering electricity can be significant, particularly GHGs for electricity generated from combustion of fossil fuels such as coal. In 2008, about 48 percent of U.S. electricity was generated from coal, followed by 21 percent from natural gas. Methods of generating electricity with little to no GHG emissions include nuclear power (19 percent of 2008 generation), and renewable sources such as hydropower, geothermal, wind, solar, and other biomass-derived sources (9 percent).[36]

Net GHG reductions, as well as fuel cost savings, are largely a function of BEV efficiency, typically expressed in kWh/mi rather than mpg. PHEV batteries range from roughly 0.2 to 0.4 kWhr/mi, with a medium- to long-term average of 0.26 kWhr/mi (see Section 3.2.4). For low-drag vehicles it is assumed that BEV battery efficiency in kWhr/mi will not vary significantly for ranges between 100 and 200 miles, with increased weight penalties largely offset by larger battery capacities and the more effective use of regenerative braking that is permitted. For example, Kromer and Heywood (2007) estimate only a mild increase in kWh/mi when moving from a 100- to 200-mile BEV range (0.22 to 0.24). However, high drag vehicles such as traditional SUV designs are likely to incur a substantial efficiency penalty in order to obtain a 200-mile operating range. For example, Bandivadekar et al., 2008, p. 300 estimates such an advanced, extended range BEV to have an efficiency level of up to 1.38 kWh/mi, for light trucks.

Due to the dramatic efficiency penalties and corresponding increases in battery size and cost associated with longer range, vehicle design is likely to have a great impact on the future BEV market. In order for BEVs to obtain reasonable ranges (upwards of 200 miles) at competitive costs, the BEV market will likely remain focused on advanced, low-drag designs. Accordingly, this analysis assumes the same efficiency value for BEVs as for PHEVs in the long run, at 0.26 kWhr/mi, for 100 to 200 miles of operating range. The extent to which these vehicles penetrate the market may be largely determined by consumer willingness to alter their traditional purchasing decisions in favor of such advanced designs and body styles.

BEV emissions are entirely dependent upon the mix of electricity sources employed and the efficiency of electricity transmission, charging, and end use. Using the *current* national electricity grid mix assumed in the GREET model, and assuming 0.4 kWh/mi, current BEVs are estimated to provide a 33 percent decrease in life-cycle GHG emissions per VMT compared to conventional gasoline vehicles. Fuel-specific life-cycle emission estimates include a six percent increase in GHGs (relative to conventional gasoline LDVs) for coal-fired utilities, a 45 percent decrease for natural gas, and a 99 percent reduction for nuclear generation.

Although overall electricity generation is projected to increase by 24 percent from 2008 to 2030, the fuel mix distribution is not projected to shift significantly under baseline projections (U.S. DOE, 2009a). The largest increase is predicted in renewables, growing from 9 to 14 percent of total generation, while coal, natural gas, and nuclear lose one to two percent each. The future electricity generation mix may be affected, however, by potential climate change policy actions at the Federal and/or multistate level, such as the adoption of a national cap-and-trade system, which would likely reduce the contribution

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[36] AEO 2009, Table 8.

of carbon-intensive fuel sources, especially coal. EPRI (2007) provides one forecast of overall improvements in electricity sector GHG intensity, as discussed in more detail in Section 3.2.4.[37] Challenges related to lowering electricity grid emissions over time are discussed in numerous studies (e.g., EPRI 2009). The range of potential GHG reductions presented in Table 2.13 are derived from EPRI modeling data for PHEV penetration scenarios, and are identical with that assumed for PHEV operation in electric (CD) mode. Additional uncertainty is associated with this range compared to the PHEV evaluation, however, as BEV charging will result in significantly higher per-vehicle electricity demand than PHEV charging, which will in turn impact electrical dispatch differently.

Table 2.13 Percent BEV GHG Reduction Range by Time Period

	GHG Reduction Compared to Baseline Conventional Gasoline Vehicle	
Timeframe	**Minimum**	**Maximum**
2030	68%	80%
2050	78%	87%

Market Penetration and Net Impacts

The AEO Reference case estimates that about 24,000 BEVs will be on the road in the United States in 2010. This represents about 0.01 percent of the total light-duty vehicle market. The Reference case forecast actually projects a decline in the number of BEVs in service by 2030, to under 5,000.[38] This is likely due to the assumption that advancements in PHEV or HEV technology will supplant demand for these vehicles. The actual balance of drivetrain electrification among HEVs, PHEVs, and BEVs will depend on how the respective technologies develop, as well as consumer preferences.

The review of the literature found very few market share projections for LDV BEVs.[39] McKinsey estimated that up to nine percent of new vehicle sales could possibly be BEVs in 2030 (or approximately five percent of the total LDV fleet, assuming rapid expansion of this technology in the near future; McKinsey, 2009). Yang et al. (2009) estimated a very

[37] The range of GHG intensity estimates from EPRI is 379-606 g/kWhr in the medium term and 240 – 421 g/kWhr in the long term.

[38] AEO 2009, Tables 47 and 58.

[39] No significant BEV penetration is assumed for the HDV market, although niche applications are possible as noted above.

aggressive long-term BEV stock level at 84 percent by 2050. This analysis assumes that the potential BEV market is no larger than the PHEV market in the long run, and is set at 56 percent. The gasoline fuel savings and GHG reduction potential associated with these levels of BEV market penetration are presented in Table 2.14. The range of possible GHG reductions corresponds to the range of GHG intensities assumed for future year BEV charging.

Given the very limited and speculative nature of future BEV market share projections, these estimates should be considered highly uncertain, even more so than the projections for PHEVs.

Table 2.14 Maximum BEV Fuel Savings and Emission Reduction Potential (National Fleet)

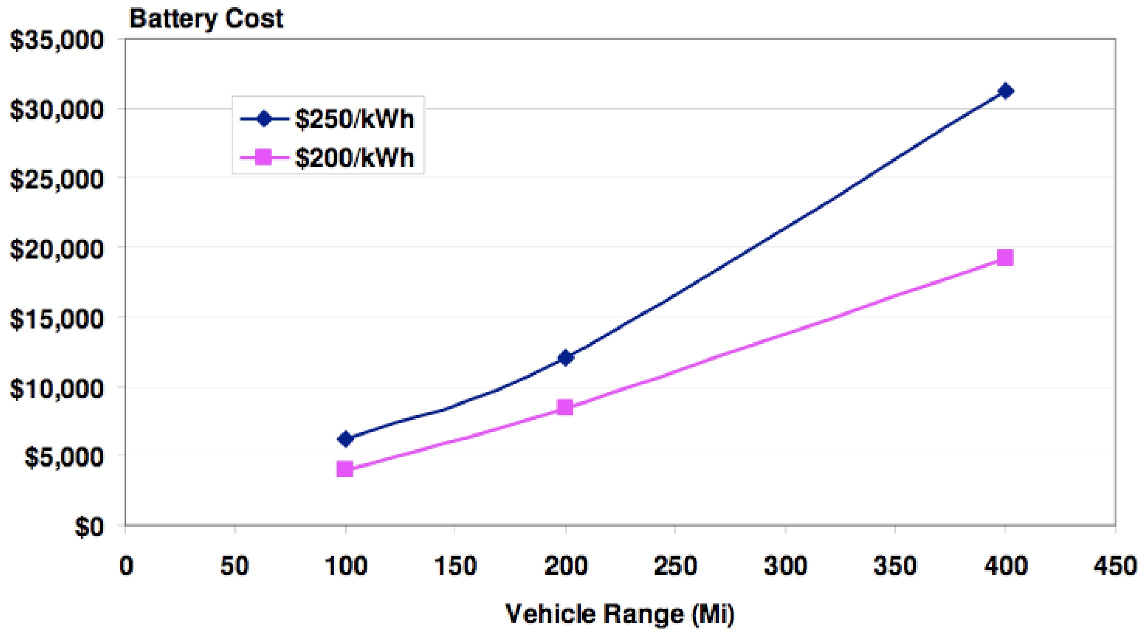
Year	Incremental #BEVs (Millions)	Fuel Saved (Mgal/Year)	GHG Reduction (mmt CO2e/yr)	
			Minimum	Maximum
2030	15	6,000	47	55
2050	161	65,000	572	643

Cost-Effectiveness

While BEV designs offer substantial cost reductions associated with certain vehicle components such as powertrains (estimated to be up to $4,000 per vehicle; Fulton and Pierpaola, 2008), battery purchase and replacement costs are even more significant. Near-term incremental BEV costs are extremely high, up to $50,000 per vehicle (Fulton and Pierpaola, 2008). Figure 2.5 illustrates the relationship between BEV range and future technology battery costs, assuming the same cost targets per kWhr as for PHEVs ($250 medium-term, $200 long-term).[40]

[40]Current Li-ion batteries in mass production for personal computer applications have achieved the $250/kWhr target. (Burke et al., 2007).

Figure 2.5 Battery Cost as a Function of Vehicle Range



Source: Burke et al., 2007.

Considering cost savings from other components, a light-duty passenger BEV built with future technology could cost about $6,000 more than conventional LDVs, assuming a 100-mile range (Burke et al., 2007). Using similar cost and efficiency assumptions, Kromer (2007) estimates an incremental cost of $10,200 for a BEV with a 200-mile range. These estimates assume roughly $250/kWh battery costs, consistent with the assumptions in this report for 2030 PHEV costs.

The typical total cost for installation of an off-board charger for residential vehicle charging is approximately $880 (U.S. DOE, 2008b). While residential infrastructure installation for BEV charging is fairly straightforward, public access charging facilities are more complicated and expensive due to the regulations, codes, and practices that must be followed. The estimated cost for a 10-space commercial recharging facility would be approximately $18,500 (reference). This cost includes labor, material, signage, and permits.[41]

Fuel costs tend to be lower for BEVs than for conventional vehicles on a per mile basis, partially offsetting incremental vehicle costs. However, a range of different factors impact

[41]Off-board charger costs are excluded from the medium and long-term cost-effectiveness assessments, assuming most BEVs would have on-board chargers by that time. Public charging station costs were also excluded from the cost assessment, given the lack of information on their potential utilization compared to home recharging.

overall costs and cost-effectiveness for BEVs. First, electricity costs vary across the United States depending on location, type of generation, and time of use. The average cost of residential electricity in 2010 is estimated at 9.8 cents per kWh, projected to increase to 11.8 cents per kWh by 2030.[42] A charging price of 10 cents per kWh is used for this analysis (Kammen). The additional electricity demand from charging of BEVs in the near term is not expected to have a significant impact on overall electricity use or prices.[43] Details regarding potential impacts of increased charging demand on electricity generation in the medium to long term are discussed in Section 3.2.4.

Assuming 10 cents per kWh, and a 0.26 kWh/mi efficiency, BEV operation costs would be approximately 2 cents per mile, compared to a conventional gasoline LDV in 2010 at about 8 cents per mile (or 12.2 cents per mile in 2030 pretax, using AEO Reference case assumptions). The resulting cost differentials are used to develop the estimated cost and cost-effectiveness estimates for BEVs, as shown in 2.15. Due to the extremely high incremental costs associated with current BEVs, a near-term scenario is not considered. This analysis also assumes that battery replacement will not be required over the useful life of the BEV.

Table 2.15 BEV per Vehicle Cost and Cost-Effectiveness Range
2030

Range (Mile)	Incremental Vehicle Cost	kWh/ mi	Lifetime Gallons Saved	Discounted Fuel Savings[a]	Net Discounted Cost/Savings	Avg. GHG Reduction (Tonnes/Year)	Dollars/Tonne	
							Calculated	Literature
100	$6,000	0.26	6,500	$11,300	-$3,500	3.1-3.7	-$90 to -$106	$100 to $343
200	$10,200	0.26	6,500	$11,300	-$1,100	3.1-3.7	-$19 to -$22	

[a] Using pretax AEO price projections for gasoline and typical electricity estimate – $3.43 and 10 cents/kWh, respectively.

The above cost-effectiveness assessment is not consistent with the values found in the literature. Estimates from Bandivadekar et al. (which utilize the same incremental vehicle cost ranges, but higher gasoline costs and lower BEV efficiency assumptions), estimated

[42] AEO Table 8.

[43] For example, an increase of 10,000 BEVs in California would only result in an increase of roughly 0.06 percent of the state's total power demand (CARB, 2003).

dollar per tonne values between $329 and $343.[44] While McKinsey (2009) estimates somewhat more favorable cost-effectiveness values for BEVs, their estimates remain over $100 per tonne as well. Using lower battery efficiency numbers (0.4 representative of battery technology from recent years), and a pretax gasoline cost of $2 per gallon (again more representative of recent conditions and other studies), cost-effectiveness estimates for the BEV200 scenario rise to $130 to $180 per tonne. Adopting GHG intensity values from GREET for grid-average electricity would increase the dollar per tonne estimates even further.

Cobenefits

BEVs provide an opportunity to significantly lessen the U.S. dependence on petroleum, as well as the potential for reduced air pollution attributed to mobile sources in urban areas. For every 28 miles traveled by a light-duty BEV in 2030, one gallon of gasoline would be conserved. Along with FCVs, the broad penetration of BEVs into the LDV market offers the largest potential for reduced gasoline consumption of any LDV strategy evaluated in this section.

Electricity generation using the current grid average may generate increases in some pollutants, including PM and SO_x (Table 2.16). However, because BEVs do not create point-of-use emissions, their use can still reduce urban air pollution for all pollutants. Furthermore, reductions in pollutants are likely to realized in the future, as discussed in Section 3.2.4 in relation to PHEVs. Given the complexity of declining emissions caps and the variability in dispatch scenarios over time, the GREET model does not provide adequate accuracy for estimating criteria and other pollutant impacts resulting from future vehicle charging demands. Assuming the same number of vehicles as for the PHEV analysis, however, the emission impacts of BEVs charging under the same conditions represented could be larger than those of PHEVs, given a BEV's greater electric range compared to PHEVs. This table shows nationwide decreases in VOC, NO_x, and SO_x of 0.6, 1.7, and 0.6 percent, respectively, but small increases in PM_{10} and mercury (0.2 and 0.4 percent, respectively), for a representative PHEV scenario.

[44] Derived from Heywood et al (2008), Tables 11 and 12.

Table 2.16 Emissions from Battery Electric Vehicle (National Average Grid Emissions) versus Conventional Gasoline

Pollutant	Change in Emissions versus Gasoline
VOC	-91%
CO	-98%
NO_x	-11%
PM_{10}	416%
$PM_{2.5}$	220%
SO_x	494%

[a] The use of national average grid emissions may not be appropriate to model the emissions impacts of electric vehicle charging demands. See Section 3.2.4 for an assessment of the nationwide changes in pollutants from a representative PHEV charging scenario; results for a BEV scenario will show similar or greater impacts.

BEVs would incur similar benefits to PHEVs with respect to grid management benefits associated with smart charging (see Section 3.2.4). BEVs also operate very quietly and can reduce noise pollution, and the charging infrastructure cannot create fuel spills as can many other alternative fuels. Many vehicle owners also may value the refueling convenience associated with home recharging, as well as the energy security benefits of reduced oil use (Burke et al., 2007).

Additionally, BEVs can have excellent acceleration, as well as fewer maintenance requirements than conventional vehicles as they have relatively simple powertrains (Kromer and Heywood, 2007). Another possible cobenefit of widespread use of BEV and PHEV charging systems would come from the use of smart chargers. These chargers could be remotely signaled to alter charge rates to perform load frequency control for the grid power system. This could result in more efficient grid electric generation if widespread use was achieved.

Some of the technology advancement from BEV research can facilitate the advancement of HEV and PHEV technology as well, and vice versa. Even if, as described above, BEV technology does not become widespread, research in this field is not lost as it can benefit other types of electric power platforms, especially with regards to battery technology.

Feasibility

Electricity is widely available, and electric vehicles can be charged at home or at public charging stations using inductive or conductive systems. Inductive charging systems use "paddles" inserted into the vehicle charging port to transfer power through the generation of a magnetic field. Conductive charging, the method used by most on-board chargers, uses a connector for direct electrical connection in the vehicle's internal charge port. The most practical option for BEV recharging is residential, where the BEV is plugged in overnight to recharge. This recharge method can utilize a standard 120 V AC outlet. However, since this type of residential outlet can only provide a relatively small amount of power, long charging times are required, possibly overnight. As an alternative, users can have a dedicated residential recharge station installed utilizing household 240 V power to allow for faster charging times.

The current operating zone for BEVs is highly limited due to the very small number of public access recharging stations. In order to circumvent the classic chicken and egg dilemma between vehicles and fueling networks, a California startup, Better Place, currently is implementing an aggressive installation scenario for thousands of public access recharging in certain vehicle operating "islands" in Denmark, Hawaii, and San Francisco. BEV purchases are offered through the company at deep discounts, with electricity purchases made through complex software management systems at designated public access locations. The company also intends to offer participants access to battery swap locations along intercity thoroughfares in order to extend operating zones beyond the core islands (BetterPlace, 2009). The ultimate success of such a "leap-frogging" approach may hinge on consumer acceptance of restricted charging and battery swap locations.

In addition to limited vehicle availability and public charging access, few mechanics have experience servicing BEVs, and most work must be done by a specialist or dealer. For this reason, most BEV leases include free dealer maintenance over the period of the contract.

In the absence of quantum "leap-frogging" of the kind described above, BEV battery energy density and cost issues must be addressed to effectively extend vehicle range. The most common types of batteries used in BEVs, as well as HEVs and PHEVs, are NiMH and Li-ion. Currently, NiMH batteries dominate the automotive battery market, although Li-ion batteries have the potential to make substantial in-roads over time. Recent testing indicates that both Li-ion and NiMH systems are likely to attain the U.S. Advanced Battery Consortium goal of a 10-year battery life.[45] Section 3.2.4 provides additional details regarding both battery technologies.

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[45] > 1,000 cycles at 80 percent depth of discharge (Burke et al., 2007).

There also are operational obstacles that go beyond battery capacity and installation of the charging infrastructure. As noted above, charge duration can require several hours. There are designs for fast chargers available, but battery life could be negatively impacted by increased charge rates. In addition, battery life also is generally determined by the total number of charge cycles. A single charge per day would allow batteries designed in the near term to last nearly the life of the vehicle. Charging multiple times per day could necessitate the early replacement of the battery near the middle of the vehicle's life at significant cost.

For centrally garaged fleet vehicles, and for private vehicles on short- and medium-distance commuting trips, the above performance limitations might not greatly affect the suitability of BEVs. The feasibility of BEVs for long-distance travel remains a challenge with current technology, although battery swap locations may ameliorate this difficulty to some extent.

With the continuing advancement in battery and vehicle technology, BEVs are capable of achieving speed performance comparable to or better than conventional vehicles. One manufacturer, Tesla Motors, currently is testing electric cars that are capable of 125 mph with better acceleration than conventional vehicles (Tesla Motors, 2009).

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3.0 Vehicle Fuel Efficiency

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■ 3.1 Summary

This section investigates technological advances that could lower GHG emissions from transportation through improved efficiency of on-road vehicles (including light- and heavy-duty vehicles), as well as of other transportation modes, including aircraft, rail locomotives, cars, and commercial marine vessels.[1] The evaluation considers technologies that currently are available or close to commercialization, as well as more advanced strategies that may not be available for a decade or more.

Improved vehicle fuel efficiency can be achieved through advanced engine and transmission designs, use of light-weight materials, improved aerodynamics, and reduced rolling resistance, among other means. Refrigerants are also discussed in this section, as hydrofluorocarbons (HFC) used in vehicle air conditioning (A/C) systems such as R134a are powerful greenhouse gases, and HFC emissions also can be reduced through improved A/C system design or the use of alternative refrigerants.[2] Vehicle technology strategies are discussed in this section for the following types of vehicles:

- Light-duty on-road vehicles (passenger cars, light trucks, and sport-utility vehicles), including advanced conventional gasoline technologies, replacement of gasoline with diesel vehicles, hybrid, and plug-in hybrid electric vehicles (Section 3.2);
- Heavy-duty on-road vehicles (heavy trucks) primarily involved in freight movement, including resistance and weight reduction strategies, as well as engine and powertrain improvement options (Section 3.3);
- Transit buses, including powertrain hybridization and alternative fuels (Section 3.4);
- Railroads, including yard and line-haul locomotives and trains (Section 3.5);
- Marine vessels in commercial use (Section 3.6); and
- Aircraft (Section 3.7).

Section 3.8 discusses strategies for reducing GHG emissions associated with air conditioning systems, including the use of alternate refrigerants and engine load reduction.

Certain advanced vehicle technologies are coupled with alternative fuel strategies that may depend on modified infrastructure, such as biofuel networks, fuel cell vehicles which rely on hydrogen, and pure electric vehicles which require a source of electricity to charge

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[1] In this section, the term "vehicles" collectively refers to aircraft, marine vessels, and rail locomotives and cars, as well as to on-road vehicles (cars and trucks).

[2] R134a has a global warming potential of 1,300 (U.S. EPA, 2009a).

their batteries. These strategies are discussed in Section 2.0, in the context of their associated fuel requirements.

Much work currently is underway in the area of evaluating the effectiveness and costs of various vehicle technologies in reducing fuel consumption and greenhouse gas emissions. The National Academy of Sciences is undertaking a study on light-duty vehicle technologies that will be available at the end of 2009 and a study on heavy-duty technologies that will be available in 2010. The National Highway Traffic Safety Administration (NHTSA) is conducting state-of-the-art vehicle simulations as part of its analysis for the notice of proposed rulemaking for the 2012-2016 Corporate Average Fuel Economy (CAFE) standard (NHTSA, 2008a). NHTSA is also working on a study of medium- and heavy-duty vehicle and work truck fuel efficiency. This Report to Congress provides information from studies available at the time of writing (generally through June 2009, although some studies released as late as September 2009 are referenced). This section of the Report to Congress attempts to provide useful information to Congress regarding the potential of vehicle efficiency strategies to reduce greenhouse gas emissions in the near, medium, and long terms by citing ranges of effectiveness and costs from the literature, evaluating technologies against a common baseline, and discussing key considerations. Key uncertainties and differences between analyses are noted.

Assessing the benefits of any particular strategy or set of strategies is a complicated and often controversial task that is best done at the time a strategy or set of strategies is being considered as a path forward. It is also critical to include in such an analysis the best, most current data and reliable assumptions.

Summary of Impacts

Vehicle fuel efficiency strategies have the potential to generate significant emission reductions, especially in the medium to long term as the vehicle fleet turns over and new technology is phased in.[3] The greatest potential exists in the light-duty sector, since it is responsible for the greatest amount of GHG emissions and also experiences relatively quick fleet turnover compared to other sectors – with the vast majority of the vehicle fleet turning over within 15 years, compared to 20 years or more for trucks and up to 40 years for locomotives, marine vessels, and aircraft. However, each of these strategies is expected to penetrate the market to some degree on its own without further government incentives or mandates. Therefore for a given market penetration level, the incremental emission reductions obtainable from these strategies will be diminished somewhat over time when compared against a baseline forecast, as opposed to current conditions.[4] Some

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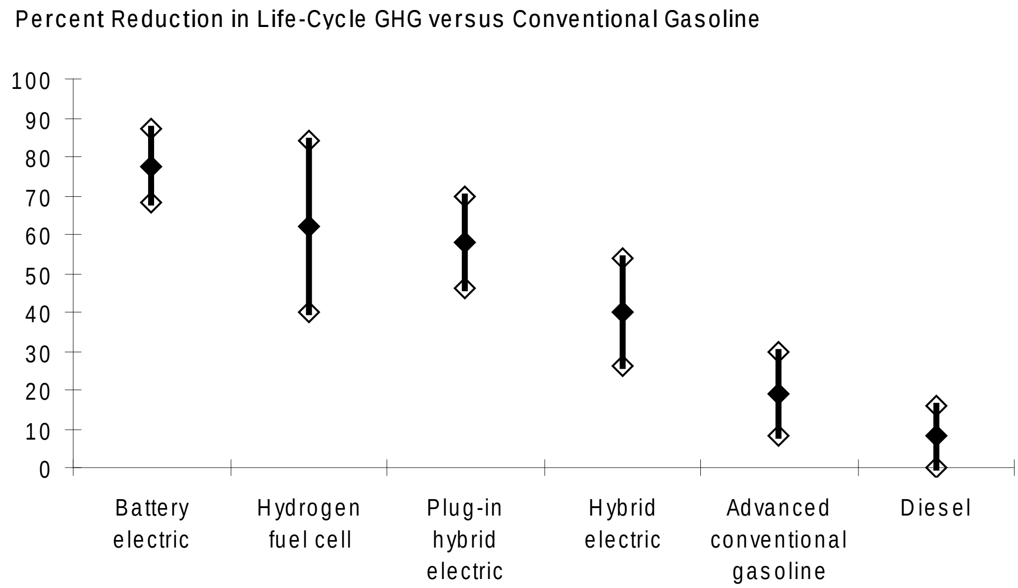
[3] In this report, "near-term" refers to the 2010-2015 timeframe, "medium-term" to 2030, and "long-term" to 2050.

[4] All comparisons in this section (and throughout this report) are made with respect to the U.S. Department of Energy (DOE) Annual Energy Outlook (AEO) Reference case forecast through

(Footnote continued on next page...)

short-term gains also are possible through retrofits to existing heavy-duty and off-road vehicles.

Figure 3.1 Projected per Vehicle GHG Reductions of Light-Duty Vehicle/Fuel Technologies Compared to Baseline Conventional Gasoline Vehicle



Source: Eastern Research Group, Inc. analysis as presented in Vol. 2, Sec. 2.8 and 2.9 (hydrogen fuel cell and battery electric) and Vol. 2, Sec. 3.2 (other vehicle types). The ranges shown represent GHG reductions for 2030 and beyond, with the low end of the battery electric and hydrogen fuel cell ranges reflecting 2030 impacts and the high end reflecting additional advances through 2050.

Advanced conventional gasoline vehicle strategies range from minor changes to current engine characteristics to complete modification in the way fuel is burned. Most of these strategies, including component electrification and advanced engine controls, already are demonstrated and are beginning to penetrate the market. These strategies are estimated to provide a reduction in fuel consumption of 8 to 30 percent per vehicle in the medium to long term. These vehicles will have very similar performance and maintenance requirements compared to conventional vehicles. Costs will be somewhat higher (up to

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2030 (April 2009 release). With respect to vehicle technology, the AEO forecast accounts for the goal established under the 2007 Energy Independence and Security Act (EISA) to obtain a new vehicle average fuel economy of 35 mpg by 2020. The forecast does not include specific CAFE updates, nor changes to the standards proposed by the Obama Administration in 2009 to be consistent with proposed greenhouse gas emission reduction requirements in California. The AEO Reference case also includes some penetration of hybrid-electric vehicles into the market (10 percent of the vehicle stock). The AEO also assumes efficiency improvements to other modes, to varying degrees, as a result of technology improvements driven by market forces.

$1,000 per vehicle), but should be more than paid back in fuel savings over the life of the vehicle.[5]

Replacing conventional gasoline vehicles with comparable **diesel vehicles** can provide substantial per-vehicle reductions in GHG emissions, about 16 percent, due to inherent efficiencies in the diesel engine cycle. Light-duty diesel vehicles, while common in Europe, are almost absent from the U.S. market, and would require ramping up of production and marketing in order to make substantial inroads in the light-duty fleet. However, diesel vehicles will face a difficult challenge obtaining market share, having to compete with advanced conventional gasoline vehicles whose future fuel efficiency levels may approach those of diesels, and at lower overall costs. Light-duty diesels are up to $2,000 higher in price than gasoline vehicles due to required engine differences and pollutant controls; they may or may not provide a lifetime cost savings, depending upon their relative efficiency compared to gasoline vehicles and the relative price difference of the fuels.

Hybrid electric vehicles (HEV) can reduce fuel consumption and GHG emissions per vehicle between 26 and 54 percent compared to conventional gasoline vehicles. Although comprising less than 2 percent of the current fleet, HEV market shares are rising rapidly, with numerous models existing or planned for launch by various manufacturers. HEVs have a cost premium of roughly $4,500 per vehicle in the near term, although these costs are expected to fall somewhat in the future, to about $3,000 per unit; fuel cost savings could potentially lead to a net savings over the vehicle's lifetime as production costs come down. The incremental benefits of HEVs are diminished somewhat as advanced gasoline vehicle market shares increase, and HEV cost-effectiveness relative to these vehicles is not nearly as favorable as compared with conventional (current technology) gasoline vehicles.

Plug-in hybrid electric vehicles (PHEV) are estimated to reduce GHG emissions by 46 to 70 percent per vehicle in the medium term and 49 to 75 percent in the long term, assuming a move towards increasingly less GHG-intensive sources of electricity generation. PHEV battery technology and cost concerns must still be addressed in order to obtain significant market share in the future. PHEV battery costs currently are prohibitively high (about $16,000 per vehicle), although projections for future year batteries suggest a cost increment of $3,000 to $8,000 in the medium to long term (depending upon the vehicle's all-electric range), which would yield net cost savings over the life of the vehicle due to fuel savings. GHG reductions and cost-effectiveness for PHEVs are very sensitive to the fuel used to generate the electricity used to charge the battery. In the absence of substantial improvements in electricity GHG intensity, the potential GHG reductions for PHEVs become more comparable to HEVs, yet costs are greater, so cost-effectiveness is lower than for HEVs.

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[5] All of the cost-effectiveness estimates presented in this section are sensitive to the projected cost of fuel in the analysis year. Cost assumptions are from the AEO 2009 Reference case for 2030 and include: gasoline and diesel – $3.43 (pre-tax); railroad diesel $3.67; jet fuel $3.33; marine bunker fuels $2.82. See Appendix A for a more detailed discussion of cost calculations.

On-road heavy-duty vehicle strategies can provide significant GHG reductions as well, beyond efficiency improvements already considered in baseline projections. Unlike most vehicle strategies evaluated here, retrofits of heavy-duty trucks (including aerodynamic fairings, trailer side skirts, and low-rolling resistance tires, among others), particularly long-haul freight trucks, can provide significant reductions in the near term. Most of these technologies currently are available. Significant additional reductions in the medium to long term are possible for engine and powertrain modifications that require time to penetrate the fleet. Examples of emerging powertrain technologies include turbocompounding, bottoming cycle, and hybridization. Some of these technologies are proven and are beginning to penetrate the market (such as hybridization), while others (such as bottoming cycle) require further research and demonstration. Per vehicle costs can be sizeable, at least $10,000 for aggressive tractor and trailer retrofits, to over $20,000 per unit for a full suite of retrofit, engine, and powertrain improvements using conventional technologies, or over $60,000 using advanced technologies on large (Class 8) trucks. Most of these improvements yield net cost savings over the lifetime of the vehicle due to fuel savings, assuming baseline AEO fuel price projections.

Bus strategies, including hybridization and fuel cells, offer substantial reductions on a per vehicle basis. However, the entire bus sector, including transit buses, school buses, and intercity buses, is responsible for less than 1 percent of total on-road GHG emissions in the U.S (about 20 mmt CO_2e). As such, no strategy offers more than modest reduction GHG potential, with benefits and costs only addressed qualitatively in this section. While technology options are generally available, capital costs currently are high due to low production volumes and other factors, although initial costs will be at least partially recouped over time through operating cost savings.

GHG reductions are possible through the use of genset and hybrid **locomotives** in rail yards (35 to 60 percent per locomotive), as well as through improvements to line-haul locomotives and train sets, including more efficient line-haul locomotives (10 to 20 percent improvement), lightweight cars, aerodynamic improvements, wheel-to-rail lubrication technologies, and drive system operation (22 to 31 percent combined improvement per train). All of these technologies are commercialized and available for immediate use, although some must be phased in over time as fleet turnover occurs. While incurring higher up-front capital costs, most of these strategies have the potential to pay for themselves in less than 10 years through fuel cost savings.

Improvements to **marine vessel** design can reduce fuel consumption and GHG emissions by 2 to 35 percent per vessel. Changes to propulsion systems (such as diesel-electric or hybrid systems) can have a similar impact for vessels that vary their operations frequently such as harbor vessel, cruise ships and vessels involved in short sea shipments. Changes in propeller design can improve efficiency by 4 to 15 percent while solar photovoltaic technologies can provide a fuel savings and GHG reduction of 5 to 7 percent. In the longer term, application of devices that utilize wind power to supplement vessel energy supply may provide fuel savings between 5 and 30 percent for long-distance vessels. All of these technologies are commercially available, although solar photovoltaics are still expensive and wind power remains in the demonstration stages. While some technologies (such as propeller designs and solar panels) can be retrofit on existing vessels and realize short-term benefits, most must be phased in with new vessels. The rate at which benefits are realized will be limited by the slow turnover rate of the commercial marine fleet, where vessels may remain in service for 30 to 40 years or more. All are expected to lead to net cost savings of the life of the vessel.

Use of new **aircraft** engine technologies such as improved current engine design, geared jet, and open rotor engines can provide an improvement in fuel consumption and reduction in GHG emissions (10 to 15 percent, with potentially up to 30 percent for open-rotor, compared to current aircraft). In the medium to long term, reductions of 20 to 30 percent may be possible on larger aircraft through the use of the blended wing body design. With the exception of improvements to the current engine design, which are commercially available, these other aircraft options may be available in the near future (5 to 10 years). On a fleet-wide basis, both aircraft engine and airframe technology improvements could potentially increase fuel consumption efficiency by 1.4-2.3% annually between 2015–2035 relative to 2015 as the base year.

Vehicle air conditioning (A/C) system measures offer modest to moderate GHG reduction potential. Adoption of a “can-ban” eliminating the practice of do-it-yourself servicing, or a deposit program for small refrigerant cans, could be implemented in the near term, These systems have been demonstrated in various test studies, but are not yet commercially available. A/C system loads also can be reduced (lowering GHG emissions by reducing main engine loads) through the adoption of reflective glazing (to lower cabin temperatures), and adoption of other A/C system modifications. Per unit costs for alternative refrigerant systems are expected to be relatively low at full production (less than $100 per vehicle), although the costs incurred for professional servicing under a can-ban can be several hundred dollars over the life of the vehicle; the cost-effectiveness of alternative refrigerants is estimated to be in the range of $40 to $90 per tonne CO_2e.

The Rebound Effect

Benefits from technology strategies may be somewhat offset due to the “rebound effect.” This effect can be characterized as the extent to which fuel savings (and corresponding GHG reductions) from vehicle fuel efficiency improvements are offset by increased travel, because travel is made cheaper per-mile due to reduced fuel costs. The National Highway and Traffic Safety Administration used a 10 percent rebound effect in its analysis of fuel savings and other benefits from higher CAFE standards for MY 2012–2016 vehicles. Recognizing the uncertainty surrounding the 10 percent estimate, the agency analyzed the sensitivity of its benefits estimates to a range of values for the rebound effect from 5 percent to 15 percent. (NHTSA, 2009). (For more detail on the rebound effect, see Appendix A.)

The impact of the rebound effect is fairly straightforward to demonstrate in the case of strategies that improve the efficiency of existing gasoline or diesel vehicles. For example, if advanced gasoline technology improved fuel efficiency by 20 percent, a 15 percent rebound effect would reduce the overall fuel savings and GHG reduction benefits by 3 percent (15 percent of 20 percent), to 17 percent. For efficiency improvements that involve the use of different fuels (such as switching from gasoline to diesel or PHEVs that run partially on electricity), the effect is more complicated as it will depend upon the relative cost per mile of the different fuels compared to gasoline.

The estimates cited by NHTSA and commonly found in the literature apply only to personal travel using light-duty vehicles. A rebound effect could theoretically be present for other passenger modes (including personal travel by bus, rail, and air) as well as for goods movement, if the total cost of travel or goods movement is reduced. However, these effects, while not extensively studied, are likely to be small. Nonfuel costs (e.g., labor) make up a more significant proportion of overall costs, and for goods, shipping costs usually make up a relatively small proportion of a product's overall costs. Furthermore, since *all* costs (including vehicle capital costs as well as fuel costs) would be passed on to the traveler or consumer—not just the per-mile costs—any increase in vehicle costs due to advanced technologies would offset reductions in fuel costs from the traveler or consumer's viewpoint.

Policy Implications

On-Road Vehicles

Policies to promote on-road vehicle technology strategies will need to overcome several hurdles. Consumers tend to "undervalue" fuel economy improvements—i.e., they value fuel savings over only part of the lifetime of the vehicle when making vehicle purchase decisions, limiting the amount of increased initial cost that manufacturers can pass on to consumers. NHTSA assumes that consumers value five years worth of fuel savings (the current average term of consumer loans to finance new vehicles) (NHTSA, 2008b). Other studies have shown shorter periods, with Greene (2007) concluding that consumers have a willingness to pay for only about two years of fuel savings. In contrast, about half of the light-duty vehicles sold in 2012 are expected to remain in service for 14 years or more.

In the absence of strong consumer interest in fuel economy, technology has been put towards increasing horsepower rather than efficiency. Uncertainty in future fuel prices also limits interest in potential advanced technologies. The vehicle fleet turns over relatively slowly, and retrofits are practical only for some heavy-duty vehicle technologies. Evidence suggests that even heavy-duty vehicle operators require a payback period of four years or less for fuel-saving improvements—meaning that many enhancements with net lifetime cost benefits may not be retrofit or introduced with new vehicles. Finally, some heavy-duty vehicle design strategies require coordination between tractor and trailer manufacturers.

Fuel economy standards have been the main policy mechanism used in the United States to improve the vehicle efficiency of light-duty vehicles. Fuel economy standards and greenhouse gas emission standards have the advantage of overcoming consumers' short payback period and undervaluing of fuel economy. The first corporate average fuel economy (CAFE) standards were passed in 1975 in the wake of the Arab oil embargo; it is estimated that light trucks and passenger cars would have emitted an additional 11 billion metric tons of CO_2 into the atmosphere between 1975 and 2005 had the CAFE standards not been enacted (NHTSA, 2009a). Recently, there has been new activity in establishing fuel economy or emission standards. The 2007 Energy Independence and Security Act (EISA) required a 40 percent increase in fuel economy, to 35 miles per gallon (mpg) by 2020 for all light-duty vehicles; required the establishment of new fuel economy standards for both medium- and heavy-duty commercial vehicles; and made other changes to allow NHTSA to establish light-duty vehicle standards to minimize adverse safety impacts. In early 2009, NHTSA set new fuel economy standards for the 2011 model year that will achieve an industry-wide combined fleet average fuel economy of 27.3 miles per gallon (NHTSA, 2009b). That rule, for the first time, incorporated an analysis of GHG impacts associated with the new standards.

In 2009, NHTSA and the United States Environmental Protection Agency (EPA) worked in concert to develop a consistent, harmonized National Program to deliver substantial further improvements in fuel economy and reductions in GHG emissions for new cars and light-duty trucks. On May 22, 2009, these agencies issued a notice of intent to conduct a joint rulemaking to establish aggressive new CAFE standards and vehicle GHG emissions standards for passenger cars, light-duty trucks, and medium-duty passenger vehicles built in model years 2012 through 2016. In addition, on September 28, 2009, NHTSA and EPA announced in the Federal Register the Proposed Rulemaking To Establish Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards (*See* 74 FR 49454). NHTSA also prepared an environmental impact statement to analyze and disclose the potential environmental impacts of the proposed model years 2012 through 2016 Corporate Average Fuel Economy standards (*See* 74 FR 48894). The proposed standards would increase light-duty vehicle fuel efficiency by an average of 5 percent each year between 2012 and 2016 and require new vehicles to meet an average of 35.5 mpg by 2016 (White House, 2009), effectively equivalent to the requirement of 250 grams of CO_2 per mile that the State of California had proposed in this same timeframe. The Agencies' announced intention is to achieve these results through the use of technology that will be commercially available and can be incorporated at a reasonable cost. In addition to the NHTSA's proposed fuel economy standards, EPA expects to propose the first ever Federal emissions standards for greenhouse gases using its authority under the Clean Air Act (CAA). The intent of the National Program is to allow auto manufacturers to build a single light-duty national fleet which satisfies requirements under both programs. Moreover, the National Academy of Sciences is currently conducting a study on fuel economy standards for work truck, medium and heavy duty vehicles that NHTSA will rely upon to set future standards for these types of vehicles.

In addition to raising standards for fuel economy, future mileage testing procedures for fuel economy standards could be modified to account for aspects of vehicle operation that currently are not included in testing, such as power steering and air conditioner operation. This would give manufacturers an incentive to increase efficiency of these components as well. Standards also could address HFC emissions used in air conditioners and refrigeration equipment, through best management practices or other regulations to reduce leaks and require proper recycling and disposal of HFCs during maintenance.

Beyond fuel economy or emission standards, a variety of other policy options can be considered to encourage consumers to purchase more fuel-efficient vehicles. Fuel economy fees and rebates ("fee-bates") provide financial incentives to purchase more fuel-efficient vehicles. An analysis for the U.S. Department of Energy (DOE) found that a feebate equivalent to a $107 rebate for each additional mile per gallon fuel economy above 26 mpg (or fee of $107 for each mpg below 26 mpg) results in a higher level of fleet fuel economy than a $3 per gallon fuel price and equivalent cumulative fuel savings in 2020, but does not achieve fuel savings as great as CAFE levels of 40/30 mpg for cars and light trucks (EEA, 2008). Fuel or carbon taxes also encourage this behavior by raising the price of fuel. Tax incentives, such as those already offered for hybrid vehicles can be used to promote particular technologies or be based on fuel consumption. Certain hybrid-electric vehicles currently are eligible for tax credits of up to $3,000 per vehicle, offered through the end of 2010 by the Internal Revenue Service (IRS); and the Energy Policy Act of 2005 included tax credits of up to $12,000 for hybrid heavy-duty vehicles, based on the fuel efficiency and weight of a particular vehicle.

Consumer education strategies, such as labeling, regarding the relative efficiency of vehicles and tires (or other vehicle components) can be used as a strategy to help consumers to integrate fuel economy into their purchasing decisions. Existing education programs include EPAs Green Vehicle Guide, first launched in 2001 to give consumers information about the environmental performance of different vehicles using a rating system; the DOEs web site, www.fueleconomy.gov, a similar initiative; and SmartWay, a voluntary collaboration between EPA and the freight industry to reduce greenhouse gases and air pollution by conferring a special designation to vehicles that perform well. Section 5.5.2 provides details on these programs. Finally, to address the slow rate of fleet turnover, vehicle scrappage programs can be used to remove old, less efficient vehicles from the roads. Such programs were first applied in California in the 1990s to remove polluting vehicles from the road. In June 2009 the Federal "Cash for Clunkers" bill was signed into law establishing the Car Allowance Rebate System (CARS), which provides a $3,500 to $4,500 rebate for trade-in of a used car or truck for a new vehicle with a minimum fuel economy improvement compared to the used vehicle (the program also allows for trade-in of older model trucks that are not rated for fuel economy).

The heavy-duty vehicle fleet offers opportunities for funding or financing retrofits with grants and low-cost loans (such as are available through EPA's SmartWay program, or have been offered through California's Carl Moyers program to reduce air pollutant emissions). Some attempts have been made to mandate improvements to the heavy-duty vehicle fleet beyond Federal regulations; the Clean Air Action Plan for the Ports of Los Angeles and Long Beach includes a Clean Trucks Program that bars pre-1989 trucks from entering the ports and imposes fees on newer vehicles that do not meet the port's standards, and the California Air Resource Board is considering measures that would require SmartWay-type retrofits on all heavy-duty vehicles (MJ Bradley, 2009). For transit vehicles, public funding can be directed at purchasing hybrid vehicles and alternative fuels.

Finally, government funding could accelerate the pace of research and development into advanced automotive technologies. This could make new technologies more cost-effective and feasible and increase the options available for the future vehicle fleet. In addition, government partnerships (such as EPA's recent partnership with UPS to introduce hybrid delivery trucks) can be used to introduce new heavy-duty vehicle technology, or to achieve coordination regarding new design standards among tractor and trailer manufacturers.

Air, Rail, and Marine

Unlike the on-road sector, there are no regulations that define fuel efficiency standards for railroads, marine vessels, and aircraft. Improvements in efficiency have been primarily driven by economic considerations; locomotives, vessels, and aircraft that have better fuel efficiency tend to have an advantage in the marketplace over competitors with poorer fuel efficiency. Fuel currently represents the largest operating cost for U.S. airlines, which increases their incentive to reduce fuel consumption. As fuel prices increase, business cost savings will probably continue to enable the introduction of new technologies.

Although there are EPA emission standards for criteria pollutants for non road categories and associated fuels, there are no standards that specifically regulate GHG emissions for railroads, marine vessels, and aircraft. Within each subsector there are voluntary programs; both governmental and nongovernmental programs have been implemented to encourage improvements in fuel efficiency and reductions in GHG emissions. For example, the Association of American Railroads created a research division, the Transportation Technology Center, to encourage the use of clean, safe, and efficient technologies by railroads. Recently, the International Maritime Organization (IMO) completed a comprehensive assessment of marine vessel GHG emissions and potential control options. Similarly, the Committee on Aviation Environmental Protection (CAEP) of the International Civil Aviation Organization (ICAO) has set international standards for new engines and has targeted an improvement in fuel efficiency of 20 percent by 2020. Currently, ICAO members are developing a global framework to address international aviation greenhouse gas emissions.

In developing new policies that encourage the introduction of new air, rail, and marine technologies it will be necessary to address barriers that include:

- Long vehicle lifespan, such that fleet turnover is relatively slow.
- The high capital cost of aircraft, locomotives, rail cars, and marine vessels, which encourages owners to maintain older technologies for as long as possible.
- The high capital cost associated with commercialization of new technologies. This is most apparent for aircraft manufacturers, where development costs often require billions of dollars of investment, and limit how frequently new aircraft designs can be introduced.
- Cost uncertainty associated with technologies (particularly for technologies that have very tight profit margins) as well as with actual fuel savings and emission reductions.
- Infrastructure issues associated with the vehicle, which may restrict application for some of the technologies investigated in this study. For example, blended wing

aircraft will need specially constructed terminals for boarding passengers and loading freight.

Federal policy and funding could potentially accelerate the introduction of new rail, marine, and aviation technologies at a faster rate than current voluntary and market-based approaches. Funding of research and development activities could advance and facilitate some of the technologies that appear to be viable but have not been made commercial. Existing State programs in California and Texas help subsidize rail and marine technologies; while these programs have been undertaken with the goal of reducing air pollution emissions, some of the technologies they have encouraged are reducing greenhouse gas emissions as well. In particular, most of the railroad gensets and hybrid engines are located in these two States. Implementation of a Federal program could help facilitate the distribution of these technologies throughout the United States.

Federal low-interest loan programs and tax incentives also have been adopted for purchase of various energy efficiency components and could be expanded to help defer capital costs for other types of equipment. For example, the EPA's SmartWay program offers a variety of financing programs for the purchase or lease of idle reduction technologies, and the Energy Improvement and Extension Act of 2008 eliminated the 12 percent excise tax on idle reduction devices for new trucks (see Section 4.4.1). Adoption of energy-efficient technologies also may be encouraged through voluntary programs such as the U.S. EPA's SmartWay Program. This program serves as a clearinghouse for information on environmentally beneficial practices in the freight industry, and offers public relations "branding" for those companies with notable environmental performance.

Summary Evaluation

Table 3.1A summarizes the strategies discussed in this section and presents estimates from the literature of per vehicle GHG reductions compared to conventional vehicles as well as a summary of key Federal policy initiatives that could be used to implement the strategy beyond current levels.

Table 3.1A Vehicle Fuel Efficiency Options Summary Evaluation

Strategy	Per Vehicle GHG Reduction Compared to Conventional Vehicle	Key Federal Policy Options
3.2 On-Road Light-Duty Vehicle Strategies		
Advanced Conventional Gasoline Vehicles	8 – 30%	Financial or regulatory incentives for improved fuel efficiency (beyond current CAFE requirements)
Diesel Vehicles	16%	Financial or regulatory incentives for improved fuel/GHG efficiency
Hybrid Electric Vehicles	26 – 54%	Financial or regulatory incentives for improved fuel efficiency (beyond current CAFE requirements)
Plug-In Hybrid Electric Vehicles	46 – 75%	Funding for additional research on battery efficiency, performance, and cost Tax credits for early introduction/adoption Public recharging infrastructure and favorable utility rates for nighttime charging
3.3 On-Road Heavy-Duty Vehicle Strategies		
Retrofits of heavy-duty trucks to use aerodynamic fairings, trailer side skirts, low-rolling resistance tires, aluminum wheels, and planar boat tails	10 – 15%	Financial incentives for purchase of retrofits Financial or regulatory incentives for improved fuel efficiency Requirements for proven technologies Demonstration programs/partnerships
Powertrain and Resistance Reduction for New Trucks	10 – 30%	
3.4 Transit Bus Strategies		
Assorted vehicle/ fuel options	10 – 50% for hybrid electric buses	Financial support for transit agency purchase of advanced vehicles
3.5 Rail		
Power System Modifications		Financial incentives for purchase of retrofits Requirements for proven technologies Demonstration programs/partnerships Long-term price incentives for increased fuel efficiency
• Common rail injection systems	5 – 15%	
• Genseit engines	35 – 50%	
• Hybrid yard engines	35 – 57%	
• Hybrid line-haul operations	10 - 15%	
Train Efficiency Improvements		
• Light weight railcars, aerodynamics, wheel to rail lubrication	4-10% individually	
• Improving load configuration for intermodal trains	up to 27%	

Table 3.1B Vehicle Fuel Efficiency Options Summary Evaluation (continued)

Strategy	Per Vehicle GHG Reduction Compared to Conventional Vehicle	Key Federal Policy Options
3.6 Marine		
Improvements to Ship Design and Propulsion Systems	4 – 15% for ship design Up to 20% for diesel electric for vessels that change speed or load frequently (cruise ships, harbor tugs, and ferries)	Work with international marine organizations to adopt technology standards and market and nonmarket incentives for fuel efficiency improvements Work with domestic operators (ports, ferry) to purchase efficient technology R&D for advanced technologies
3.7 Aviation		
Advanced Engine Technologies	10 – 15%	R&D for advanced technologies
Advanced Air Frame/Wing Design	1.6 – 10%	Demonstration program/partnerships Financial or regulatory incentives to accelerate new technologies
Aircraft fleet-wide advanced engine and airframe technologies	Annual reduction of 1.4–2.3 during 2015-2035 relative to year 2015 as the base year	
3.8 Vehicle Air Conditioning System Strategies		
	Reduction of mobile air conditioner emissions	
Can Deposit/Can-Ban	Banning "do-it-yourself" refrigerant refills in California was estimated to reduce that State's mobile air conditioner emissions by 66%	Regulatory action to require deposit or ban do-it-yourself refrigerants
Alternative Refrigerant Systems and A/C System Management	Changing refrigerant types could reduce mobile air conditioning emissions by 91.3 to 99.9% depending on refrigerant type and mechanical efficiency	Federal action to phase out existing refrigerants Support for industry/government partnerships to develop new systems standards Modify vehicle certification test procedures to reflect improvements in accessory efficiency

Cobenefits and Implications for Other Key Transportation Goals and Objectives

Vehicle technologies can be evaluated against five goals identified in the U.S. DOT's Strategic Plan, as well as against additional planning factors cited in the *Safe, Accountable, Flexible, And Efficient Transportation Equity Act: A Legacy for Users* (SAFETEA-LU) of 2005.

- **Safety –** Most of the strategies discussed in this section are not expected to impact vehicle safety, although strategies that result in substantially smaller or lighter vehicles may adversely affect safety. Improved vehicle maintenance options such as regular tire inflation should result in minor safety improvements. Issues related to alternative fuel safety are discussed separately in Section 2.0.

- **Reduced Congestion/Increased Mobility –** The technology strategies investigated here may result in some rebound effect due to reduced operating costs per unit of travel. The rebound effect represents a benefit to consumers, who are able to travel more due to reduced fuel costs; however, this benefit is estimated to represent only a small fraction of the total benefits from alternative fuel economy standards (NHTSA, 2008b). Weight reduction strategies for heavy-duty vehicles may allow for increased payloads for some fraction of freight movement, thereby reducing the total number of trucks on the road. Use of larger, more efficient locomotives and vessels will reduce the amount of railroad and marine vessel traffic while handling more cargo. Beyond that, these options are not expected to change the number of vehicles in operation or the overall mobility of the associated transportation system.

- **Global Connectivity –** The technology strategies evaluated here are not expected to impact network operations or global connectivity.

- **Environmental Stewardship –** Technological improvements in vehicle efficiency are likely to reduce air pollutant emissions as well. However, the proportionality with GHG reductions will differ among pollutants, and some measures may even result increased emissions (e.g., NO_x associated with higher compression engines). Also, the location of emission reductions will vary; strategies that reduce emissions in densely populated areas (e.g., roads, rail yards, and airports in population centers) will have a greater benefit to public health than those that reduce emissions in rural areas or over the ocean. Most light-duty vehicle strategies are unlikely to result in significant air pollution benefits because these vehicles currently are regulated to a fleetwide average, although HEVs may have an easier time meeting stringent emission standards than non-HEV gasoline or diesel vehicles (true for heavy-duty on-road and rail vehicles as well), and PHEVs will not produce any emissions when operating on all-electric mode. Heavy-duty vehicle resistance reduction strategies may reduce emissions as a result of reduced engine loads. On-road, rail, and marine vessel strategies involving electric batteries may require additional attention to waste disposal and recycling to avoid the improper disposal of toxic materials. In addition, alternative materials and manufacturing techniques may have unintended GHG impacts and should be subject to life-cycle analyses.

- **Security –** Advanced vehicle technologies utilizing conventional fuels may benefit national security by reducing dependence upon foreign oil. The reduction in oil use will be in direct proportion to GHG reductions for each strategy.

- **Livability –** Most of these strategies are not expected to significantly impact livability. A few may increase or decrease noise from vehicles.

- **Economic Vitality –** There may be employment benefits associated with these new technologies, particularly if demand for these technologies increases employment opportunities in the U.S.

- **Efficient System Management and Operation –** These technologies do not affect the management and operation of the transportation system.

- **System Preservation –** Most of the vehicle technologies are assumed to have negligible impact on preservation of the existing infrastructure. However, use of larger ships and locomotives could have negative impacts on port cargo handling equipment, rail lines, and yard cargo handling equipment by increasing wear and tear on equipment and rail infrastructure; and larger trucking payloads could impact road wear rates through increased loads per axle. Use of single-wide tires on heavy-duty trucks also may affect highway pavement maintenance requirements, although recent design advances may minimize its impact.

Effects on Infrastructure Funding

Improvements in on-road vehicle fuel efficiency will lead to proportionate reductions in motor fuel sales and therefore reduced revenue for transportation programs, under the current finance structure. The Federal Highway Trust Fund was established in 1957 as a dedicated, user-funded source of revenue for the United States highway system and is the source of revenue for the Federal-aid Highway Program. Net receipts in FY 2007 were $34.3 million to the Highway Account and $5.0 million to the Mass Transit Account (FHWA, 2008).

The on-road vehicle fuel efficiency strategies analyzed in this report will reduce total Federal Highway Trust Fund revenues in rough proportion to fuel savings and GHG reductions. So, for example, if advanced light-duty gasoline vehicles were to achieve a 20 percent efficiency improvement by 2030 and reach a market penetration of 60 percent, Highway Trust Fund revenues would decline by 8 percent, or about $3.1 billion compared to FY 2007 receipts.[6] Strategies focused on heavy-duty vehicles will have a somewhat

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[6] Gasoline tax receipts accounted for about $25.5 billion of trust fund revenue in FY 2007, or about two-thirds of total receipts, so 20 percent * 60 percent * 2/3 = an 8 percent reduction or $3.1 billion. This calculation assumes that trust fund revenues remain constant through 2030,

(Footnote continued on next page...)

greater proportional impact than those focused on light-duty vehicles because of the higher tax rate on diesel fuel (24.4 vs. 18.4 cents per gallon). A shift from gasoline to diesel light-duty vehicles would have a smaller revenue impact, since while less total fuel is consumed, the tax rate on diesel fuel is higher.

This analysis describes potential impacts to Federal transportation revenues under the current finance scenario. Funding shortfalls could be mitigated or avoided in the future through shifts in tax structures or through alternative infrastructure funding mechanisms.

■ 3.2 On-Road Light-Duty Vehicles

Light-duty vehicles (LDV) include passenger cars, light trucks, minivans, and sport-utility vehicles (SUV).[7] These vehicles are primarily used for personal transportation, although some are placed in service for commercial purposes. Light-duty vehicles are the single largest GHG-emitting subset of the transportation sector, accounting for over half of U.S. transportation greenhouse gas emissions—57 percent, or 1,232 mmt CO_2e in 2006. Future efficiency improvements established under the 2007 EISA are expected to reduce their contribution somewhat, to 1,081 mmt CO_2e or 50 percent of all transportation emissions in 2030. However, light-duty vehicles still represent the single-largest opportunity for reducing GHG emissions from the transportation sector.

Strategies for improving the efficiency and reducing GHG emissions from light-duty vehicles discussed in this section include:

- Advanced conventional gasoline vehicles, which utilize improvements to the gasoline internal combustion (IC) engine along with drivetrain and other vehicle attributes (such as wind resistance and weight) to improve fuel efficiency;
- Enhanced diesel vehicles that can meet stringent new emissions standards while providing the efficiency and GHG benefits of diesel engines;
- Hybrid-electric vehicles (HEV) that combine the internal combustion (IC) engine of a standard vehicle with the motor and battery technology of an electric vehicle; and
- Plug-in hybrid electric vehicles (PHEVs), which are similar to HEVs but have more batteries and can plug into the local power grid, beginning each trip on battery power.

Fuel-cell and battery electric vehicles also offer the potential for significant long-term gains in light-duty vehicles energy efficiency. These technologies rely on fundamentally

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which is consistent with AEO Reference case projections of relatively constant fuel consumption (with increases in VMT offsetting increases in fuel efficiency).

[7] Trucks and larger vans are classified as light-duty if they have a gross vehicle weight rating (i.e., total load carrying capacity) of less than 8,500 pounds.

different fuel sources (hydrogen and electricity) and therefore are discussed in Section 2.0, Low-Carbon Fuels.

This report focuses on the potential GHG benefits of each of these vehicle technology strategies if pursued individually. The benefit estimates rely on estimates of both per-vehicle GHG reductions, and the potential market penetration of a given vehicle type. As such, the GHG benefits of individual vehicle technology strategies cannot be combined to give total benefits. It is possible in the future that one particular technology path could be taken, or that multiple technologies could be used in different applications, depending upon where they are most advantageous. While beyond the scope of this report, estimates of total GHG benefits achievable from the light-duty vehicle sector could be developed through the analysis of alternative market penetration scenarios that combine different technology types. Nevertheless, the information presented in this report is helpful in assessing which vehicle technology options may provide the greatest benefits, as well as the costs or cost savings that might be realized from each technology.

Trends in Light-Duty Vehicle Use and Efficiency

The total miles traveled by LDVs has increased quite steadily over the past 35 years, more than doubling since 1970. During this time, both the total number of vehicles and the average miles traveled per vehicle have increased considerably, as has the share of heavier, lower fuel efficiency SUVs and light trucks, which now constituting about half of all new vehicle sales in the United States (AEO Table 57).[8] All of these factors have contributed to the steady growth in GHG emissions from LDVs. Other factors have tended to diminish LDV emissions during this time, however. For example, the adoption of the CAFE standards in the 1970s significantly constrained GHG reductions over time. According to the 2008 EPA Fuel Economy Trends report, "Since 1975, the fuel economy of the combined car and light truck fleet has moved through several phases: 1) a rapid increase from 1975 to the early 1980s, 2) a slow increase to the fuel economy peak of 22.0 mpg in 1987, 3) a gradual decline from the peak to 19.3 mpg in 2004, and 4) consecutive annual increases beginning in 2005, growing to 20.8 mpg in 2008" (U.S. EPA, 2008a). Figure 3.2 displays these trends since 1975.

While LDV fuel economy has remained relatively flat since the mid 1980s, the automotive industry has continually improved the efficiency of the vehicles themselves. However, these advances have been used to enhance vehicle performance and utility, and to permit weight increases, rather than in the service of increasing miles per gallon ratings. In fact,

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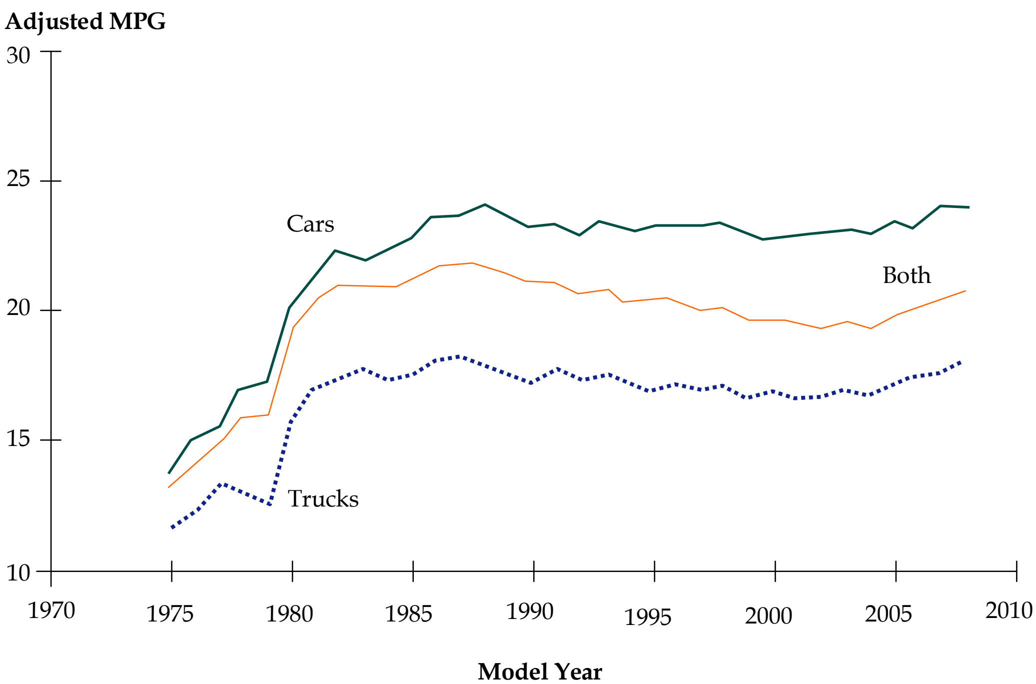
[8] The sales fraction of light trucks and SUVs has been roughly constant since 2002 (U.S. EPA 2008), and is assumed to remain at these levels into future years for the purposes of this analysis. Heywood et al point out that even with sizable swings in these sales fractions (between 30 and 70 percent), the resulting impact on fleet wide GHG emissions varies only by about 2 percent through 2035 (Heywood et al., 2008).

it has been estimated that if the technology advances that took place between 1981 and 2003 had been applied exclusively to fuel economy, fleet average mpg would have increased by 33 percent during this period (Bandivadekar et al., 2008). However, beginning in 2005 this trend has changed somewhat, with technology improvements also being used to improve vehicle fuel economy as well as performance (U.S. EPA, 2008a). The recent CAFE revisions will result in further reductions. For example, the adoption of the 2011 CAFE standards will increase the fleet average fuel economy by 7.9 percent to 27.3 mpg, at a relatively low cost of about $91 per vehicle (NHTSA, 2009b).

Figure 3.2 Fuel Economy Trends



Source: U.S. EPA (2008a).

Most of the GHG reduction strategies under consideration for LDVs are only available through new vehicle manufacture and purchase, rather than through retrofit. In addition, the LDV fleet has a lengthy turnover time, with passenger cars and light trucks lasting about 16 years on average before retirement (ORNL 2008, Tables 3-10 and 3-11). As such, new technology strategies can take a substantial amount of time before they enter the market in adequate numbers to generate notable impacts. Considering manufacturer product planning and design cycles, one assessment estimates that "if the decision to completely redesign vehicles were made today, it would take about 10 years to fully implement it in new vehicles." (Greene and Schafer, 2003). Bandivadekar et al. consider even longer timelines to be necessary, depending upon the technology and fuel in question, as summarized in Table 3.2A.

Table 3.2A Estimated Time Lag for Major Market Share Penetration for Selected Technologies

Implementation Stage	Gasoline Direct Injection Turbocharged	High-Speed Diesel with Particulate Trap, NO_x Catalyst	Gasoline Engine/Battery-Motor Hybrid	Gasoline Engine/Battery-Motor Plug-in Hybrid [a]	Fuel Cell Hybrid with On-Board Hydrogen Storage
Market Competitive Vehicle	~2-3 years	~ 3 years	~ 3 years	~ 8-10 years	~12-15 years
Penetration Across New Vehicle Production	~10 years	~15 years	~15 years	~15 years	~20-25 years
Major Fleet Penetration	~10 years	~10-15 years	~10-15 years	~15 years	~20 years
Total Time Required	~20 years	~25 years	~25-30 years	~30-35 years	~50 years

Source: Bandivadekar et al., (2008), adapted from Schafer et al., 2006.

[a] The time lag for PHEVs with different electric mode ranges could be significantly different. For example, lower electric range PHEVs with smaller batteries (and therefore lower incremental costs) might enter the market more quickly than those with larger batteries, if consumer acceptance generates adequate demand.

For many technology and fuel options considered in this report, most or all of the incremental vehicle costs may be recovered through subsequent fuel savings. However, the payback period may be lengthy (e.g., over 10 years for some of these measures) (U.S. EPA, 2005). As LDVs are often resold multiple times over their useful life, a vehicle purchaser may not obtain payback during their limited ownership period.[9] Accordingly, additional incentives may be required to promote market penetration of these technologies, even if the net present value of the technology option is positive over its lifetime.[10]

The GHG reduction technologies being evaluated for the LDV market fall into three broad categories: hybrid power systems, fuel cells, and other advanced design features. Technologies from one category can have corresponding technologies in another category that, by their nature, have increased benefit potential when employed together. As noted above, fuel cell technologies are discussed separately in Section 2.0.

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[9] According to industry estimates, payback periods of more than 3 to 4 years are not adequate in themselves to drive the market for new technologies (U.S. EPA, 2005).

[10] This conclusion depends on the extent to which vehicle resale prices incorporate the value of future fuel savings (U.S. EPA, 2005).

Methodological Issues

The LDV analyses presented below are based on findings from the relevant literature regarding the effectiveness and costs of the various efficiency improvement options. The studies consulted frequently featured different assumptions and calculation methods, including the type of vehicle(s) evaluated (e.g., compact, mid-sized, trucks), driving patters (urban versus highway), and the technology package of the vehicle to which the technology is compared. In addition, assumptions regarding vehicle miles traveled, retail price markups, the treatment of fuel taxes and subsidies, acceptable payback periods and discount rates vary between studies as well, all of which can have substantial impacts on cost and cost-effectiveness estimates. Finally, the elements of the "technology packages" evaluated in these studies were often different as well. As such, direct comparison of the findings from these studies is difficult, and their subsequent use in this analysis must be viewed as providing generalized estimates, rather than precise assessments of the different technology costs and benefits.

Advanced Conventional Gasoline Vehicles

Overview

Engine and powertrain advancements can increase the efficiency of converting fuel energy to vehicle movement. These technologies range from minor changes to current engine characteristics to complete modification in the way fuel is burned. These technologies are not available for retrofit, and will penetrate the marketplace only through the purchase of new vehicles. Many of these technologies will be adopted to meet upcoming CAFE requirements. These strategies also may be adopted on an accelerated schedule and/or at a higher market penetration level in order to extend their benefits beyond the regulatory base case scenario.

Some of the technologies discussed below can be applied to gasoline or diesel engines, while others apply only to gasoline systems. Many improvements intended for gasoline engines attempt to make them operate more like their more efficient diesel counterparts by reducing throttling losses or increasing compression ratios. In effect, these technologies attempt to capture diesel-cycle efficiencies without the increased pollutant formation.

Technologies that vary air intake and exhaust valve timing, compression ratio, and engine displacement all allow engines to operate more efficiently over a wider range of conditions. Variable valve timing and variable displacement are technologies currently available on a wide range of vehicles, but are still being advanced in ways that can provide substantial fuel consumption benefits. Variable valve timing is particularly common, being found on approximately half of all new vehicles, while variable displacement is less common, being limited to larger six to eight cylinder engines with larger pumping losses. (Bandivadekar et al., 2008). On the other hand, variable compression ratio technology is not expected to enter the market in a substantial way for at least five years, and will likely have lower penetration due to its greater complexity. As a group, these technologies hold promise primarily for gasoline engine improvements, but could benefit diesel engines as well.

Other potential improvements in engine operation include changes to gasoline combustion systems. Gasoline direct injection (GDI) allows more precise control over in-cylinder combustion by injecting finer droplets of gasoline into the cylinder instead of the intake, as is the case with conventional fuel injection. This technology also allows for higher compression ratios to be used, which result in greater engine efficiency. GDI has the additional benefit of increased torque output. A long-term goal of GDI research is the development of lean (or stratified) burning gasoline engines which would provide further increases in efficiency, although increased NO_x emissions would need to be offset by further improvements in exhaust treatment technologies.

Advanced Conventional Gasoline Vehicles

Per-Vehicle GHG Reductions: 8-30% e

Net Included Costs: **Net Savings**: -$180 to -$30 per tonne

Confidence in Estimates: **Moderate**

- Primary benefits uncertainty is market penetration
- Cost-effectiveness will depend on fuel prices

Key Cobenefits and Impacts: **Insignificant**

Feasibility: **High**

- Many technologies proven

Key Policy Options:

- Financial and/or regulatory incentives for improved fuel efficiency

Another combustion improvement option is Homogeneous Charge Compression Ignition (HCCI). Instead of a spark plug causing fuel ignition as in a standard gasoline engine, the HCCI combustion method uses the heat of compression to cause ignition in a fashion similar to a diesel engine. HCCI requires high rates of Exhaust Gas Recirculation (EGR), a technology currently employed in both gasoline and diesel engines. A high rate of EGR allows for higher engine efficiency by eliminating the throttling losses experienced in a gasoline engine at low engine loads. This technology can achieve efficiency gains similar to those of lean-burn GDI engines, without the increased exhaust pollutant formation. One drawback is that HCCI combustion can only take place over a limited range of operating conditions and an enhanced electronic control system must manage the engine across different combustion modes.

Two transmission technologies are being developed to increase powertrain efficiencies. One new technology that is commercially available is the continuously variable transmission (CVT). Instead of discrete gears, this type of transmission changes its gear ratio in a seamless fashion to eliminate shifting and allow the engine to stay in the most efficient operating condition possible. Internal power losses in this type of system partially negate its benefits, however. Another transmission technology currently entering the market is the dual-clutch transmission (DCT). This type of transmission offers automated control of discrete gears as in an automatic transmission, but eliminates much of the hydraulic loss associated with an automatic. It operates by having two separate power flow paths, each with a clutch, that alternate with each shift. Shifts can take place more quickly as one clutch can be released as the other is engaging.

Another option being investigated for LDVs involves higher voltage DC systems. In conventional vehicles, mechanical power is taken from the engine to run accessory functions such as power steering, oil pumps, and water pumps. These accessories tend to be overdriven at higher engine speeds. Improvements can be made allowing engine accessories to run off of electrical power using a higher voltage system, running them only when needed and at their most efficient speeds. Adopting a higher voltage electrical system also would enhance the ability to offer automatic start/stop operation similar to that of a hybrid vehicle. By having more battery power available, a vehicle's engine could be shut down during braking and idling to save fuel, then instantly restart when the driver is ready to accelerate.

In an internal combustion engine fuel energy is transformed into rotational power and heat that enters the vehicle's cooling system and exits with the engine exhaust. Nearly 70 percent of the fuel energy that enters a conventional engine is lost as waste heat, but research is underway to find means of recapturing this lost energy. A leading option in this area is a thermoelectric generator which can create electrical power flow in the presence of a temperature difference. If efficient enough, a thermoelectric device in the exhaust stream of an engine could allow the elimination of the alternator and its associated mechanical power consumption. This technology could be employed with hybrid vehicles or with conventional vehicles that have electrically powered accessories.

In addition to vehicle powertrain and engine improvements, other strategies such as reduced vehicle weight, lower rolling resistance tires, improved aerodynamics, and improved lubricants also can reduce energy consumption. These technologies generally improve the state of conventional technology gradually and offer relatively small fuel efficiency benefits with each succeeding model year, instead of providing a step change upon market penetration as expected with many of the technologies listed above.

Vehicle weight reduction strategies include material substitution, vehicle redesign, and market shifts to smaller and lighter vehicles. Weight reduction offers particular promise as a GHG reduction strategy, due to positive synergies with other LDV design considerations. For example, reductions in weight allow for secondary downsizing of components that no longer need to be as large in order to perform their functions. It is estimated that secondary reductions can total 50 percent of the primary reduction (Bandivadekar et al., 2008).

Material substitution in LDVs has been taking place over the last 20 years, primarily through the increased use of aluminum and high strength steel (HSS), used to replace mild steel and iron. In addition, the use of various materials such as plastic, magnesium, and carbon- and glass- reinforced composites may become more widespread in the future to further reduce vehicle weight.

It also is possible to reduce vehicle weight by changing the design of vehicles. An example of this type of change was the movement from body-on-frame cars to unibody construction which reduces weight without requiring higher-cost materials. Designs that provide increased actual or perceived interior volume, while decreasing outside dimensions, also can result in weight reduction. The final method, shifting market demand to smaller vehicles, depends largely on changes to consumer demands.

Even after considering the adoption of weight reduction strategies to date, average vehicle weight in the United States has been increasing at a rate of about 1 percent per year since the early 1980s (Bandivadekar et al., 2008). This is due in large part to the recent increase in SUV sales; however, many individual models have increased in size and weight with each redesign cycle. Adding features for comfort, utility, and safety generally increases the weight of vehicles, so efforts to decrease weight must overcome these upward trends.

Magnitude and Timing of Emission Reductions

The GHG reduction obtained by replacing a conventional gasoline LDV with an advanced gasoline LDV depends upon the fuel economy difference between the conventional and the advanced vehicle, and the miles traveled per year. However, the fuel economy of the baseline vehicle fleet is dynamic, improving over time in response to market forces such as higher fuel prices, as well as to mandates such as the revised CAFE standards. For example, the 2009 AEO projects that in-use vehicle efficiency for LDVs will increase from 21.8 miles per gallon (mpg) in 2010 to 28.2 mpg in 2030.[11] In order to evaluate the benefit of replacing conventional gasoline vehicles with advanced technology packages, comparisons are made relative to the baseline (AEO forecast) future year fleet average fuel economy.

Individual Technology Benefits

While some of the technology options discussed in this section are readily available to the consumer, others are just entering the marketplace, while still others are in an early development phase. In general, multiple options are expected to penetrate the market in varying degrees over time, depending upon regulatory mandates, fuel prices, and consumer preferences. The AEO Reference case includes a highly detailed breakout of 63 technologies, many of which involve efficiency improvements, providing yearly market penetration levels reflecting revised CAFE impacts through 2030.[12] This provides a baseline for which additional improvements can be compared against.

The following analysis provides a brief discussion of some of the more significant efficiency improvement options and their estimated market penetration potential.

[11] As discussed in Appendix A, this forecast accounts for targets for corporate average fuel economy (CAFE) standards established in 2008 under the 2007 Energy Independence and Security Act, but not for revised standards considered in 2009 by the Obama Administration.

[12] See AEO 2009, Supplemental Table 68. Many of these options involve the same technology implemented in varying degrees of intensity—for example, Engine Friction Reduction I-IV.

Aggregate CO_2 reduction potential is then calculated for the entire package of technologies assumed in the AEO Reference case.

Continuous variable valve timing (3-6 percent fuel consumption reduction potential), **variable valve lift** (4–10 percent fuel consumption reduction potential), and **variable displacement** (3–6 percent fuel consumption reduction potential) technologies currently are available. According to AEO estimates, variable valve timing is projected to reach its maximum market penetration of about 70 percent within the next five years. Variable valve lift presents greater cost and integration challenges compared to variable timing, as production tolerances must be closely controlled in order to maintain air/fuel ratio at low valve lift. AEO estimates that variable valve lift will achieve peak penetration of about 40 percent in 2014 and actually decline somewhat thereafter, as it is supplanted by other, mutually exclusive advances. Variable displacement is generally only effective for larger engines over 3.5 liters and it may not ever achieve substantial market penetration.

Variable compression ratio technology is limited by cost/complexity and possible effects on driveability. Additionally, these engines require a significant design change, and also can cause an emissions disbenefit due to increase in crevice volumes preventing complete combustion, and the inability to maintain ideal cylinder head geometry over the entire compression range (Shaik et al., 2007). Variable compression ratio is still in its infancy, and has yet to come to market. In three to five years, this advancement may begin to make headway with a fuel consumption reduction potential of 2–6 percent. However, the AEO Reference case projects only 4 percent market penetration by 2030 (EPA, 2008b; EPA, 2005; NESCCAF, 2004).

With respect to combustion technologies, **GDI** already is available in a few vehicles (Pontiac Solstice GXP, Volkswagen GTI), and is expected to provide fuel consumption reductions between 2 and 3 percent using stoichiometric combustion, and up to 8 percent for lean-burn combustion (EPA, 2008b; NESCCAF, 2004). AEO market penetration estimates for GDI options increase appreciably in about five years, reaching almost 30 percent of the fleet in 2030. **HCCI** is not yet available in the marketplace, but as the technology fully matures it could provide a 4 to 7 percent fuel consumption reduction (NESCCAF, 2004). HCCI is not expected to reach noteworthy volume production for at least 5 to 10 years, (EPA, 2008b) and is not included in the AEO Reference case.

With respect to transmission technologies, **DCT** is just being introduced into the LDV market. DCT could provide fuel consumption reductions between 7 and 13 percent, although the AEO Reference case only assumes 11.5 percent penetration in 2030. **CVT** currently is available in a small fraction of the market, and provides a 4 to 8 percent fuel consumption reduction. AEO projections estimate 20 percent CVT market penetration within five years, and a maximum penetration of 25 percent.

Higher voltage DC systems are still in developmental stages, but they are expected to eventually provide a fuel reduction benefit of 3 to 6 percent (EPA, 2008b). AEO projections estimate approximately 15 percent penetration within five years, and over 40 percent by 2030. Similarly, thermoelectric generators are in the design phase as well. They are expected to eventually provide a fuel consumption reduction of anywhere from

1 to 14 percent (U.S. DOE, 2007), although they are not expected to appear in the market for a number of years, and are not included in the AEO Reference case.

Vehicle technology improvements such as **lower weight, reduced drag**, and **reduced tire friction** are estimated to have the ability to reduce fuel consumption by 6 to 9 percent in the near term, and by a total of 10 to 13 percent in the long term (NRC, 2008). AEO projections estimate close to 100 percent penetration of some form of these technologies by 2030. It is estimated that a **vehicle weight reduction** of 10 percent can result in a 3.3 to 8 percent reduction in fuel consumption for a light-duty vehicle (NHTSA, 2009b; Bandivadekar et al., 2008). The benefit is greatest for the least efficient and heaviest vehicles.

While many of the technologies discussed here are not expected achieve 100 percent market penetration, most are expected to be commercially viable in the near term. A recent study performed for EPA estimated most technology options discussed above will attain technical "production readiness" (if not market penetration), within five years, with HCCI requiring up to 10 years (U.S. EPA, 2008b). Generally speaking, advanced combustion engine design features, along with hybrids, are expected to incrementally gain market penetration without incentive programs or other market interventions.

It also is important to note that the fuel economy benefits of these different measures are not purely additive, and integrated packages of these technologies will produce somewhat lower improvements than the sum of the individual measures.

Combined Per-Vehicle Benefits

Various estimates have been developed regarding the fuel consumption and CO_2 reduction potential of different technology packages. Studies conducted by the National Academy of Sciences and the Northeast States Center for a Clean Air Future estimated CO_2 reduction potentials from 24 to 30 percent for large SUVs, and 17 to 29 percent for midsized cars (U.S. EPA, 2005). A more recent assessment conducted for EPA estimated fuel consumption and CO_2 reduction potentials between 22 and 30 percent for selected packages, depending on vehicle class. These packages also were estimated to have roughly similar performance levels compared with conventional gasoline vehicles (U.S. EPA, 2008b). The AEO Reference case assumes a 22 percent CO_2 reduction potential for passenger cars and a 24 percent reduction for light trucks and SUVs occurring between 2008 and 2030.

For advanced conventional light-duty vehicles, the technology packages found in literature frequently do not contain the same group of technologies. Therefore, a group of improvements for advanced gasoline vehicles was chosen for evaluation. These technologies represent those identified most often in the literature evaluating advanced gasoline LDV systems. In the long term, they represent almost all of the foreseeable improvement in fuel economy available to conventional gasoline engines. In the medium and long term, these technologies include the maximum foreseeable accessory electrification, short of full hybridization.[13] The technologies included in the package analysis for advanced gasoline vehicles are shown in Table 3.2B.

Table 3.2B Advanced Gasoline Vehicle Technologies Packaged for Analysis

	Advanced Design Feature
Near-Term	• GDI • Turbo (cylinder deactivation – trucks) • Cam phasing • Electric power steering • Improved alternator • AMT or CVT • 10% reduction in rolling resistance • 8-10% reduction in aerodynamic drag
Mid-/Long-Term	• All of above plus: • Throttleless – full valve control • 42V Start/Stop • 25% weight reduction from materials

The above combinations of technologies are estimated to provide an 18 to 25 percent reduction in fuel consumption over the AEO Reference case in the near term, and an 8 to 30 percent reduction in the medium to long term, as shown in Table 3.2C (NESCCAF, 2004; Greene et al., 2004; Fulton and Cazzola, 2008; Pischinger et al., 2006). The low end of the fuel consumption reduction range decreases with time, largely as a result of more of these technologies penetrating the baseline fleet, while high-end estimates assume steadier technological advances over this period. These estimates can be compared with those developed by NHTSA in its analysis in support of the establishment of 2011 CAFE standards (NHTSA, 2009b). NHTSA estimated efficiency benefits of 12 to 24 percent for passenger cars and 12 to 21 percent for light trucks from a combination of advanced gasoline vehicle technologies, which overlaps the benefits estimates used in this analysis. The NHTSA findings are discussed in more detail below under “costs.”

[13] HCCI engines are not included here because the literature suggests that, in order to achieve reductions more significant than those given, HCCI combustion may require a different type of fuel than conventional gasoline or diesel.

Table 3.2C Advanced Gasoline Fuel Economy and Consumption Improvement Potential

	Conventional Vehicle MPG (AEO Base)	Scenario MPG		Fuel Consumption Reduction Range	
		Minimum	Maximum	Minimum	Maximum
2010	21.9	26.7	29.3	18%	25%
2030+	28.2	30.8	40.4	8%	30%

Costs

Incremental vehicle and operating costs are obviously important determinants in a vehicle owner's purchasing criteria. Other less tangible factors also are important in the consumer's decision-making process, such as the value associated with demonstrating a commitment to the environment, which make it more difficult to estimate vehicle purchase decisions and perceived payback (Turrentine and Kurani, 2006). Nevertheless, the cost analysis presented below and in other sections only considers directly quantifiable cost factors such as incremental capital and fuel.

Implementation of variable intake and exhaust valve timing, compression ratio, and engine displacement is expected to cost up to $1,500 per vehicle if all technologies are implemented. GDI and HCCI, may have an implementation cost of anywhere from $200 to $600 per vehicle (NESCCAF, 2004). Transmission technologies such as DCT and CVT are expected to add between $140 and $350 to the cost of a new vehicle (U.S. EPA, 2005).

Costs associated with higher voltage DC systems and thermoelectric generations are strongly dependent on the type of implementation. These systems could range in cost from $70-$280 for simple electrification of any or all engine accessories, to over $1,500 for full electrification, including start/stop capability (NESCCAF, 2005; U.S. EPA, 2005). Thermoelectrics are still in the design phase and future cost estimates are not readily available.

The cost of nonpowertrain advancements are likely to be added more gradually to the cost of vehicles over years. The costs of vehicle weight reduction are strongly dependent on the materials and manufacturing methods used. According to literature, HSS and aluminum are the lowest cost weight reduction options, estimated from a slight savings up to $1.76 per pound of weight reduction. Carbon- or glass-reinforced plastics costs vary widely depending on manufacturing methods, and are estimated to be between $1 and $6.2 per pound of reduction (Bandivadekar et al., 2008).

EPA has estimated the incremental vehicle cost associated with adoption technology packages including most of the above options, but excluding the more long-term technologies of HCCI and thermoelectric, at about $1,500 per vehicle. This estimate assumes full economies of scale and therefore does not account for transition costs associated with ramping up production. In addition, EPA used a retail markup factor of

26 percent, which is considered low by industry standards. Therefore this analysis adjusted the EPA estimate to reflect a retail markup factor of 70 percent, which corresponds closely to the 75 percent factor applied by NREL (U.S. EPA, 2005; Markel et al., 2006). The final adjusted incremental vehicle cost is therefore estimated to be $2,000.

Cost estimates of the above technology packages were found in the literature, and the AEO Reference case also provides average LDV costs by year. Incremental technology cost increases for advanced LDVs were taken from the literature, and the net increase above the AEO average vehicle price was subtracted for the near- and medium-term evaluations, providing the incremental cost of the technology packages relative to the AEO base case.[14]

For the advanced conventional gasoline package, vehicles in the near, mid, and long terms offer a net savings over the entire range of costs and benefits. This is due to fuel savings and to the possibility that engine downsizing could reduce estimated vehicle costs (as presented in the literature in some cases). The cost per tonne of CO_2 reduction calculated using the above methodology and assumptions is negative, meaning that there would be a net savings over a vehicle's life, as well as CO_2 reductions. In the near term, however, the cost per tonne range extends into both negative and positive values. The cost-effectiveness values reported in the literature include both negative and positive values as well, from -$175 to +$161 per tonne. (Bandivadekar et al., 2008; Lutsey, 2009; CARB, 2004; Fulton and Cazzola, 2008). In general, the literature cost per tonne values were higher than those calculated in this analysis. Although detailed cost assumptions and calculation methods were not specified in all of the sources reviewed, the higher end cost-effectiveness values were likely based on lower assumed gasoline prices than the current AEO projections. Fuel price assumptions are a driving factor in cost-effectiveness determination, and in turn, dollar per tonne estimates should be considered quite uncertain due to fuel price volatility alone. Nevertheless, there is general agreement that advanced technologies available for conventional gasoline vehicles will be cost-effective options for reducing GHG emissions in the long term.

The emission reduction and cost estimates from NHTSA's final rulemaking for the 2011 CAFE standards are presented in Table 3.2D. The CAFE analysis performed a highly detailed, bottom-up assessment of the costs and benefits associated with a large number of possible technologies that could be applied to the LDV market in the near term. The analysis also evaluated the potential interactions among the different technologies and the development "path" that might be followed, considering the order in which individual technologies might be added to increasingly complex packages (NHTSA, 2009b). These packages do not directly correlate with the gasoline package presented in this report, however, as they included different groupings of technologies. While the NHTSA

[14] Lifetime per vehicle costs and benefits were calculated for advanced LDVs replacing conventional gasoline LDVs for the different time frames. Pre-tax fuel prices obtained from AEO projections were utilized to estimate fuel savings over the life of the advanced vehicle. The specific assumptions regarding mileage accumulation rates, useful life, and assumed discount rate are discussed in Appendix A.

approach was very detailed in how the benefits were combined, a simplified approximation can be made assuming sequential multiplicative application of the estimated benefits for each individual technology. The individual technologies used in the advanced gasoline package for this report are compared with the NHTSA estimates in Table 3.2G. Benefits are combined multiplicatively, while costs are simply additive. The resulting net reductions and costs for the technologies in a representative near term gasoline LDV package are shown, along with the relevant values calculated in the analysis for this report.

Table 3.2D Comparison of Advanced Gasoline Technology Package with Costs and Benefits from 2011 NHTSA CAFE Rulemaking

	Passenger Cars				Light Trucks			
NHTSA CAFE	**Cost per Vehicle ($)**		**percent CO_2 Reduction**		**Cost per Vehicle ($)**		**percent CO_2 Reduction**	
2011 Analysis	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Gasoline direct injection	$293	$558	1.9	2.9	$293	$744	1.9	2.9
Turbo/downsize	$822	$1,223	2.1	5.2	$822	$1,229	2.1	5.2
Cam phasing	$61	$122	2	3	$61	$122	2	3
Electric power steering	$105	$120	1	2	$105	$120	1	2
Alternator	$84	$84	0.2	0.9	$84	$84	0.2	0.9
Dual-clutch transmission	$68	$218	2.7	7.5	-$97	$218	2.7	4.1
Rolling resistance reduction	$6	$9	1	2	$6	$9	1	2
Drag reduction	$60	$116	2	3	$60	$116	2	3
Total[1]	**$ 1,499**	**$ 2,450**	**12.2%**	**23.8%**	**$ 1,334**	**$ 2,642**	**12.2%**	**20.9%**

[1] – Totals are additive for costs and multiplicative for percent reductions.

Analysis for Section 3.2.1 – Average Light-Duty Vehicle

	Low	**High**
Cost	**- $ 60**	**$2,399**
Percent CO_2 Reduction	**18%**	**25%**

It can be seen that the overall range of CO_2 emission reduction for both approaches is relatively consistent. The literature review did find a larger cost range than that found by adding the cost estimates from the CAFE report. While the upper ends of the cost ranges are similar for both approaches, the lower end is significantly different. The primary cause of this difference is that the literature cited in this report found that, in some cases, engine and powertrain downsizing could lead to cost savings that would pay for the addition of the turbocharger and other components, while the findings of the CAFE analysis did not show that to be the case.

Cobenefits

In many cases advanced gasoline LDVs may have lower criteria and toxic emissions than comparable conventional gasoline LDVs, resulting from lower fuel consumption and better engine load management, potentially smaller engines, and other factors. However, variation across the different available models makes it difficult to quantify criteria pollutant reductions for advanced gasoline LDVs as a whole, and engines will generally be designed to meet pollution control standards.

Some of the technologies in question offer cobenefits to vehicle owners/operators. Transmission technologies such as DCT and CVT offer the added advantage of reduced shift time or the elimination of shifting all together. Possible cobenefits of higher voltage DC systems and thermoelectric generation technologies include faster engine warm-up from increased control of the water pump, and increased power output at high RPM from not overpowering vehicle accessories.

Most of the improvements discussed here will not impact vehicle safety, with the possible exception of weight reduction strategies, which may require expenditures for additional safety features.

Feasibility

The level of market penetration attainable by these technologies will depend largely on regulatory drivers such as CAFE and possibly other GHG reduction mandates, as well as fuel prices and consumer preferences. Regulatory and other policy issues regarding LDV fleet efficiency improvements are discussed in Section 3.1, while fuel price impacts are evaluated under cost-effectiveness above. The following discussion focuses on technical barriers, cost, and other constraints associated with advanced technology deployment.

In order to realize the full benefit from GDI technology, the engine can be calibrated to run lean (i.e., with an excess of oxygen in the cylinder). Under such conditions, NO_x formation is increased, which would require an enhanced and more costly form of after-treatment. Costs of GDI technology also prevent widespread implementation in the near term. HCCI technology, meanwhile, is not yet mature enough to operate seamlessly over the wide range of conditions encountered while in use. In addition, the benefits of HCCI cannot be realized with a cold engine, with the associated efficiency improvements limited to hot operating modes.

In addition to cost, a significant barrier to the further market penetration of CVT technology is that its transmission efficiencies are typically lower than conventional automatic or manual transmissions, due to the lower efficiency of the ratio adjustment mechanism. While this inefficiency is offset by the increased engine efficiency, the ultimate balance of these losses and gains will decide the future of CVT technology. The primary barrier to DCT adoption is cost and complexity.

A transition to 42V electrical systems would mark a significant change from the existing 12V standard. Until 42V systems are fully developed, it is possible that a 12V starter motor would still be required for cold temperature starts. Maintaining both voltages during the 12V to 42V transition would increase vehicle weight and cost.

Current thermoelectric generation devices are only 5 to 10 percent efficient and LDVs do not generate enough waste heat to permit eliminating vehicle alternators without further improvements in efficiency. In addition, the usefulness of waste heat capture is likely to be limited in cold weather environments.

A final uncertainty lies in how these technologies are deployed within the vehicle system design. Some of the options can be used to improve vehicle performance or efficiency. As such, manufacturers may elect to employ some of these strategies to provide additional power output rather than improved fuel economy. The ultimate utilization of these options will therefore be influenced by government policy as well as by consumer preferences, which historically lean toward high performance in times of relatively low fuel prices, and fuel economy in the face of higher fuel costs.

Enhanced Diesel Vehicles

Overview

Diesel engines operate more efficiently than gasoline engines for comparable vehicle packages. This higher efficiency is primarily due to the higher compression ratios that compression ignition (i.e., diesel) engines allow. Additionally, diesel engines do not regulate their power output with a throttle, which results in energy loss as air is brought into the engine. Accounting for diesel fuel's higher energy and carbon content per gallon, and its slightly lower energy intensity requirements for refining, a diesel LDV's overall life-cycle GHG emissions are approximately 16 to 21 percent lower than a comparable gasoline LDVs' emissions (EPA, 2005).

Enhanced Diesel Vehicles

Per-Vehicle GHG Reductions: 0-16%

Confidence in Estimates: **Low**

- Highly uncertain market penetration
- Cost-effectiveness will depend on fuel prices and relative efficiency of gasoline versus diesel

Key Cobenefits and Impacts: **Insignificant**

Feasibility: **High**

- Primary barrier is ability to meet emission standards, but current standards can be met at a cost

Key Policy Options:

- Financial and/or regulatory incentives for improved fuel efficiency

While diesel vehicles dominate the medium- and heavy-duty vehicle market, they comprised less than 2 percent of the LDV stock in the United States in 2008, with over

85 percent of these vehicles in the light-truck category.[15] Because of their higher engine weight and power output, they offer the greatest benefit to larger vehicles. Thirteen diesel passenger car and light-truck models currently are offered for sale in the United States (Diesel Technology Forum, 2009), although numerous models are available in Europe and elsewhere around the world. In fact, diesel vehicles represented over 50 percent of new European purchases in 2007 (Dieselnet.com, 2008), as a result of higher gasoline prices, favorable taxation policies, and less stringent NO_x and PM emissions standards. However, late model European diesel vehicles would have to achieve a 45 to 65 percent reduction in NO_x emissions in order to meet current United States Tier 2 emission standards (NHTSA, 2009b).

Accordingly, utilizing diesel engines instead of their gasoline counterparts in the same application should result in reduced fuel consumption and GHG emissions. Unfortunately, current diesel engines produce higher NO_x and PM emissions than do today's advanced gasoline engines, and generally cannot meet the stringent Tier 2 and California LDV emission standards without advanced treatment technologies. While such advanced pollutant control options exist, they are frequently costly and may reduce engine efficiency along with emissions. The analysis in this section assumes that such pollution control technologies advance so that diesel is a widely viable alternative for light-duty vehicles. Some of the emission control technologies have minor impacts on fuel efficiency, but not to the extent that the GHG benefits of diesel are greatly reduced.

Diesel vehicles also can benefit from many of the same technologies described in Section 3.2 to improve the efficiency of gasoline vehicles, particularly weight reduction, aerodynamics, transmissions, and electrical systems.

Magnitude and Timing of GHG Reductions

Benefit per Vehicle

For the near term, the analysis focuses on benefits that are possible with substitution of gasoline vehicles with diesel vehicles using today's technology. In the medium and long term, the analysis assumes substitution with advanced diesel engine and vehicle technologies (including many of those adopted for gasoline vehicles) that represent the most efficient foreseeable options. Table 3.2H lists the technologies included in the analysis of diesel vehicles. Many of the vehicle technologies are described in detail in Section 3.2.1.

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[15] AEO 2009, Supplemental Table 58.

Table 3.2E Advanced Diesel Vehicle Technologies Packaged for Analysis

	Diesel Vehicle Feature
Near-Term	Modern (current-term) diesel combustion with the following: • Improved alternator • AMT or CVT • ~10% reduction in rolling resistance • ~10% reduction in aero drag
Mid-/Long-Term	All of above plus: • Start/stop • 25% weight reduction from materials • Improved combustion

The fuel economy and consumption improvements for the diesel package of technologies relative to the AEO Reference case are presented in Table 3.2I (Fulton and Cazzola, 2008; NHTSA, 2009b). The near-term efficiency estimates are taken from the 2011 CAFE Final Rule, and incorporate a detailed evaluation of the fuel economy penalties associated with various NO_x control strategies and engine sizes.[16] The medium-/long-term high-end estimate is taken from Bandivadekar et al., (2008), based on the relative energy consumption benefit of a 2035 diesel with a 2035 conventional gasoline vehicle.[17] The low end estimate reflects the possibility that advanced gasoline vehicles will effectively "close the gap" with diesel vehicles by adopting numerous efficiency improvements such as turbocharging, as discussed in the previous section (Fulton and Cazzola, 2008).

Table 3.2F Diesel Fuel Economy and Consumption Improvement Potential

	Conventional Vehicle MPGGE[a] (AEO Base)	Scenario MPGGE		Fuel Consumption Reduction Range[b]	
		Minimum	Maximum	Minimum	Maximum
2010	21.8	27.6	31.2	21%	29%
2030+	28.2	28.2	33.2	0%	16%

[a] MPGGE = Miles per gallon gasoline equivalent.

[b] Physical gallon basis.

[16] The range provided in the CAFE Final Rule of 19 to 26 percent is adjusted to reflect the improvement per gasoline gallon equivalent.

[17] Estimates for passenger vehicles and light trucks are weighted to estimate composite fleet benefit.

Cost-Effectiveness

A diesel vehicle that meets current emissions standards will cost more than a comparable gasoline vehicle. While PM and NO_x control technologies add to the cost of their powertrains, diesel engines also have greater material costs because they must be stronger in order to withstand higher combustion and fuel injection pressures. The 2011 CAFE final rule provided a range of incremental diesel vehicle costs for the near term, from $1,567 to $5,617, depending upon engine size and technology package. Cost ranges for near-term diesel vehicles versus current conventional vehicles as found in the literature range from $1,900 to $3,400 (Bandivadekar et al., 2008; Fulton and Cazzola, 2008).

Cobenefits

Current light-duty diesel vehicles are generally comparable in terms of performance compared to conventional gasoline vehicles. In fact, diesels are known for relatively low maintenance costs, as well as their improved towing capacity for larger trucks.

Given the fuel neutral nature of EPA's Tier 2 emission standards, these vehicles must meet the same low NO_x and PM tailpipe standards as gasoline engines. In addition, diesel fuel has negligible evaporative emissions, thereby lowering VOC emissions substantially compared to gasoline. The GREET model estimates life-cycle reductions in criteria pollutant emissions for light-duty diesels relative to gasoline vehicles as shown in Table 3.2M, assuming current emissions control technology. While certain tailpipe emissions such as NO_x and PM would tend to be equal to or higher than those from gasoline vehicles, upstream emission reductions incurred during diesel production result in reductions across all pollutants.

Table 3.2G Pollutant Emissions, Diesel versus Conventional Gasoline Vehicle

Pollutant	Percent Change versus Gasoline
VOC	-62%
CO	-85%
NO_x	-16%
PM_{10}	-22%
$PM_{2.5}$	-17%
SO_x	-30%

Feasibility

One often-cited barrier to widespread acceptance of light-duty diesels in the United States is their reputation as loud, inconvenient to fuel, slow, and malodorous. These attitudes are changing with time, as noise, odor, and performance problems have largely been eliminated, and diesel is now being marketed as an environmentally friendly (in terms of GHG reduction) alternative to conventional vehicles. The increased cost of the diesel engine also is a deterrent, and extended periods like those of late in which diesel fuel is priced higher than gasoline exacerbate cost concerns.

Motorists also have expressed reservations regarding access to diesel fuel. In one survey 46 percent of motorists were concerned about fuel availability, and only 35 percent felt that fuel availability was adequate (Greene et al., 2004). Similar concerns may be held regarding the limited number of diesel makes and models currently offered for sale in the U.S. Nevertheless, diesel fuel currently is offered for sale at over 100,000 locations in the U.S., so concerns about access may be more related to perception than actual availability.[18]

Other barriers to diesel market expansion concern the advanced emissions reduction technologies used to meet current LDV emission standards. In addition to the incremental costs, widespread use of selective catalytic reduction (SCR) after treatment requires the addition of a small on-board reluctant tank, in addition to operator education regarding reductant handling and regular replacement. Tank refilling intervals for LDVs are expected to be about as frequent as oil changes (U.S. DOE, 2009a). Some infrastructure development also will be required for reductant distribution and storage. In addition, in order to meet emissions requirements, vehicles may be designed to be inoperable when the reductant runs out. As such, reliability concerns could limit the acceptance of this technology. There also are concerns over the longevity of new components for SCR as well as exhaust gas recirculation (EGR) coolers and diesel particulate filter (DPF) units.

Increased demand for diesel fuel itself poses its own concerns. There may be a limit to increasing the proportion of diesel versus gasoline that is refined from a fixed amount of crude oil. As that limit is neared, differences in gasoline and diesel fuel prices would be expected to change, limiting the market share increase of diesel fuel (Leister, 2008). In addition, substantial investment may be needed to expand current diesel refining capacity to accommodate production increases.

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[18]NGA, 2008.

Hybrid Electric Vehicles

Overview

Hybrid Electric Vehicles (HEV) combine the internal combustion (IC) engine of a standard vehicle with the motor and battery technology of an electric vehicle. This combination offers reduced fuel consumption and GHG emissions when compared to conventional vehicles, with no appreciable reduction in range or power. The two primary benefits of drivetrain hybridization include recouping energy that would otherwise be wasted during braking, and allowing the engine to spend more of its running time at its most efficient operating point. Various HEV configurations utilize one or both of these efficiency improvement strategies. Essentially all hybrid systems also shut down their IC engines at idle to further save fuel. Light-duty HEVs have significantly better fuel economy than conventional gasoline engines, with passenger cars typically ranging from 30 to 50 mpg, while retaining comparable vehicle range and overall performance.

Hybrid Electric Vehicles

Per Vehicle GHG Reduction: 26-54%

Confidence in Estimates: **Moderate**

- Cost-effectiveness and market penetration will depend on fuel prices

Feasibility: **High**

- Proven, in-use technology

Key Policy Options:

- Financial or regulatory incentives for improved fuel efficiency

Gasoline HEVs have been commercially available in the United States for several years, including the Toyota Prius and the Ford Escape hybrid models. The estimated number of passenger HEVs in the United States in 2008 was 970,000, while HEV light trucks were estimated at 280,000, corresponding to approximately 0.5 percent of the 2008 U.S. LDV fleet.[19] HEV options are expected to be offered for an increasing number of LDV models in the United States over the next few years, including pickups and SUVs, although the benefit of hybridization for heavier trucks with significant towing requirements will likely be less than that of lighter vehicles (Bandivadekar et al., 2008). Certain HEVs currently also are eligible for tax credits of up to $3,000 per vehicle, offered through the end of 2010 by the Internal Revenue Service (IRS, 2009).

All hybrid vehicle designs rely on dedicated batteries as a storage medium for additional power delivery beyond that of the IC engine. Typically, hybrid drivetrain configurations are classified in three types, according to the way that power flows through them: series, parallel, and power-split. A series hybrid uses an IC engine to directly power an electric generator which, in turn, powers one or more electric motors to drive the vehicle. This type of system has the advantage of allowing the engine to run continuously at its most

[19] AEO 2009, Table 58.

efficient operating point, but suffers losses due to inefficiencies in the generator and motor(s). Battery packs are generally larger for series hybrids than other configurations, resulting in relatively higher costs, although they are most effective in slow speed, stop-and-go driving conditions. Accordingly, series configurations are most common in heavy-duty applications (Friedman, 2003).

In a parallel hybrid, power can flow directly to the wheels from the generator, engine, or both as needed. The Honda Civic hybrid utilizes a parallel configuration. This type of design requires the engine to run over a wider and less efficient operating range, but reduces generation losses by having a direct link from engine to the wheels. Parallel hybrid vehicles operate more efficiently at highway speeds than series configurations, although low-speed, urban type operation is not as efficient (Friedman, 2003).

A series/parallel, or "power-split" design attempts to capture the benefits of both of the above systems by allowing the motor and generator both to directly drive the wheels, but decoupling them so the engine can operate more efficiently as in a series hybrid. The Toyota Prius utilizes this type of system. Costs are generally higher for power-split designs compared to parallel configurations due to the larger battery pack and increased complexity of the system (Friedman, 2003). While current hybrid vehicles primarily utilize either parallel or power-split designs, it is likely that the power-split design will become more common over time for conventional HEVs.

Diesel powered HEVs may provide additional fuel economy improvements and GHG emission reductions over and above gasoline HEVs. Diesel engines themselves are inherently more efficient than comparable gasoline engines, as discussed in Section 3.4. In addition, the higher NO_x and PM emission rates associated with the diesel cycle may be controlled more easily in a hybrid configuration, which minimizes transient engine operation (i.e., rapid changes in engine RPM and load) (EPA, 2005). However, at this time, there are no diesel HEV models offered for sale in the United States, although a limited number are available in the European market. Diesel hybrid configurations currently are being demonstrated for the heavy-duty market, as discussed in Section 3.3.2.

The following analysis evaluates the fuel economy benefits of gasoline hybrids, although it should be noted that diesel hybrids may provide about 5 percent additional fuel economy improvement (Bandivadekar et al., 2008).

As discussed in Section 3.3.1, advanced conventional gasoline technology packages are expected to involve electrification of some vehicle components and functions, such as an integrated starter/generator, which allows for turning the engine off at idle, or possibly offering a limited amount of regenerative braking. Such packages are sometimes referred to as "mild" hybrids, as opposed to "full" hybrids which are capable of full electrical operation under certain engine loads and speeds (Friedman, 2003). This section focuses on full hybrid vehicles, and their benefits and costs are assessed relative to comparable fleet average baseline gasoline vehicles for the given time period under evaluation.

Magnitude and Timing of GHG Reductions

Per-Vehicle Benefits

Additional advances are assumed for HEV fuel economy over time, associated with further battery and other technology improvements. The AEO Reference case assumes HEV fuel economy improvement will increase from 31.2 mpg in 2010 to 38.6 in 2030. Independent studies estimate current HEV mpg reductions between 17 and 60 percent, and future year HEV fuel economy levels between 26 and 54 percent in the medium to long term (Jones, 2008; Lutsey, 2008; McKinsey, 2009; Bandivadekar et al., 2008; IPCC, 2007; Fulton and Cazzola, 2008). The percentage reduction ranges were applied to AEO base fuel economy estimates to obtain possible mpg ranges for HEVs. These figures are summarized in Table 3.2N. Although broader in range, the 2010 range is fully inclusive of the CAFE NPRM estimates of 25 to 40 percent for HEVs relative to a 2008 conventional vehicle(NHTSA, 2008b).[20]

Table 3.2H HEV Fuel Economy and Consumption Improvement Potential

	Conventional Vehicle MPG (AEO Base)	Scenario MPG		Fuel Consumption Reduction Range	
		Minimum	Maximum	Minimum	Maximum
2010	21.8	26.2	53.9	17%	60%
2030+	28.2	38.3	60.8	26%	54%

Cost-Effectiveness

Gasoline HEVs currently carry a cost premium over comparable conventional vehicles. Findings from the literature suggest incremental costs between $3,700 and $5,700 in the near term, consistent with the CAFE NPRM estimates across two-mode and power-split HEVs[21] (NHTSA, 2008b). Incremental costs are expected to fall somewhat in the medium to long term to $2,300 and $4,100 per LDV due to further advances in battery technology, and possibly further economies of scale and technological learning (Bandivadekar et al., 2008; Lutsey, 2008; McKinsey, 2009; IPCC, 2007; Fulton and Cazzola, 2008).

This evaluation indicates that HEVs offer the largest potential GHG reductions on a per-vehicle basis short of plug-in HEVs (see Section 3.6), and appear to be generally cost-

[20] Range across two-mode and power-split hybrids.

[21] Comparable diesel HEV premiums are estimated to be somewhat higher in an EPA analysis, between $4,100 and $5,900 in the near term (EPA, 2005).

effective replacements for conventional gasoline LDVs, now and into the future. However, it is instructive to consider the cost-effectiveness of HEVs from the perspective of advanced gasoline vehicle systems, above and beyond those assumed for the AEO Reference case baseline vehicle. For example, one evaluation estimated the incremental cost of full hybrids relative to "maximum ICE improvements" to be 22 percent, but the associated fuel consumption benefit was estimated to be only 5 percent beyond the maximum ICE level (McKinsey, 2009, page 97). As such, additional investments in moving from advanced gasoline vehicles (see Section 3.3) to HEVs will suffer from diminishing returns as the potential for incremental GHG reductions decreases.

Cobenefits

HEVs generally have lower criteria and toxic emissions than comparable conventional gasoline LDVs, resulting from lower fuel consumption and engine-on time, better engine load management, and generally smaller engines, among other factors. HEVs may meet more stringent emission standards than those currently required of conventional LDVs, particularly, California's most stringent Partial Zero Emission Vehicle (PZEV) standard (JDPower, 2009). Variation across the different available models make it difficult to quantify criteria pollutant reductions for HEVs as a whole, however.

HEV brake maintenance costs for HEVs with regenerative braking are expected to be lower than conventional vehicles, about $400 to $500 over the vehicle life (EPA, 2005). The longer range of LDV HEVs results in decreased refueling times. Otherwise, performance characteristics of HEVs are generally similar to that of conventional gasoline vehicles.

Feasibility

HEVs are now penetrating the LDV market, with the number of models increasing each year. Although initial concerns regarding battery life were expressed, current nickel-metal hydride (NiMH) batteries and other hybrid system components are commonly covered by 8-year/100,000 mile warranties, and 90 percent of HEV battery packs are anticipated to survive 14 years (EPA, 2005).

The overriding issue facing HEVs today focuses on their cost, primarily battery costs. The literature on the subject assumes advancements will likely continue to be made in terms of cost, size, weight, charge capacity, and longevity. Current HEVs use NiMH batteries, although research is being performed regarding lithium ion (Li-ion) batteries because of their greater charge density (which can provide greater vehicle range per unit weight), and lower cost potential. Li-ion batteries currently are expected to enter production in some HEVs over the next two years, although they are not yet as stable as current NiMH batteries, with some Li-ion systems involved in recalls in the consumer electronics market. If overcharged or overheated, these batteries have been known to catch fire in the past (Kromer and Heywood, 2007). However, several researchers have concluded that the remaining technical difficulties associated with Li-ion performance are likely to be solved in the near term, clearing the way for wide scale deployment in HEVs, as well as PHEVs and BEVs (Bandivadekar et al., 2008).

Plug-in Hybrid Electric Vehicles

Overview

Plug-in Hybrid Electric Vehicles (PHEV) are a recent development in hybridization for LDVs.[22] PHEVs contain a drivetrain that includes both an electric motor, as well as an internal combustion engine (ICE) or fuel cell.[23] Similar to conventional HEVs, the drivetrain can be arranged in series, parallel, or split series/parallel configurations. In contrast to HEVs, these vehicles also can plug into the local power grid, beginning each trip on battery power. The distance that a PHEV can travel solely on electric power is designated as its all electric range, or AER. A PHEV with an AER of 20 miles is referred to as a PHEV20. AER values found in the literature range from 10 to 60 miles, with 20 to 40 miles being the most common values assumed for commercial adoption of PHEVs.

Plug-in Hybrid Electric Vehicles

Per Vehicle GHG Reductions:

- 46–70% in 2030
- 49–75% in 2050

Confidence in Estimates: **Moderate**

- Range of benefits reflects different all-electric ranges and electricity generation mix

Key Cobenefits and Impacts: **Positive**

- Zero vehicle emissions in all-electric mode

Feasibility: **Moderate/High**

- Battery technology still needs development

Key Policy Options:

- R&D support for battery technology (durability, weight, cost)
- Tax credits for early introduction/adoption
- Public recharging infrastructure and favorable utility rates for nighttime charging

PHEVs can be classified according to the mode in which they operate. A fully charged PHEV can be said to operate in charge-depleting (CD) mode until it reaches a certain level of battery depletion, which is usually between 75–80 percent. After this point, the vehicle switches to a charge-sustaining (CS) mode. In addition, PHEVs can be further classified based on its CD mode, as either range-extended (where the PHEV operates as an electric vehicle up until its CS threshold is reached) or blended (where the vehicle uses its ICE to supplement power demand as needed during CD mode) (Shiau et al., 2009). Blended

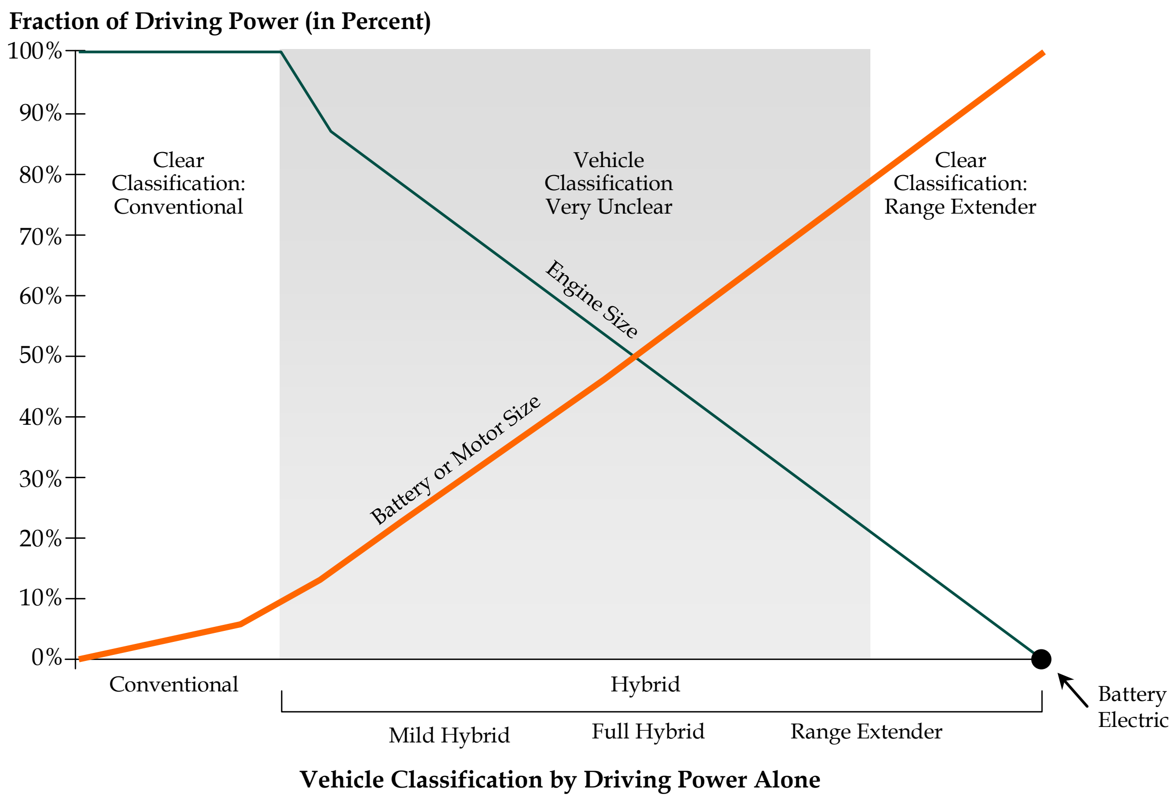
[22] Lighter HDV applications may be good candidates for PHEV systems as well, (EPRI, 2007a) although little research or analysis has been performed for these vehicles. Many heavier HDV applications such as long-haul Class 8b trucks may not lend themselves to PHEV technology as easily, given their power demands and fueling constraints. As such heavy-duty PHEV potential is uncertain and is not considered in this analysis.

[23] Only ICE PHEV systems are considered for this evaluation. Section 3.8 for a detailed discussion of fuel cell technology.

mode operation is similar to that of HEVs, although in this case most vehicle energy requirements are met by the electric battery while the ICE just provides intermittent power boosts for high load events. Blended mode PHEV designs allow smaller, more cost-effective battery designs while providing most of the benefits of range-extended vehicles (Elgowainy et al., 2009).

There is in fact a continuum between conventional LDVs which rely solely on IC engines for power, and fully battery electric vehicles (BEVs – see Section 2.9) which only utilize battery power. Figure 3.3 illustrates how engine and battery size tradeoffs are qualitatively associated with different vehicle categorizations. In the figure PHEVs are classified as "range extenders" which permit a certain amount of all electrical operation. Most of the literature on the topic defines the low end of range extension to be 10 miles for PHEVs, or alternatively, defines a PHEV battery capacity to be five kW or greater.

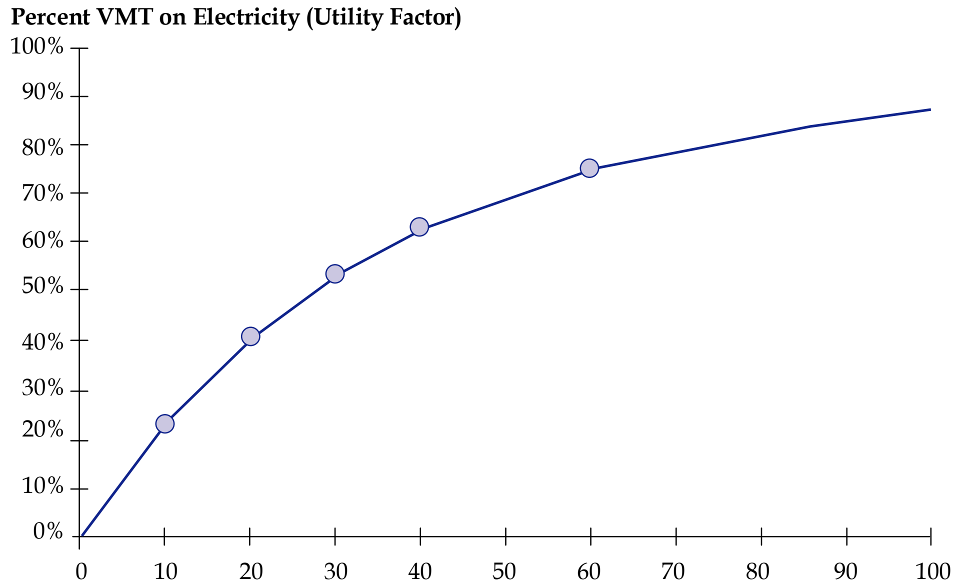
Figure 3.3 Classification of Hybrid Vehicles by Onboard Electrical Power



Source: UCS 2003.

A PHEV's impact on both fuel usage and GHG emissions also depends on the fraction of travel occurring in the CD mode. Those LDVs that travel relatively short distances each day may operate in the CD mode most or all of the time, while LDVs that regularly travel greater distances on a daily basis will operate a good portion of their time in CS mode, thereby diminishing the relative benefits of the PHEV system compared to standard HEVs. Figure 3.4 shows the estimated national average "Utility Factor" for LDVs as a function of AER. As seen in the figure, PHEVs with an AER of 30 miles are estimated to operate in CD mode approximately 50 percent of the time (i.e., gasoline consumption is reduced by 50 percent).[24]

Figure 3.4 Percent of VMT on Electricity versus All-Electric Range (AER)



Source: Elgowainy et al., 2009.

Currently, the PHEV industry is still in its infancy, with fewer than 250 light-duty PHEVs deployed in the United States as of the end of 2008 (U.S. DOE, 2008). Original equipment manufacturer (OEM) PHEVs are not commercially available at this time, but several manufacturers are pursuing their development. Although none of the major manufacturers have committed to make available a mass-market PHEV prior to 2010, several have prototypes in the testing phase, including Toyota, GM, Ford, and Chrysler. Still, it is unlikely that a competitive mass-market vehicle will reach the market sooner than 2015 (Bandivadekar et al., 2008). Nonetheless, PHEV aftermarket kits are available now at a considerable cost for consumers who wish to modify an existing HEV to permit plug-in electrical power.

Magnitude and Timing of GHG Reductions

Per-Vehicle Benefits

Determining the GHG reduction potential of PHEVs is more complex than for most other technology/fuel strategies. Emission reductions vary depending upon AER, assumed

[24]This analysis assumes that PHEVs will only be charged once a day. To the extent that public charging stations and other access points allow for multiple charges per day, the effective utility factor for a given AER could rise significantly.

utility factor, and electricity source, as well as standard considerations such as ICE and electric efficiency. AER values of 10 and 60 were selected for this analysis, to illustrate the full range of possible benefits associated with this technology. Using the utility factor estimates shown in Figure 3.4, PHEV10 vehicles are estimated to operate in CD mode 23 percent of their mileage, and PHEV60 vehicles are estimated to operate in this mode for 75 percent of their mileage.

GHG emissions resulting from charging will vary depending on the mix of electricity sources utilized, which in turn vary by time of day, season, region of the country, and time period of evaluation. While most PHEV analyses assume vehicle charging occurs in the evening or at night, utilizing baseload power, variation in GHG emissions were evaluated for different electricity production scenarios, utilizing estimates from EPRI (2007a). The EPRI study conducted sophisticated modeling of a range of different GHG-intensity mixes as well as PHEV penetration scenarios, estimating the likely emissions associated with PHEV demand at the margin. Most PHEV analyses found in the literature assume system average emissions associated with electricity production. However, the EPRI analysis found that, due to even small incremental changes in dispatch as well as capacity retirements and expansions, the GHG intensity of the marginal electricity used for PHEV charging can vary substantially.

While this analysis does not attempt to replicate the precision of the EPRI study, the range of GHG intensity estimates from EPRI is used to provide a sense of the uncertainty associated with PHEV charging emissions for different time periods:[25]

- Medium-term GHG intensity range – 379-606 g/kWhr; and
- Long-term GHG intensity range – 240-421 g/kWhr.

These GHG intensity ranges for electricity generation must be combined with PHEV battery efficiency values in order to estimate the GHG emissions associated with vehicle charging requirements. Battery efficiency estimates for the CD operation mode as reported in the literature range from 0.19 to 0.43 kWh/mile.[26] These estimates cover a wide range of assumptions regarding vehicle size and driving conditions, but are largely

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[25]The GHG intensity range for the medium term analysis is based on the minimum and maximum g/kWhr values reported for the EPRI analysis across the low/medium/high CO_2-intensity and PHEV dispatch scenarios, for the time period between 2020 and 2030. The GHG intensity range for the long term case reflects the EPRI ranges between 2040 and 2050 (EPRI, personal communication 2009). Note that even under the highest GHG intensity scenario relying on old technology coal generation, PHEVs operating in CD mode still result in lower GHG emissions than corresponding conventional gasoline vehicle operation, on a per mile basis. For example, assuming a very low battery efficiency of 0.4 kWhr/mi (perhaps for a large SUV), and a GHG intensity of 1,041/kWh ("Old Coal" scenario), CD mode operation provides a 12 percent decrease in GHG emissions relative to a current gasoline vehicle. Under these extreme circumstances, however, CD mode operation will not provide benefits relative to an HEV baseline.

[26]EPRI (2007a), Vyas et al. (2007), Samaras (2009), Kammen (2008), Shiau et al (2009). CD values from Elgowainy et al were not considered as these were for blended mode operation.

independent of AER.[27] An average future year efficiency value of 0.255 kWhr/mi is used in this analysis, following EPRI (2007a).

The PHEV efficiency estimate is then combined with assumed CS mode operating efficiencies (assumed to provide a 40 percent fuel consumption improvement relative to base case conventional LDVs in 2030, consistent with future year HEV estimates) in order to estimate fuel savings and emission reductions for all operation modes. The estimates account for the relative miles traveled in CD and CS modes, considering the utility factors associated with PHEV10 and PHEV60 scenarios. The GHG reduction percentages relative to conventional vehicles are based on GREET outputs for CS (HEV) modes, and EPRI estimates for the range of electricity generation intensities (EPRI, 2007a). Table 3.2R summarizes the estimated GHG reductions for PHEV10s and PHEV60s.[28] Results for PHEV40s, which may be considered a "most likely" future technology, would fall in between these ranges.

Table 3.2I Percent GHG Reduction Range by AER and Time Period

Timeframe	CS Mode (HEV-Average)	CD Mode (All AER)		PHEV10 (All Modes)		PHEV60 (All Modes)	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
2030	40%	68%	80%	46%	49%	61%	70%
2050	40%	78%	87%	49%	51%	68%	75%

As seen in Table 3.2P, future year PHEVs offer substantial GHG reduction opportunities beyond conventional vehicles, as well as HEVs. This conclusion is dependent upon a continual decrease in the GHG intensity associated with electricity production over time, as modeled by EPRI (2007a). Under these assumptions, the greater the miles traveled in CD mode, the greater the GHG reduction.

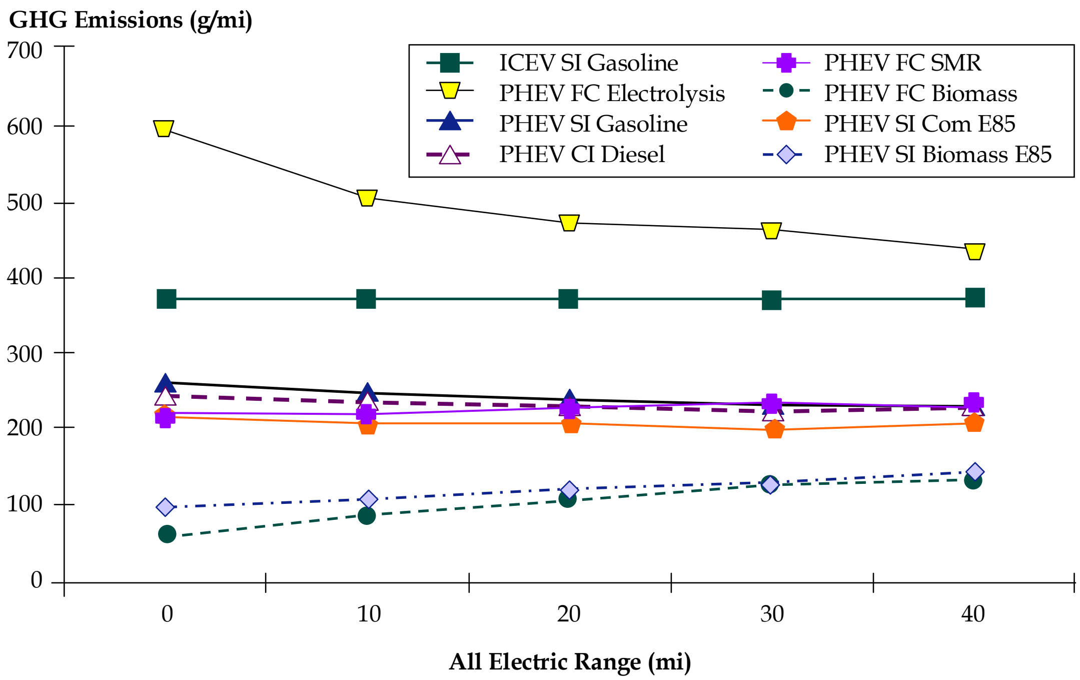
In the absence of substantial improvements in electricity GHG intensity, the potential GHG reductions for PHEVs become more comparable to HEVs. Figure 3.5 demonstrates this general finding for a number of different PHEV fuel scenarios (gasoline, diesel, biomass, fuel cell, etc.) and AERs. As such, under higher GHG intensity conditions,

[27] While the increased battery mass associated with higher AER values tends to decrease vehicle efficiency, this effect is countered by improved electric drive system performance (EPRI, 2007a).

[28] Reductions are relative to a fleet average conventional gasoline vehicle (GREET basis). Note that any advances in HEV efficiency over time are assumed to be approximately equal to corresponding advances in conventional vehicle efficiency over time. Therefore the percentage GHG reduction benefits provided by HEVs compared to conventional vehicles are assumed to be constant across time periods.

extending PHEV range provides little if any GHG reduction benefit beyond that already obtained by the base HEV.[29]

Figure 3.5 GHG Emissions versus AER for Different PHEV Fuel Sources



Source: Elgowainy et al., 2009.

SI = spark ignition; CI = compression ignition; FC = fuel cell; SMR = steam methane reforming.

Cost-Effectiveness

The incremental cost for PHEVs varies substantially depending upon AER, due to increased battery capacity requirements. The vast majority of the incremental vehicle costs associated with PHEVs (above HEVs) result from battery requirements. Current PHEV battery costs are prohibitively high, estimated at about $1,300/kWh,[30] or about $16,000 for a PHEV20 (assuming a 12.7 kWh capacity). However, advances in battery technology as well as cost reductions associated with OEM economies of scale are expected to bring down battery costs substantially. Vyas et al. (2007) estimate costs falling to approximately $500/kWh in the near future, while the DOE has adopted a goal of

[29] The exception is the distributed electrolysis scenario for hydrogen fuel cell vehicles, which results in a net increase in GHG emissions (Section 3.8) because of the grid electricity assumptions for electrolysis. Those scenarios that utilize renewable pathways for liquid fuel or hydrogen production (for example, SI and FC biomass) result in the trend being reversed, as biofuel or biomass-derived hydrogen use generates lower GHG emissions per-mile than grid electricity.

[30] Kammen et al. (2008), page 8, assuming retrofit of a current HEV.

$250/kWh (Vyas et al., 2007). The U.S. Advanced Battery Consortium has adopted a long-term goal of $200/kWh (Samaras, 2009). The $250 and $200 values are adopted in this analysis for medium- and long-term battery costs, respectively.

Table 3.2T presents expected battery energy needs and associated incremental costs for a variety of PHEV AER levels, relative to a conventional gasoline vehicle. While the PHEV10 and 60 entries are intended to bracket the cost analysis, the PHEV40 value may provide a more realistic point of reference for the future PHEV market. Note these estimates assume a $2,100 incremental cost associated with an HEV technology package (for CS mode operation), in addition to the incremental PHEV battery costs.[31]

Table 3.2J Projected Incremental PHEV Costs by AER and Time Period

AER Range (mi)	Battery Energy Requirement (kWh)[a]	Incremental Vehicle Cost (Medium-Term)	Incremental Vehicle Cost (Long-Term)
PHEV10	4	$3,100	$2,900
PHEV40	16	$6,100	$5,300
PHEV60	24	$8,100	$6,900

[a] Average values derived from Kalhammer et al., 2009.

The future year estimates in Table 3.2S for PHEV10 and PHEV60 vehicles are used for estimating PHEV cost-effectiveness below.

The effect of future electricity prices also must be taken into account for the purposes of estimating the cost-effectiveness of PHEVs relative to conventional vehicles and HEVs. National average residential electricity rates are estimated to be 10 cents per kWh (Kammen et al., 2008), although peak rates can be substantially higher.[32] Combined with the future efficiency of CD mode operation (0.26 kWh/mile), such low electricity rates lead to particularly low operation costs, on the order of 2 cents per mile, about one-fifth of conventional gasoline vehicle operating costs. Thus, while PHEVs entail a substantial incremental vehicle cost, fuel cost savings will offset at least some of this increase.

The PHEV cost-effectiveness values found in the literature for the medium term vary over an extremely wide range, from as low as -$149/tonne for a PHEV30 light truck at $5.00 per gallon gasoline (Bandivadekar et al., 2008), to $588/tonne for a PHEV50 with $4.00 per

[31] $2,100 is net of projected HEV battery costs, estimated assuming $600/kWh x 1.5 kWh (Kammen et al., 2008).

[32] Most PHEVs and BEVs are expected to recharge overnight, during off-peak rates. See Section 3.D.9 for a more detailed discussion of battery charging practices, as well as electricity and BEV costs and benefits in general.

gallon gasoline (Samaras et al., 2009). The one long-term estimate found in the literature ranged from $40 to $150/tonne (Fulton and Cazzola, 2008).

The cost-effectiveness ranges in this analysis are roughly consistent with those found in Bandivadekar at $5.00 per gallon for gasoline, although decidedly lower than most other estimates. However, employing current retrofit battery prices of $1,000 per kWh and gasoline prices at $2.00 per gallon pre-tax (values more typical of many of the literature studies), the current estimates become more consistent with the literature, between $62 and $477 per tonne. This illustrates that PHEV cost-effectiveness values are highly dependent on both gasoline prices and battery costs. According to Kammen et al., the adoption of PHEVs in the marketplace will depend primarily upon technological and economic advances in battery technology, because fuel savings cannot compensate for current PHEV capital costs at low gasoline prices. For a PHEV purchase to be economical to the consumer, one of two things must happen: either battery prices must reach levels of approximately $500/kWh, or gas prices in the United States must exceed $5 per gallon for sustained periods.[33] Further, a $250/kWh mass production battery cost will be required for drivers who travel up to 65 mi between charges (Kammen et al., 2008).

There also is a general consensus that today's PHEVs using current grid-average electricity are only marginally more effective at reducing GHGs compared to HEVs, and significant GHG intensity improvements (like those assumed for the medium and long term) will be needed to make these incremental improvements substantial. Therefore, in the near term the primary value of PHEVs relative to conventional vehicles and HEVs arises from the PHEV's potential for reducing gasoline consumption (Kammen et al., 2006). In addition, lower AER PHEVs are generally more cost-effective at this time due to the reduction in battery size, weight, and cost.

Finally, it is instructive to compare the cost-effectiveness of PHEVs directly with HEVs, in order to assess the incremental value of the additional PHEV cost from the perspective of GHG reductions. PHEVs are not cost-effective relative to HEVs given current battery costs. By setting the CS operation mode equal in efficiency to a baseline conventional gasoline vehicle, however, the proportion of PHEV cost-effectiveness benefit in the future due to standard HEV operation can be assessed. Removing the 40 percent benefit assumed for CS mode operation, as well as the $2,100 incremental HEV package cost, the resulting PHEV cost-effectiveness values are actually slightly better than those for HEVs. This finding indicates that, assuming advanced high-efficiency, low-cost batteries, PHEVs will have somewhat improved cost-effectiveness relative to HEVs, and substantially improved estimates relative to conventional vehicles.

[33] PHEV cost-effectiveness is not particularly sensitive to electricity prices; even a 50 percent increase in electricity charges to $0.15 per kWhr increases PHEV60 estimates by only about $20 per tonne.

Cobenefits

Although PHEVs may not offer dramatic benefits with respect to life-cycle GHG emissions relative to HEVs, they do provide an opportunity to significantly lessen the U.S. dependence on petroleum, as well as the potential for reduced air pollution attributed to mobile sources in urban areas (Kammen et al., 2008). Based on the assumed utility factors, we assume a PHEV10 will reduce gasoline consumption by 23 percent, and a PHEV60 by 75 percent for a national average vehicle. The broad penetration of PHEVs into the LDV market offers by far the largest potential for reduced gasoline consumption of any LDV strategy evaluated in this section; only BEVs and fuel cell vehicles (Section 2.8 and 2.9) have the potential for greater reductions in LDV gasoline consumption.

In addition to the substantial fuel savings and associated energy security benefits associated with PHEV use, sizable reductions in other pollutants may be realized. However, PHEVs (and BEVs) present unique air quality considerations due to the split location of emissions between stationary source power plants and mobile on-road vehicles. On-road vehicles are subject to manufacturer emission certification requirements, although actual end-use emissions can vary in both their grams per-mile emission rates, as well as their total mass emissions, depending upon driver behavior, maintenance levels, and total miles traveled. On the other hand, electric power plants are subject to firm emissions caps, enforced by stringent monitoring requirements. In addition, these emission caps are independent of electricity demand, so if demand increases, emission intensity must decrease in order to meet the specified emission limits.[34] The specific caps on NO_x, SO_x, and mercury emissions decrease over time, which will further reduce their associated emission rates per kWh.

Because PHEVs can operate for limited ranges without creating create point-of-use emissions and powerplants are often located in rural areas, their use can reduce air quality problems in densely populated areas. On all-electric mode PHEVs also operate very quietly and can reduce noise pollution. Another possible cobenefit of widespread use of PHEV charging systems would come from the use of smart chargers. These chargers could be remotely signaled to alter charge rates to perform load frequency control for the grid power system. This could result in more efficient grid electric generation if widespread use was achieved.[35] Finally, some of the battery technology advancement

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[34]Reliance on electricity generation for charging PHEVs and BEVs also changes the spatial distribution of emissions, which can in turn have significant (usually favorable) impacts on ozone formation and pollutant deposition patterns. See EPRI (2007b) for a detailed analysis of national air quality impacts, as well as water impacts, associated with different vehicle charging scenarios.

[35]Off-peak charging of large numbers of PHEVs using smart charges that communicate directly with the grid will permit improved voltage and frequency regulation as well as some improved management of "spinning reserves" at the system level. Fine tuning of PHEV charging times and intensities is particularly helpful for the integration of renewable into the power grid, given the variability of wind and solar power inputs (EPRI, 2009).

from PHEV research can facilitate the advancement of HEV and BEV technology as well, and vice versa.

Feasibility

The development of battery technology for use in PHEVs presents a significant challenge, and is generally considered the dominant factor in determining the future penetration of PHEVs into the overall fleet. PHEVs can be manufactured with today's technology, but current performance with respect to energy density, battery lifetime, and cost is not adequate to allow PHEVs to compete effectively with other transportation options at this time (U.S. DOE, 2006a). The development of a charging infrastructure also is a potential barrier.

Battery Technology

The most common type of battery currently used in HEVs are nickel-metal hydride (NiMH), although Lithium-Ion (Li-ion) are expected to gain market share over the long run. The disadvantages of NiMH batteries are that they are heavier and bulkier than Li-ion batteries. Advances in battery science, along with economies of scale, have brought the costs of Li-ion to levels below that of NiMH (in terms of cost per energy storage capacity), and can be expected to enable cost improvements into the future. Nevertheless, it is likely that this type of battery will continue to be expensive for some time.

In addition, Li-ion batteries have had the potential to overheat and cause a pressure buildup in the past, resulting in battery failure and, in some extreme cases, fire. Development of more stable cathode materials and electrolytes is likely to resolve this concern in the future (Bandivadekar et al., 2008). As such, Li-ion batteries have the potential to erode market share and perhaps eventually phase out NiMH batteries in most hybrids in the long run.

When compared to HEVs, PHEVs require a larger battery capacity, which in turn results in higher cost and weight, and reduced vehicle utility or passenger space. PHEV battery packs are projected to contain from 5 to 20 or more kWh of electrical power, and weigh 300 kg or more (Kalhammer et al., 2009).[36]

Another important concern for future PHEV battery development is the need for both deep discharge and daily charging, with both activities having a detrimental effect on battery life. While existing HEV batteries typically discharge only about 5 percent before recharging, future PHEV needs will include daily deep discharges of up to 90 percent as well as the frequent shallow charge/discharge cycles of a standard HEV. While battery life for recent technology Li-ion batteries was not acceptable for market use, recent advances may permit these batteries to last 10 to 15 years, given adequate temperature control and State of charge management (Kalhammer et al., 2009).

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[36] Assuming 70 Wh/kg and 20 kWh capacity.

PHEV Charging and Electrical Generation

Most PHEVs will not require changes to residential electrical systems, with PHEVs expected to have both 120-volt and 240-volt AC charging capabilities. It is expected that suburban vehicle owners, who have garages available for charging PHEVs in their homes, will be more likely to adopt this technology than urban owners, who may not have overnight plug access available. For those operators without access to an outlet for overnight charging, the typical total cost for installation of a 120V AC, single phase, 20A circuit for residential vehicle charging is estimated between $500 and $1,000, while the cost for installing a 240V AC, single phase, 40A circuit are substantially higher (Samaras, 2009). Outlet installation can also be cumbersome due to permitting and inspection requirements.

The time necessary to recharge a PHEV20 from 20 percent to a full 100 percent charge utilizing a standard 120-volt outlet ranges from 4 to 8 hours for battery pack sizes ranging from 5.1 to 9.3 kWh, although the time to charge to approximately 80 percent of capacity can be substantially shorter (Hadley and Tsvetkova, 2008).[37] PHEVs with particularly large battery capacities (e.g., SUVs and large trucks and/or vehicles with higher AERs) may require charging through 240-volt outlets, which allow for faster charging, in order to obtain acceptable charge times (Elgowainy et al., 2009). There are designs for fast chargers available, but battery life is negatively impacted by increased charge rates. In addition, battery life also is generally determined by the total number of charge cycles. Charging twice per day is more likely to necessitate the replacement of the battery near the middle of the vehicle's life, at significant cost (Kromer and Heywood, 2007).

While the power source for charging PHEVs at most residences is readily available, there is a need to develop some level of publicly accessible charging infrastructure to allow PHEVs to be charged away from users' homes. Public access recharging could substantially extend a PHEV's effective AER, depending upon trip lengths and available charge time (although the impact of multiple daily charge cycles would need to be clearly demonstrated with respect to battery durability and life-cycle costs). While residential infrastructure installation for PHEVs is fairly straightforward, public access charging facilities are necessarily more expensive. The estimated cost for a 10-space commercial recharging facility would be approximately $18,500 (U.S. DOE, 2008). This cost includes labor, material, signage, and permits. Some utilities such as Southern California Edison are currently preparing public access charging plans.

While PHEVs will increase total electrical power demand they may not require increases in generation capacity, at least in the near term, since PHEVs will most commonly be charged during off-peak hours and total vehicle numbers will likely be small (EPRI,

[37] Near-term battery technologies may require additional time for cooling after use before recharge commences (EPRI, 2007a).

2007a).[38] As noted above, very substantial PHEV penetration levels could be accommodated without significantly expanding electric capacity. In the long term, however, substantial penetration of PHEVs into the LDV fleet could impact both base load and peak-period electric generation requirements, which without market intervention could be partially met by coal fired units, minimizing some of the GHG reduction potential of PHEVs. In this case both "smart metering" and charge control will likely be required at the utility level to encourage off-peak charging by consumers in order for overall system efficiency to be maximized, at least during periods of peak demand (U.S. DOE, 2006a). Reliance on such controls and utility incentives for off-peak charging will help minimize the need for new capacity deployment in the long term.

[38] Although unlikely, if multiple PHEVs simultaneously utilized high-voltage fast charging were serviced by the same transformer (typically serving about five customers), then transformer life could be shortened significantly (e.g., by a factor of 10 or more). Reliance on smart-charging strategies will minimize such risk in the future, even at high PHEV market penetration levels (EPRI, 2009).

3.3 On-Road Heavy-Duty Vehicles: Trucks

Heavy-Duty Trucks

Per Vehicle GHG Reduction:

- Retrofit to use low resistance rolling tires, planar boat tails, front fiarings, trailer side skirts, and aluminum wheels: 10 to 15%

Confidence in Estimates: **High**

- Many technologies proven

Key Cobenefits and Impacts: **Positive**

- NO_x and PM reductions anticipated from reduced fuel consumption and engine loads

Feasibility: **Moderate**

- Operational and maintenance issues may limit potential for some technologies

Key Policy Options:

- Financial incentives for purchase of retrofits
- Financial or regulatory incentives for improved fuel efficiency
- Incentives for trailer owners
- Requirements for proven technologies
- Demonstration programs/partnerships

Heavy-duty vehicles (HDV)[39] cover a wide range of sizes and applications, ranging from Class 3 small trucks and panel vans used primarily for urban deliveries and light commercial hauling, to Class 8 tractor-trailer rigs up to 80,000 lbs used for commercial freight transport. Other HDV categories include delivery trucks, transit and school buses, and a variety of vocational applications such as refuse haulers and utility vehicles. Unlike LDVs, HDVs currently are not subject to fuel efficiency standards, although standards development currently is underway as mandated by EISA.

According to EIA estimates, 9.5 million HDVs traveled 231 billion miles in 2008, or about 10 percent of all miles traveled on–road.[40] In this same year HDVs consumed the equivalent of 2.4 million barrels of oil per day, about 21 percent of petroleum utilized for on-road transportation.[41] During the period from 1996 through 2006, HDV registrations have increased by an annual average of 2.3 percent, miles traveled by 2.0 percent, and fuel consumption by 2.6 percent (ORNL, 2008, Tables 5-1 and 5-2). On a Btu basis, the vast majority of HDV fuel consumption is attributable to diesel (95 percent), with gasoline contributing less than 5 percent.[42] Accordingly, the following analysis focuses exclusively on diesel powered HDVs.

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[39] Trucks greater than 10,000 lbs. and less than 26,000 lbs. in gross vehicle weight are often referred to as medium-duty vehicles. For convenience, this analysis refers to both medium and heavy-duty vehicles as HDVs.

[40] AEO 2009, Supplemental Table 67.

[41] AEO 2009, Table 7.

[42] AEO 2009, Supplemental Table 67. The implementation of new heavy-duty diesel emission standards in 2007 and 2010 is increasing new truck costs by many thousands of dollars. As such, some increase in gasoline engine use can be expected in the medium-duty vehicle market. However, given the diesel engine's inherent advantages in durability and maintenance, a

(Footnote continued on next page...)

HDV operators are subject to different economic influences and constraints than LDV owners. Profitability margins within the trucking industry are low and operating costs due to fuel are relatively high (about 33 percent of costs per mile in 2006) (21st Century Truck Partnership, 2009). Accordingly, market forces will encourage some development and adoption of fuel efficiency improvements for U.S. trucks. In addition, voluntary initiatives such as EPA's SmartWay Transport Partnership have helped promote the adoption of energy efficiency improvements among many of the largest freight carriers in the United States. Adoption of SmartWay certified vehicles and trailers is estimated to result in a 10 to 20 percent reduction in fuel use per truck compared to conventional truck/trailer combinations (U.S. EPA, 2007b). In spite of these factors, HDVs have only witnessed modest gains in fuel efficiency over the past several decades, improving by about 0.5 percent per year for single unit (straight) trucks, and 0.2 percent per year for the larger combination (tractor/trailer) trucks between 1970 and 2006 (ORNL, 2008, Tables 5.1 and 5.2). As such, substantial opportunities for further efficiency improvements remain.

Energy consumption and therefore fuel use by HDVs varies substantially depending on vehicle size and weight. As a general rule Class 8 tractor-trailer rigs tend to travel more miles per year (about 46,000 on average) and have lower fuel efficiency (about 5.7 mpg) than lighter vehicles. For comparison, HDVs less than 26,000 pounds gross vehicle weight average about 13,000 miles per year with a fuel efficiency average of 8.0 mpg. This disparity leads to a disproportionate impact for Class 8 trucks, which comprise about 41 percent of HDV registrations but are responsible for about 78 percent of total HDV fuel consumption (ORNL, 2008, Table 5-4). As such, identifying opportunities for reduced fuel consumption among Class 8 HDVs is a primary focus of this section.

Unlike LDVs, the most appropriate way to measure the efficiency of HDVs is usually in terms of fuel use per unit of work performed (e.g. ton-miles hauled or horsepower-hours per gallon). Although a simple miles per gallon metric is utilized here for consistency with other sections, it provides a somewhat crude and imprecise measure of efficiency for these sources.

A vehicle's operation-cycle (e.g., frequency of starts and stops, acceleration requirements, average speed, percent of time at idle) also has a direct impact on fuel consumption and GHG emissions. The frequent acceleration and braking events commonly encountered in urban operations result in very poor fuel efficiency. For example, full-sized transit buses operating under central business district conditions average only 3.2 mpg (21st Century Truck Partnership, 2009). Operation at very high speeds and extended idle time also decrease fuel efficiency for freight trucks.

Energy audits for two key HDV categories—a Class 8 truck and a typical medium-duty truck—are presented in Figures 3.6 and 3.7. These figures help identify the primary energy requirements for conventional diesel HDV operation as well as opportunities for reducing fuel consumption. The target energy consumption levels represent the goals for the 21st Century Truck Partnership, a partnership between the Federal government and

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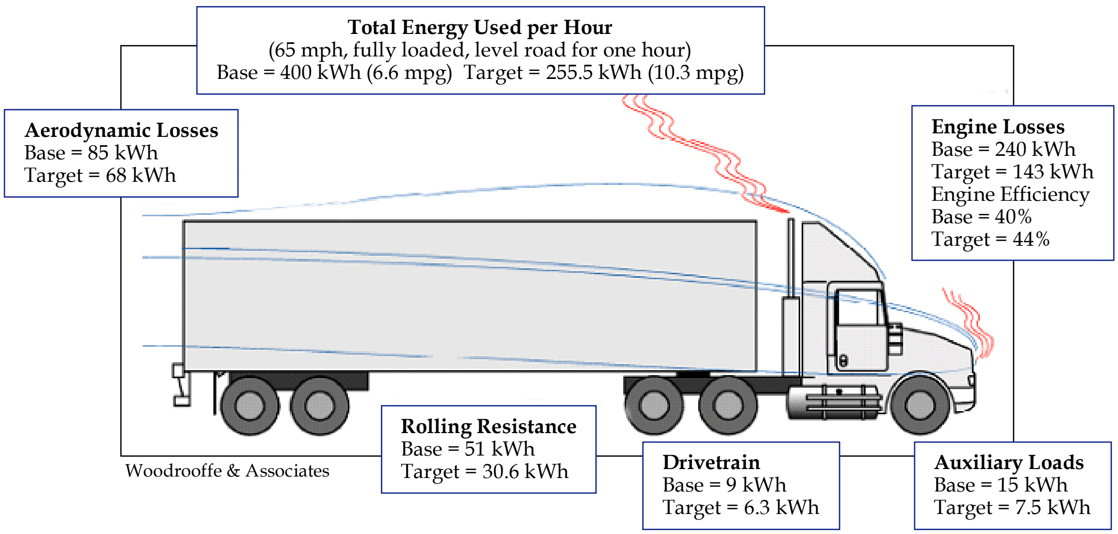
dramatic shift to gasoline engines is not anticipated for the medium duty vehicle market (Reinhart, 2009).

the U.S. trucking industry intended to promote research and development for efficiency and other improvements. The specific performance targets were established considering emerging technologies not yet widely adopted in the fleet, and represent "long-term stretch goals for which technology breakthroughs will be required" (21st Century Truck Partnership, 2009). As indicated in the figures, engine losses are substantial for all diesel engines, with roughly 60 percent of fuel energy being converted to waste heat rather than usable work.[43]

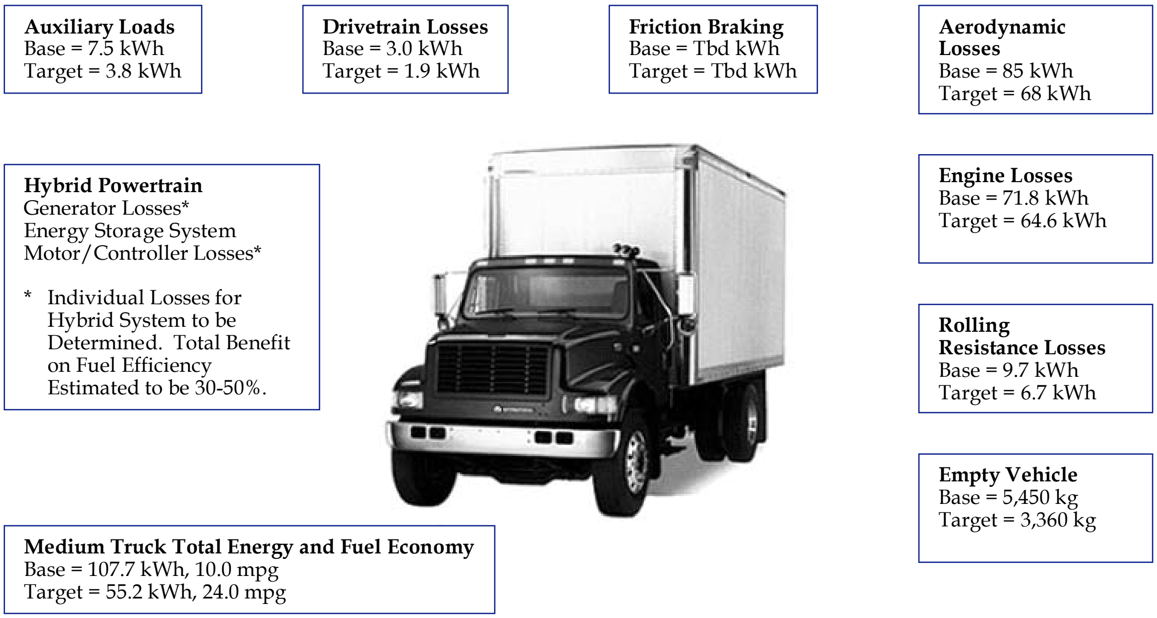
Figure 3.6 Class 8 Truck Energy Audit



Source: 21st Century Truck Partnership.

[43]Due to the fundamental limits of physics, no engine can operate at a thermal efficiency of 100 percent. The most efficient stationary diesel engines operate at approximately 50 percent efficiency, which can be considered a practical limit for the diesel combustion cycle. However, a modern diesel engine is significantly more efficient than a corresponding gasoline engine which operates at approximately 25 percent efficiency (reference).

Figure 3.7 Class 6 Truck Energy Audit



Source: 21st Century Truck Partnership.

Other energy use requirements depend upon vehicle weight and operation cycle. About one third of the energy requirements for operating fully loaded Class 8 trucks at highway speed come from aerodynamic drag and tire rolling resistance. In contrast, transit buses operating at slower urban speeds encounter negligible aerodynamic drag (less than 1 percent) and rolling resistance levels only about half that of the Class 8 truck example (about 5 percent). On the other hand, transit buses incur substantial losses for auxiliary loads (e.g., for HVAC and lighting, at about 25 percent) and to a lesser extent, braking (about 6 percent). Non-engine losses are more evenly distributed for the Class 6 delivery truck example, with aerodynamic drag, rolling resistance, and auxiliary loads all contributing nontrivial energy requirements (over 5 percent each).

Different GHG reduction strategies are appropriate for addressing the different types of energy loss. Technologies currently being explored for the HDV market fall into five categories: engine power systems and transmissions, drag reduction (including aerodynamic and rolling resistance), weight reduction, accessory and "hotel" loads, and idle reduction. (Idle reduction strategies are considered a system efficiency improvement and are discussed in Chapter 6.) In addition, technologies from one category can have synergistic effects (both positive and negative) when employed together, and possible interactions are discussed as appropriate.

Due in part to their relatively high unit costs, some of the GHG reduction strategies under consideration for HDVs such as hybridization are only available through new vehicle manufacture and purchase, although certain aerodynamic improvements, low-rolling resistance tires, and auxiliary power strategies are possible through retrofit. However, HDVs have a slower turnover time compared to LDVs, with a typical HDV lifetime of close to 30 years (ORNL, 2008, Table 3.12). Therefore substantial penetration of new OEM technologies can take several years after commercialization.

On the other hand, OEM strategies should have a disproportionately large impact on fuel consumption since older vehicles travel significantly less on average than new vehicles. A 10-year-old truck travels only about 40 percent of the distance annually of a new truck, and a 20-year-old truck less than 20 percent.[44] The effectiveness of different efficiency strategies also will vary with vehicle age due to the fact that vehicles may change operators and duty-cycles after a number of years. For example, Class 8 trucks commonly spend the first four to six years of their life in long-haul service, which entails higher speed operation (and greater mileage accumulation) than other service types (Lutsey, 2008). After this time, these trucks are often moved into lower mileage, urban/short-haul applications. These different service types and operation modes obtain substantially different benefits from different efficiency technologies. For example, aerodynamic and rolling resistance strategies obtain their maximum benefit at highway speeds, while hybrid technologies are best suited for lower speed urban drive cycles.

In addition to advancements related to vehicle efficiency, diesel HDVs are in the process of adopting control technologies in order to meet increasingly stringent NO_x and PM emission standards. The latest EPA heavy diesel standards require 90 percent reductions in PM in 2007 and 90 percent NO_x reductions by 2010 relative to prior emission standards (U.S. EPA, 2006). The technologies used to meet these standards, such as particulate filters and NO_x absorbers, have their own energy requirements, and add weight to the vehicles. As such, these technologies may reduce fuel efficiency in some cases by about one percent for particulate filters, and roughly five percent for NO_x control using exhaust gas recirculation, and other recent strategies (U.S. DOE, 2009b; Greszler, 2008). Newer emission control technologies may increase fuel efficiency to the extent that they allow the diesel engine to operate more efficiently.

The following sections discuss resistance reduction strategies, weight reduction, engine improvements (including hybrid power systems), and strategies to reduce vehicle accessory loads. (Alternative fuel and fuel cell strategies are discussed in tandem with their associated fuel type in Section 2.0.) The baseline emission estimates used below are based on the AEO Reference case for 2030, which estimates fleet average fuel efficiency on an annual basis. Annual incremental emission reductions and total costs for each technology option are based on a variety of projections found in the literature. The cost-effectiveness of packages of multiple technology strategies (e.g., hybrid electric vehicles with advanced aerodynamics) are discussed separately at the end of the HDV section.

[44] Based on mileage accumulation data from EPA's MOBILE6 emission factor model.

Resistance and Weight Reduction Strategies

Overview

The total drag on a moving tractor-trailer is the sum of the air resistance acting on it and the mechanical friction in the wheel bearings and tires. Technologies that aim to reduce drag will make the tractor-trailer more efficient either aerodynamically or mechanically. Drag reduction measures are of particular interest with respect to GHG reductions, as many of these options can be introduced to the fleet relatively quickly through retrofit, as opposed to most other vehicle and powertrain options, which must be implemented through redesign of new vehicles.

Aerodynamic drag is particularly sensitive to vehicle speed, with power requirements increasing with the square of velocity. Rolling resistance also increases directly with speed and mass (Vyas et al., 2002). Aerodynamic improvements will have the greatest impact for those vehicles traveling at highway speeds (60+ mph). When heavy-duty trucks are traveling at these speeds, approximately 65 percent of the engine power produced is used to overcome aerodynamic drag (Vissier, 2005). In addition, about 70 percent of fuel use by Class 8 HDVs is estimated to occur on trips greater than 100 miles, which occur primarily at highway speeds. By contrast, the majority of fuel use for smaller delivery trucks (as well as vocational trucks and transit buses) is attributable to trips of less than 100 miles, typically occurring at lower urban speeds (21st Century Truck Partnership, 2009). Accordingly, aerodynamic improvement options are evaluated here only for Class 8 freight trucks, although some benefits also are possible for smaller, urban-based trucks as well.

The aerodynamic drag of tractor-trailer rigs has dropped significantly since the 1980s, improving fuel efficiency by about 15 percent per truck (Schubert and Kromer, 2008). Some of the currently available truck/tractor drag reduction options include a **cab top deflector**, **sloping hood**, and **cab side flares**, as shown in Figure 3.8. These design concepts already are widely implemented for line-haul trucks. In fact, implementation on Class 7 and 8 cabs and hoods already have achieved a high level of market penetration (about 70 percent by 2006).[45] However, there is potential to further increase the aerodynamic efficiency of current Class 8 HDVs by making additional changes to the shape of these vehicles, from the front bumper of the truck to the back of the trailer.

[45] At 70 percent market share, according to AEO 2009 – Table aeo2009.d120908a.

Figure 3.8 Aerodynamic versus "Classic" Cab Profile

Aerodynamic styled truck with low profile front, aerodynamic bumper, full-height roof fairing, hidden exhaust stacks, and fuel tank side fairings.

Typical classic styled truck with long nose, flat bumper, low-roof, and exposed air cleaners, exhaust stacks, and fuel tanks.

Source: Schubert and Kromer, 2008.

Aerodynamic drag reduction options such as **closing or covering the gap between the tractor and trailer**, a lower **front bumper air dam**, **underside air baffles**, and **wheel well covers** are available as retrofit technologies and have not yet achieved significant market penetration (projected at 1 percent in 2009).[46] These options take the airflow smoothing concept further by attempting to reduce turbulence under the truck, at the uneven surfaces near the wheels, and in the gap between the truck and trailer.

Side mirrors are another source of turbulence and drag and can be modified as well. **Electronic vision systems** offer a more advanced alternative, replacing large protruding side mirrors with small cameras that can be integrated into the shape of the cab in order to minimize further air resistance. These systems are not commercially available at this time, although penetration is possible in the near term if safety regulations were modified to allow downsizing or replacement of mirrors (Lovins et al., 2005).

There also is potential for airflow improvements from changes to **trailer geometry** as well. Employing curvature to the leading and trailing edges of trailers can reduce turbulence and drag. These measures are just beginning to penetrate the fleet, estimated at 2 percent in 2008.[47]

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[46] AEO 2009 – Table aeo2009.d120908a.

[47] AEO 2009 – Table aeo2009.d120908a.

The **cross-flow vortex trap device** (CVTD) is a series of vertical surfaces extending forward from the trailer in the gap area, designed to trap vortices that form in the airflow from one side of the gap to the other. CVTD technology is mutually exclusive with the gap covers mentioned above. There also are many concepts that attempt to reduce the drag caused by the flow separation and turbulence at the rear of the trailer. Passive designs include the **vortex strake device** (VSD), **undercarriage flow device** (UFD), and **planar boat tail plates**. **Pneumatic flow control systems** operate similarly to the VSD, except that they use air forced from near the edges of the trailer instead of raised strakes. This air flow can be generated by a diesel-powered compressor installed in the trailer similar to current refrigeration units, bleeding pressurized air from the truck's forced induction system, or a chain drive to the trailer's wheels. These systems may be optimized to react dynamically for the purposes of enhancing braking or stability by varying the aerodynamic forces on the trailer. Additional blowing can be implemented to provide lift at the trailer, thereby reducing rolling resistance (Vyas et al., 2002). Pneumatic flow control systems have been demonstrated in pilot testing, but are not anticipated to penetrate the market commercially for the next few years (U.S. DOE, 2009b).

Additional possibilities for GHG reduction can result from changes to tires and their interaction with the road surface. **Auto tire inflation systems** help minimize energy losses to due to the increased rolling resistance of underinflated tires by continually monitoring and adjusting the air pressure in each tire using onboard compressed air. These devices have the benefit of increasing tire life as well as decreasing truck turnaround and maintenance time, since tires do not need to be checked by hand. In addition, such systems reduce the chances of a blowout. These systems should be retrofitable on most or all trucks, and are now commercially available although current market penetration is assumed to be minimal (U.S. EPA, 2004a).

Low-rolling resistance tires exhibit reduced drag due to the use of new construction materials such as silica and synthetic elastomers (Frey and Kuo, 2007). This type of tire can be retrofitted on most existing trucks and trailers, and have achieved approximately 4 percent market penetration as of 2008.[48] As an alternative for new Class 8 trucks, **single-wide-based tires** can be used to replace wheel and tire pairs on each axle on trucks and trailers. This type of wheel and tire offers reduced weight, rolling resistance and aerodynamic drag over the dual wheel and tire combinations used today. This technology matches well with auto tire inflation systems due to the increased need to monitor tire pressure to reduce the chance of a blowout. Single wides also provide weight reduction benefits, reducing vehicle weight between 800 and 1,000 lbs, which in turn reduces fuel consumption (U.S. EPA, 2004b).[49] Single-wide tires currently are commercially available.

Weight reduction strategies also offer promise for reducing fuel consumption. Recent tests estimate a potential fuel consumption improvement of approximately 0.6 percent per

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[48] AEO 2009 – Table aeo2009.d120908a.

[49] Weight reduction may permit additional freight to be hauled on a given truck. In this case fuel reduction benefits can be measured on a gallon per payload ton-mile rather than a mpg basis.

1,000 pounds of weight reduction for fully loaded combination trucks on a highway drive cycle (NESCCAF/ICCT, 2009). Both mechanical drag on the truck and the energy required to accelerate it to highway speeds are dependent on weight. In some cases, total vehicle weight is the limiting factor as to how much cargo a truck can carry, so a reduction in the weight of the truck itself would allow more cargo to be carried in each trip. Increased cargo capacity can thereby reduce the number of total trips required to move a given amount of freight, with an associated reduction in fuel consumption per ton-mile hauled. In this instance the fuel consumption improvement increases to 2.2 percent per 1,000 pounds of weight reduction, on a ton-mile per gallon basis (NESCCAF/ICCT, 2009).

Weight reduction can be accomplished by substituting conventional materials with lighter ones. The primary candidate for material replacement is steel. **Aluminum, plastics, composites**, or **high-strength steel alloys** can be used in place of steel in both the truck and trailer to achieve weight reduction. Replacing steel wheels and axle hubs with aluminum can reduce truck weight by over 500 pounds (U.S. EPA, 2004c), while steel-shell brake drums can reduce weight by an additional 100 pounds. Moreover, redesigned sleeper cabs can reduce weight by several hundred pounds. Trailers can be designed to reduce weight not only in the wheels, brakes, and axles, but in the container structure as well. Aluminum roof posts, side, posts, and floor joists could save about 1,000 pounds overall to the weight of a trailer. Aluminum construction offers relatively near-term benefits because the technology currently is available. It is estimated that aluminum substitution could remove about 3,000 pounds from a heavy-duty truck in the short term (U.S. EPA, 2004c). In the long term, use of composite materials has the potential to increase benefits to a 9,000-pound reduction as research progresses and these materials become available at a lower cost (Vyas et al., 2002). Trailers used in trailer on flat car (TOFC) service (i.e., carried on rail cars) and containers on truck chassis have additional strength requirements that limit weight reduction strategies

Magnitude and Timing of GHG Reductions

Individual Technology Benefits

Aerodynamic and rolling resistance improvements are considered in isolation as well as in combination packages, with individual measures summarized below. Benefits are considered for Class 8 (predominantly long-haul) trucks. Aerodynamic options are listed below that are most often considered for adoption in the literature in the near to medium term.[50]

- **Basic Cab Improvements –** Cab top deflector, sloping hood, cab side flares. These options are common on new truck models and already have obtained substantial market penetration. Additional application is possible through retrofit of older units. Per unit miles per gallon improvements range from 1.0 to 2.0 percent (TIAX, 2008).

[50]Certain devices such as VSDs may offer additional benefits, but may provide diminishing returns if implemented with other strategies.

- **Enhanced Cab Improvements –** Gap reduction between tractor and trailer, improved bumper, underside air baffles, fuel tank fairings, and wheel well covers. These technologies currently are available for retrofit. Per unit mpg improvements are estimated at approximately 2.4 percent (Vyas et al., 2002).

- **Basic Trailer Improvements –** Rounding of front and back edge curvatures. These options currently are available for purchase with new trailers, with a per unit mpg improvement estimated at about 1.3 percent (Vyas et al., 2002).

- **Additional Trailer Improvements –** Front fairings and side skirts may be retrofitted onto existing van trailers, and currently are available. Per unit mpg benefits are estimated between 1.0 and 2.0 percent for front fairings, and between 4.2 and 7.8 percent for side skirts (CARB, 2008a).

- **Planar Boattail Plates –** Devices to reduce aft-end trailer drag, currently under development and demonstration. Potentially available for retrofit, but most suitable to conventional van trailers due to configuration constraints. Per unit mpg improvements are estimated between 2.8 and 4.0 percent (TIAX, 2008; Frey and Kuo, 2007).

- **Vehicle Load Profile Improvements –** This option involves covering flatbed freight with tarpaulins and keeping load profiles low in order to smooth airflow. Improvements can be made immediately at very low costs, resulting in per unit mpg improvements of about 2.5 percent (Frey and Kuo, 2007). This strategy is limited by the relatively small fraction of fleet using flatbeds. In addition, implementation of this strategy relies upon the cooperation of the vehicle operator, who may have no incentive to expend the required time and effort.

Technologies that reduce energy consumed to overcome rolling resistance generally offer smaller improvements compared to aerodynamic technologies. Low-rolling resistance tires can result in between 2.7 and 4.8 percent reduction in mpg for each truck (Vyas et al., 2002; Frey and Kuo, 2007). Single wide tires are estimated to provide a full 6 percent fuel consumption improvement, with an additional 4.0 percent estimated with future technology improvements (NESCCAF/ICCT, 2009).

For weight reduction strategies, EPA estimates that a 3,000-pound reduction in truck weight increases its fuel efficiency by 1.8 percent (U.S. EPA, 2004c). This estimate is consistent with the 0.6 percent improvement per thousand pounds of weight reduction noted above (NESCCAF/ICCT, 2009). It is estimated that pursuing weight reduction for heavy-duty trucks could improve mpg between 5 and 10 percent (Vyas et al., 2002). A related strategy involves replacing conventional wheels with aluminum wheels, estimated to improve fuel efficiency by 2.0 percent as a result of the associated weight reduction (TIAX, 2008). Reduction strategies will reduce both mechanical friction and the energy required to accelerate the truck from a stop. In fact, weight reduction strategies should be even more effective for urban operations due to the increased number of starts and stops, relative to highway driving. As such, weight reduction can reduce GHG emissions from all trucks in the fleet, from short-distance delivery trucks to long-haul trucks that travel primarily over the highway.

Combined Per-vehicle Benefits

Estimates have been developed for the per vehicle fuel consumption and GHG reduction potential from broad adoption of several of the above technologies on a Class 8 truck, ranging from 12 to 20 percent (Muster, 2000; 21st Century Truck Program, 2009; Frey and Kuo, 2007; Vyas et al., 2002; Lovins et al., 2005).[51] Certain aerodynamic and resistance reduction strategies are available for retrofit under a near-term scenario, similar to the options considered by California CARB for its recent HDV rulemaking (CARB, 2008a). These strategies may be implemented relatively quickly, since they do not rely on OEM implementation and fleet turnover in order to obtain significant market penetration. The package of strategies considered for the near-term benefit evaluation is described below in Table 3.3A. Additional aerodynamic and resistance reduction strategies are considered in tandem with powertrain measures for the medium to long term in the following section.

Table 3.3A Aerodynamic and Resistance Reduction Technologies Packaged for Near-Term Analysis

	Technology
Near-term	• Low-rolling resistance (single-wide) tires • Planar boat tails • Front fairings • Trailer side skirts • Fuel tank skirts • Aluminum wheels

As applied to a fleet average Class 8b diesel truck in 2010, the above combinations of technologies are estimated to provide a 10 to 15 percent reduction in fuel consumption over the AEO Reference case for highway operation in the near term, as shown in Table 3.3B (Frey and Kuo, 2007; TIAX, 2008; CARB, 2008a; Vyas et al., 2002; NESCCAF/ICCT, 2009). Unlike LDVs, the most appropriate way to measure the efficiency of HDVs is usually in terms of fuel use per unit of work performed – e.g. ton-miles hauled or horsepower-hours per gallon. Although a simple miles per gallon metric is utilized here for consistency with other sections, it provides a somewhat crude and imprecise measure of efficiency for these sources.

[51] Analysis accounts for mutually exclusive options such as low rolling resistance and single-wide tires.

Table 3.3B Aerodynamic and Resistance Reduction Technologies Fuel Efficiency and Consumption Improvement Potential

	Conventional Class 8b MPG (AEO 2010)	Scenario MPG		Fuel Consumption Reduction Range	
		Minimum	Maximum	Minimum	Maximum
Near-term	6.34	7.00	7.45	10%	15%

Many of the above strategies also are applicable to smaller HDVs and/or lower operating speeds, but at a reduced level of effectiveness. For example, one study estimates a 1.0 percent fuel efficiency improvement for Class 8 trucks with basic aerodynamic cab treatments at low speeds typical of urban operation, compared to 2.0 percent at highway speeds. Similarly, this same study estimated that straight trucks in the Class 3–6 range would obtain a 1.4 percent fuel efficiency improvement for low-rolling resistance tires, compared to 2.9 percent for this measure when applied to Class 8 tractor-trailers (Schubert and Kromer, 2008). Nevertheless, strategies such as low-rolling resistance tires, front fairings, and aluminum wheels may still provide effective GHG reductions for smaller trucks. On the other hand, certain strategies tailored to high-speed long-haul operations are generally not applicable to smaller HDV categories, including trailer side skirts and boat tails.

Costs

The incremental costs associated with resistance reduction strategies are relatively low compared to the base price of HDVs (commonly more than $100,000 for Class 8 tractor rigs, and an additional $20,000 or more for trailers).[52] Cost estimate ranges are provided in Table 3.3E by truck class group (Frey and Kuo, 2007; Schubert and Kromer, 2008; Vyas et al., 2002; CARB, 2008a; NESCCAF/ICCT, 2009). Unit costs for trailer treatments have been multiplied by 2.5 to reflect the fact that there are approximately 2.5 trailers for each tractor in service today (Schubert and Kromer, 2008).

[52]Primarily Kenworth models.

Table 3.3C Incremental Costs of Resistance Reduction Strategies

	Per Unit Incremental Cost	
Strategy	Class 3 to 7	Class 8a and 8b
Basic cab aero	$750	$750
Enhanced cab aero	$800	$1,500
Trailer edge curvatures	N/A	$1,250
Front fairings	$2,000 to $2,500[a]	$2,000 to $2,500[a]
Side skirts	N/A	$2,500 to $6,500[a]
Boat tails	N/A	$1,250[a] to $5,600[a]
Advanced trailers (UFD)	N/A	$2,500[b]
Advanced trailers (CVTD)	N/A	$500[b]
Electronic vision systems	N/A	$1,000[b]
Single-wide tires and aluminum wheels[53]	$1,680[a]	$3,920[a]
Automatic tire inflation systems	N/A	$500 to $900

Sources: Vyas et al., 2002; Lovins et al., 2005; Schubert and Kromer, 2008; Frey and Kuo, 2007; NESCCAF/ICCT, 2009.

[a] Without side skirts.

[b] Includes installation and taxes.

[c] Includes lifetime replacement costs.

N/A – estimates not available or not applicable.

The one value found in the literature which focused exclusively on similar retrofit strategies found a cost effectiveness of -$60/tonne (CARB, 2008a).[54]

Cobenefits

In addition to fuel savings and associated GHG reductions, various other benefits are anticipated with the adoption of rolling resistance technologies. Notably, the reduced power requirements associated with these strategies can lower NO_x and other emissions substantially. A detailed study evaluating potential retrofit impacts on Class 8 trucks in California estimated NO_x reductions roughly comparable to GHG reductions for such

[53] Adoption of single wide tires has a wider cost range depending on circumstances. When purchasing a new truck or trailer, single-wide wheels and tires may be less expensive than traditional duals (U.S. EPA, 2004b).

[54] Based on an annualized cost of $400 million per year and a nationwide GHG reduction of 6.7 mmt in 2020.

measures on a percentage basis, ranging from 1.2 times the fuel efficiency benefit for long-haul operations, to 0.58 times the fuel efficiency benefit for short-haul duty-cycles (Schubert and Kromer, 2008). The sensitivity of PM emissions to duty-cycle makes benefit estimates for this pollutant highly uncertain.

EPA has provided States with air quality guidance to quantify the co-benefits of improved tire and aerodynamic technologies.[55] Rolling resistance strategies may provide other types of benefits as well. For example, automatic tire inflation systems are estimated to extend tire life by 8 percent or more, while saving time and labor associated with pressure gauge checks (U.S. EPA, 2004b). These systems also may improve overall safety by lowering the frequency of blowouts and roadcalls (Lovins et al., 2005). Conversely, single-wide tires may lead to increased maintenance requirements due to greater pavement rutting and deformation.

The decreased engine loads associated with these options also may permit some degree of engine downsizing, which could in turn provide additional fuel consumption benefits. One recent study estimated a 3.0 to 4.0 percent fuel consumption benefit associated with a 20 percent reduction in engine power for Class 8 combination trucks operating on the highway (NESCCAF/ICCT, 2009). However, it is uncertain to what extent consumers would be willing to accept the degradation in acceleration and hill climbing performance associated with reduced power. Therefore the potential equipment cost reduction, fuel savings, and emission reductions associated with such downsizing are uncertain and are not included in the above analysis.

Finally, decreased vehicle and trailer weight will improve absolute fuel efficiency for volume-limited payloads, and will allow for increased freight (and reduced fuel consumption per ton-mile hauled) for weight-limited payloads, thereby reducing costs to shippers.

Feasibility

All of the technologies discussed in this section have undergone some amount of demonstration and many are commercially available. In addition, most resistance strategies are only beginning to be deployed and have significant market penetration potential remaining. Accordingly, the primary barriers to long-term adoption of these technologies are economic, logistical, and informational.

Long equipment life, and the desire to reduce time lost to maintenance, have the effect of slowing the market penetration of new technologies in the HDV sector. Some of the aerodynamic design improvements listed above, such as underbody baffles and trailer side skirts, may make some maintenance work more difficult or expensive and reduce vehicle ground clearance, which could limit the utility of trucks and trailers.

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[55] See http://www.epa.gov/OMSWWW/Stateresources/transconf/policy/420b07004.pdf

Strategies such as closing the truck/trailer gap and boat tail plates may, depending on their design, increase the time required to hitch and unhitch trailers and load/unload cargo. Damage to gap reduction features is common during tight maneuvering, where the angle between the tractor and trailer can become extreme. In addition, placement during installation must carefully consider the location of the fifth wheel and kingpin. Trailer side skirts also present certain operational concerns, including reduced ground clearance (possibly resulting in skirt damage), and ice/weight accumulation in cold climates. Additionally, some of the above technologies will increase vehicle weight, which can in some cases limit the total cargo that can be carried.

Another primary barrier to the widespread use of rolling resistance technologies is cost, even though payback periods for many of these measures are less than four years.[56] The majority of trucks are in small fleets (one to five trucks) or held by owner-operators. Profit margins in the trucking industry tend to be small, and operators typically only makes improvements to vehicles and systems when the costs and benefits are clear and previously demonstrated in real-world operations. This is a barrier (for example) to automatic tire inflation systems—manual tire pressure checks are relatively easy to perform, so individual or small fleet owners may not consider the payback for an automated system to be worth the cost. The early adopters of such technologies are likely to be the top-of-the-line truckload carriers that have very sophisticated maintenance management systems, but these carriers are relatively few and operate a relatively small percentage of total tractors.

With regard to single-wide tires, there also is concern over decreased redundancy in the case of a flat tire or blowout, although this risk may be exaggerated.[57] There also could be resistance to adopting this technology because of parts commonality within fleets and the desire to maintain a single set of wheel and tire types. In the period before these tires achieve a large market penetration, there also could be perceived difficulty in easily finding replacements when away from urban centers. This is a particular concern among smaller fleets without recourse to effective network support. Some low-rolling resistance tires require higher pressure and increased monitoring (Vyas et al., 2002), although this concern could be minimized with the adoption of automatic tire inflation systems. Finally, vehicles that frequently travel off-road or operate on low friction surfaces may require higher traction tires for safety reasons (NESCCAF/ICCT, 2009).

In addition, reduced resistance will necessarily entail increased braking loads with likely increases in brake maintenance, unless vehicle speeds themselves are lowered. Cab modifications also may be limited to some extent by additional underhood requirements, such as the need for new EGR and enhanced cooling equipment in order to meet late model emission standards (21st Century Truck Partnership, 2009).

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[56] There is evidence that trucking companies base their purchasing decisions on low amortization periods of about two to three years (NESCCAF/ICCT, 2009; Greene and Schafer, 2003).

[57] On a conventional wheel, a blow out frequently overloads the matching double, causing it to blow out as well (Lovins et al., 2005).

There are a few other potential safety concerns for resistance strategies. For example, while electronic visions systems are just entering the market in Class 8b trucks, these systems are being deployed as a supplement to standard side mirrors, not as a replacement, which would require changes in safety regulations (Kenworth, 2001). Accordingly further demonstration and testing will be required to ensure these systems provide adequate safety and performance in the absence of side mirrors. Also, as noted above, certain measures may result in unacceptably low air flow and component cooling if implemented together, such as trailer side skirts and undercarriage baffles.

Adopting aerodynamic retrofits or purchasing cabs with enhanced profiles may also be reduced due to traditional buyer preferences. The "classic" cab profile shown in Figure 3.8 is still favored by many buyers, particularly owner-operators, in spite of their demonstrably lower efficiency (NESCCAF/ICCT, 2009).

Trailer strategies are likely to be particularly difficult to implement due to ownership and operation practices. First, long-haul tractors and trailers are commonly owned by different entities, with carriers controlling the tractors and shippers or other third parties controlling the trailers. For this reason coordinated implementation of full system packages may be difficult. In addition, since there are approximately 2.5 trailers for every tractor in the U.S., retrofitting trailers will necessarily be less cost-effective than tractor retrofits, for similar efficiency improvements (Schubert and Kromer, 2008). As such, fleetwide cost estimates are adjusted for the anticipated lower utilization of trailers compared to tractors.

The primary barriers to implementation of weight reduction technologies are cost and difficulty of retrofits. Unlike some aerodynamic improvements, weight savings must take place at the design stage. The notable exception would be retrofits of aluminum wheels, as discussed above. In terms of aluminum substitution materials in the truck and trailer structures, it also is common for owners to perceive lighter weight materials as not being as durable (U.S. EPA, 2004c).

One potential Federal policy approach to promote adoption of these strategies is to undertake demonstration projects and information dissemination for advanced truck, trailer, and engine designs, with coordination between large long-haul freight carriers and vehicle OEMs. To help overcome financial barriers, low-interest loans may be provided for smaller carriers (e.g., owner-operators) to encourage retrofitting of older trucks with significant remaining life (such as has been done through EPA's SmartWay financing programs). California and Texas also have implemented financial incentives to encourage retrofitting of older heavy-duty vehicles with improved emissions control technology – a model that could potentially be applied to fuel-saving technologies as well. The Federal government also may play a role in helping to coordinate design improvements between tractor and trailer manufacturers and operators in order to obtain maximum benefits from "system" integration. The Federal government could potentially promulgate requirements to adopt certain technologies that have been determined to be feasible and cost-effective. This approach has been taken to control emissions of criteria pollutants and precursors from stationary sources of pollution regulated under the Clean Air Act.

Finally, fuel prices—whether affected through policies or market forces—will play an important role in affecting truck purchasers' decisions regarding fuel efficiency savings, as well as manufacturers' decisions to invest in more efficient technology. The expectation of sustained higher fuel prices would likely encourage more manufacturers and operators to adopt fuel efficiency improvements.

Heavy-Duty Engine/Powertrain Measures and Integrated Strategies

Overview

Current heavy-duty diesel engines operate at approximately 40 percent thermal efficiency under optimal operating conditions. Taken with auxiliary loads and drivetrain losses, 66 percent of fuel energy is not converted to motive power (ORNL, 2000). Technologies can be implemented to reduce this energy loss and make heavy-duty trucks more efficient.

There are four primary ways in which heavy-duty powertrains can be modified to reduce GHG emissions:

1. In-cylinder/combustion improvements;
2. Accessory load reduction;
3. Frictional loss reduction;
4. Hybridization strategies; and
5. NO_x aftertreatment strategies.

The first three of these technologies will reduce the waste heat lost from drivetrain components. HDV hybridization strategies share many characteristics with LDV hybrids, described in the previous section. Unless otherwise noted, the specific technologies under consideration for HDVs are just now entering the marketplace, or are expected to become available in the next few years (U.S. DOE, 2009b). In-cylinder and combustion improvements modify the way that air and fuel are brought into the engine and how the fuel is burned to convert its chemical energy to mechanical power. Accessory load reduction decreases the power needs for pumps, air compressors, electrical power generation, cooling fans, and air conditioning. Frictional losses generate waste heat in the engine and transmission, decreasing the power that could otherwise be used to drive the wheels. Hybridization approaches utilize two power delivery sources and recover braking energy to improve overall efficiency. NO_x aftertreatment strategies reduce the amount of energy dedicated to lowering NO_x emissions through control efficiency improvements, thereby reducing fuel consumption.

Today's diesel engines typically use turbochargers to compress the intake air, leading to greater efficiency and power output. Technologies aimed to improve turbocharger operation can improve efficiency, drivability, and emissions. One modification that recently entered the market is the **variable geometry turbo (VGT)**. This type of turbo involves moveable surfaces in the exhaust turbine that allows control over the speed of the compressor. With the use of exhaust gas recirculation (EGR), the VGT has become universal. Ironically, the VGT system is generally used to *reduce* the efficiency of the turbocharger. In order to flow an adequate amount of EGR in a high pressure loop EGR system, the pressure in the exhaust manifold must be higher than the pressure in the intake manifold. This situation is referred to as running a negative Δp. If an efficient conventional turbocharger is used, the intake manifold pressure is often higher than the exhaust (positive Δp). The VGT is adjusted to maintain a negative Δp to the extent required to provide the correct EGR flow.

Two-stage turbocharging, which utilizes a high pressure and a low-pressure turbo, also can increase engine efficiency over a wide range of operating conditions. These two units can be connected in series, or flow can be directed to only one unit depending on how the engine is operating. A two-stage turbocharger system requires the use of an EGR pump, a backpressure device, or a turbocompound system to flow EGR in an engine that uses high pressure loop EGR. Both VGT and two stage turbo charging reduce lag effects during transient operation, allow increased power output, and reduce NO_x emissions when used in concert with control technologies such as exhaust gas recirculation.

Improved materials and designs may eventually permit higher cylinder pressures and therefore improved fuel efficiency, without a durability penalty. Higher pressures also provide higher power density. Such improvements are constrained by NO_x formation, however. While high-compression ratios and combustion temperatures lead to high thermal efficiency, durability concerns, and emissions regulations force a tradeoff by limiting compression-related forces and allowable NO_x emissions. Technologies to increase engine efficiency must pursue the benefits of high combustion temperatures without the associated increases in engine-out NO_x when possible. Exhaust aftertreatments are employed to bring final emissions down to allowable levels, although these devices are generally not as cost-effective as in-cylinder design changes. This is a field of continued study, and it is expected that as diesel NO_x aftertreatment becomes more effective, cylinder pressures will be increased in search of efficiency gains and increased power density.

Improved fuel injectors also are the focus of research to improve engine efficiency. Recently, manufacturers have begun moving to common rail systems whereby all injectors are fed fuel from a single reservoir at extremely high pressure. Higher pressures generally allow more effective mixing of air and fuel, leading to reduced PM emissions and greater efficiency. These designs also allow flexibility with multiple injection strategies whereby fuel is injected at more than one point during cylinder compression and expansion. This approach can allow fuel to burn longer into the compression stroke without reaching as high a flame temperature, thereby reducing NO_x formation. There are a variety of multiple injection strategies being pursued.

In addition to combustion improvement strategies, **reducing engine accessory loads** can improve the operating efficiency of HDVs. Accessory loads require around 4 percent of engine power output from a truck traveling at 65 mph (ORNL, 2000). The air conditioner compressor, alternator, air compressor, cooling fan, and water pump are generally connected directly to the engine by means of gears or a belt, so these devices are driven at a speed directly proportional to the speed of the engine. Because accessories need to function acceptably at all engine speeds, they are typically driven faster than necessary at high engine speeds. Decoupling accessories from engine speed can reduce power requirements while allowing for better performance over the engine's operating range. The primary way to decouple accessories from engine speed is by electrification, driving each accessory with an electric motor that can run at the accessory's optimum speed. By using this method, only smaller engine loads associated with electrical generation are required, resulting in reduced fuel consumption. Another option is to clutch accessories, so that they only operate when needed. This is normally done with the cooling fan and air conditioning compressor, but the idea can also be applied to the alternator and air compressor as well.

Even assuming significant improvements in combustion efficiency and accessory loads, large amounts of energy will continue to be in the form of heat energy in the exhaust stream. Conventional turbochargers are designed to operate using some of this otherwise-wasted energy. There are three other emerging technologies that can allow even more of this energy to be used for the necessary functions of the truck. **Thermoelectric generators** can use the temperature gradient between the exhaust and ambient air to generate electricity. These devices also are described in the LDV section, but are anticipated to be promising for heavy-duty long-haul trucks because these trucks operate under fairly high load the majority of the time and subsequently produce a relatively continuous supply of high-energy exhaust.[58] These systems are still in development and are not yet commercially viable.

Another option to recoup exhaust energy is **turbocompounding**. Turbocompounding uses an exhaust turbine for shaft power, either as a stand alone system or in addition to powering the intake compressor. The output shaft can be connected to an electric generator or to a transmission connected to the engine's crankshaft. Excess turbine power can then be used to either assist the engine shaft output or to reduce the alternator's electrical generation load, either partially or completely.

A third option, a **bottoming cycle**, consists of a heat engine that uses waste heat from the primary diesel engine to produce additional work. There are many concepts available for use in a bottoming cycle, including refrigerant-based cycles and steam turbines. The great advantage of a bottoming cycle is that it uses "free" energy—energy that is going to be lost by the primary engine. The great disadvantage of a bottoming cycle is that its efficiency is limited by the poor quality (i.e., relatively low temperature) of most waste heat from the engine. In addition, the amount of waste heat available also varies greatly with the engine's operating condition. Bottoming cycles have been used for many years in stationary power plants, but so far they have not found application in vehicles because of cost, weight, packaging, reliability, and performance issues (NESCCAF/ICCT, 2009).

Friction reduction can contribute to overall truck fuel efficiency. Design changes to the bearings, seals, and mating surfaces in engines, transmissions, and differentials can reduce energy requirements. Additionally, designing these devices to take advantage of lower viscosity lubricants can reduce energy lost to pumping fluids through the engine and

[58] Diesel exhaust temperatures are reduced by lean operation, the presence of EGR, and turbocharger use, all of which will tend to reduce the effectiveness of thermoelectrics.

transmission. The use of lower viscosity lubricants typically requires the use of higher cost synthetic oils. However, manufacturers have limited control over the lubricants used by customers.

Both OEM **electric and hydraulic hybrid configurations** currently are under development for heavy-duty trucks. While the application for heavy-duty electric hybrids differs somewhat from light-duty vehicles, the technology is similar and is discussed in the light-duty section above. Heavy-duty hydraulic hybrids, in contrast, combine hydraulic pumps with an internal combustion engine and store energy in a hydraulic accumulator instead of a battery. During vehicle acceleration, pressurized gas in the accumulator channels fluid through a hydraulic motor, which in turn supplies power to the driveshaft. Fluid used in this manner is collected in a reservoir, which is later pumped back to the accumulator when the vehicle brakes, using the energy of the vehicle's forward motion to effectively recharge the system. Currently, retrofit options for electric and hydraulic technology on existing trucks is not considered feasible (ATA, 2006).

Hydraulic hybrid vehicles are capable of braking energy transfer at a relatively high rate, but are limited by the amount of energy they can store. Because of this, hydraulic hybrids are well suited to stop-and-go applications on relatively heavy vehicles such as refuse haulers or large parcel delivery vehicles. On the other hand, while electric hybrid batteries also can store more energy than hydraulic systems, they cannot charge or discharge as rapidly as their hydraulic counterparts, so they are more appropriate for applications with smaller instantaneous power requirements, such as LDVs (ATA, 2006). A tax credit of up to $18,000 is available for the purchase of qualified heavy-duty HEVs with a gross vehicle weight rating of more than 8,500 pounds (AFDC, 2009).

Advanced integrated aerodynamic designs are also under development, with a focus on line-haul combination truck applications. These improvements include utilization of tear-drop shaped trailers, underbody treatments, wheel skirts or hubcaps, integrated gap treatments, and other assorted measures. They require coordinated redesign of the tractor and trailer as a unified system, and cannot be applied through simple retrofit.

Finally, certain theoretical advances were identified in the literature that have the potential for dramatically improving engine efficiency as well as lowering pollutant emissions, such as the Sturman Digital Engine combustion cycle (NESCCAF/ICCT, 2009). Due to lack of test data and cost estimates, however, such options are not evaluated in this report.

Engine and powertrain strategies also can be combined with resistance reduction strategies for maximum potential benefits. This section evaluates the potential GHG reductions and costs associated with advanced integrated packages in the medium to long term.

Magnitude and Timing of GHG Reductions

Individual Technology Benefits

Systems that enhance turbocharger operation, such as multistage turbos, have recently entered the market, and can reduce fuel consumption by approximately 2 percent (NESCCAF/ICCT, 2009). Design changes that can allow increased cylinder pressure are estimated to improve fuel efficiency by 3.6 percent (Frey and Kuo, 2007). Continued optimization of fuel injection systems and combustion is estimated to allow up to a 5 percent improvement in fuel efficiency (U.S. DOE, 2009b). Many of the above technologies will enter the market in the short term.

Recuperation of exhaust heat energy via mechanical turbocompounding is estimated to allow fuel consumption to be reduced by approximately 2 to 3 percent, while bottoming cycle benefits have potential reductions between 8 and 10 percent (NESCCAF/ICCT, 2009).[59] When thermoelectrics become efficient and durable enough to be used in heavy-duty applications (estimated to be in the medium to long term), research has shown that their use could reduce fuel consumption by 6.5 percent. Accessory electrification could reduce fuel consumption by 2 percent (Frey and Kuo, 2007). It is estimated that using electric turbocompounding for electric generation could reduce fuel consumption by 3 percent to 5 percent, including the benefits of accessory electrification (NESCCAF/ICCT, 2009; Hopmann, 2004). Mechanical turbocompounding systems currently are just entering the market, with no electrical systems planned as yet (Reinhart, 2009).

Lower viscosity lubricants and engine materials that reduce engine frictional losses could reduce fuel consumption by one to two percent (U.S. DOE, 2009b; Greszler, 2008). Transmission fluids and materials that reduce transmission heat losses could provide similar fuel consumption reductions to engine friction reduction. While the engine and waste-heat technologies listed above are not likely to be retrofitable, low-viscosity lubricants could quickly enter the fleet during routine oil changes, although extra costs could present a barrier for vehicle owners.

While interest in development of heavy-duty hybrid technology has intensified in recent years due to increased fuel costs, development has lagged behind light-duty hybrid technology. Heavy-duty market penetration is perhaps 8–10 years behind the current-level in the light-duty marketplace, with heavy-duty hybrids in the early demonstration phase. However, heavy-duty prototype vehicles currently are in development in a wide variety of market sectors, including delivery trucks, refuse trucks, utility service trucks, and transit buses. A high-profile example of this type of development is EPA's ongoing partnership with UPS in developing a hydraulic hybrid parcel delivery truck.

Early heavy-duty hydraulic hybrid vehicles show a gain of 30–50 percent in fuel efficiency over standard diesel heavy-duty vehicles for short-haul, stop-and-go applications (ATA, 2006). Because long-haul trucks are estimated to realize only a 3–9 percent fuel efficiency improvement using this technology, and because of the relatively high incremental cost in the near term, it is unlikely that heavy-duty hybrid technology will penetrate the long-haul fleet in large numbers in the near term. However, several manufacturers have announced production plans for hybrid electric offerings over the next few years (NESCCAF/ICCT, 2009).

[59] Turbocompounding, bottoming cycles, and thermoelectrics are mutually exclusive strategies.

Integrated aerodynamic measures are mutually exclusive with the retrofit package items discussed in the previous section, and are estimated to provide about a 14 percent fuel consumption reduction in the medium to long term (NESCCAF/ICCT, 2009).

Strategies that lower engine out NO_x more efficiently can reduce fuel consumption as well. For example, improvements in exhaust gas recirculation cooling could reduce fuel consumption by about one percent, although this strategy cannot be effectively coupled with the thermal and air handling management approaches noted above, because exhaust temperatures are lowered, reducing the effectiveness of these approaches (NESCCAF/ICCT, 2009).

The minimum and maximum fuel efficiency improvements found in the literature for the different resistance and powertrain technologies are presented in Table 3.3G below by truck class category. These values reflect the benefits only for those vehicles considered likely candidates for these technologies, and do not reflect fleet average impacts. Adjustments for anticipated market penetration are provided in Table 3.3J below.

Table 3.3D Range of HDV Fuel Efficiency Improvements for Resistance and Powertrain Technologies

	Class 4-7		Class 8	
Technology	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Basic cab aero	2.3%	2.3%	1.0%	2.0%
Enhanced cab aero	3.6%	3.6%	2.3%	2.3%
Trailer edge curvatures	-	-	1.2%	1.2%
Advanced integrated aero			14.1%	14.1%
Low-rolling resistance tires and aluminum wheels	1.9%	2.3%	3.0%	10.6%
Auxiliary electrification	-	-	2.0%	2.0%
Lubricants and bearings	-	-	1.0%	2.0%
Peak cylinder pressure	-	-	3.6%	3.6%
Improved injection/combustion	7.2%	7.2%	5.4%	5.4%
Turbocomponding (mechanical)	-	-	2.4%	2.9%
Bottoming cycle	-	-	8.0%	10.0%
Hybridization	30%	50%	3.0%	9.0%
Weight reduction	0.6%	1.2%	0.6%	1.8%
Boat tails	-	-	2.8%	4.0%
Load profile improvement	-	-	2.5%	2.5%
Front fairings	4.9%	4.9%	1.0%	2.0%
Side skirts	-	-	4.2%	7.5%

Combined Per-Vehicle Benefits

Benefits associated with selected resistance reduction strategies available for retrofit were presented in the previous section for the near-term scenario. Additional resistance strategies as well as powertrain approaches introduced through the purchase of new vehicles are considered here. A broad package of resistance reduction and powertrain strategies identified in the literature are listed in Table 3.3H for the medium- to long-term scenario. The appropriate truck classes also are specified for each measure.[60] Engine measure naming conventions follow those from EIA (U.S. DOE, 2009b). An attempt also has been made to remove measures that are mutually exclusive or redundant. In addition, hybrid and other advanced measures are evaluated separately below.

Table 3.3E Powertrain and Resistance Reduction Technology Package for Medium- to Long-Term Analysis

	Technology/Truck Class
Resistance Strategies	• Basic aerodynamic improvements – cab/hood (all classes), trailer gap (Class 8) • Enhanced cab—wheel wells, underside baffles, bumper (all classes) • Trailer edge curvatures (Class-8) • Advanced integrated aero (Class-8)[a] • Low-rolling resistance tires and aluminum wheels (all classes) • Planar boat tails (Class 8) • Front fairings (all classes) • Trailer side skirts (Class 8) • Load profile improvement (Class 8 – flatbeds only) • Weight reduction (all Classes)
Powertrain Strategies	• Lower friction, improved injectors and combustion (all classes) • Improved lubricants and bearings (all classes) • Increased peak cylinder pressure (Class 8) • Improved injectors and combustion (all classes) • Turbocompounding (Class 8) • Bottoming cycle (Class 8) • Auxiliary electrification (all classes)[b]

[a] Mutually exclusive with other aero treatments.

[b] Part of base hybrid packages—benefits and costs netted out for hybrid analysis..

For this assessment, individual benefit estimates for each measure were applied successively in multiplicative fashion to calculate the net improvement in fuel

[60]For example, trailer treatments would not be applicable to most Class 4-7 (straight) trucks.

consumption and GHG emissions relative to a conventional vehicle (at 7.30 mpg in 2030 from AEO).[61] Additional evaluation and modeling would be required to more accurately assess the net impact of these strategies taken together, considering positive and negative interactions among the different measures.

Estimates from the literature for the per vehicle fuel consumption and GHG reduction potential from broad adoption of several of the above technologies on a Class 8 line-haul box truck range from 24 to 40 percent, excluding the most aggressive technologies such as hybrids and bottoming cycles.[62] A very similar range of benefit estimates were developed for this analysis, between 22 and 33 percent for the adoption of similar Class 8 box truck measures, relative to a conventional diesel truck in 2010. Benefits for nonbox trucks and for trucks traveling at slower speeds are anticipated to be lower, as the ranges of applicable resistance measures is smaller and their effectiveness is decreased.

Table 3.3I summarizes the fuel efficiency and consumption improvement potential for the package of measures specified in Table 3.3H, for the medium-/long-term scenario. These estimates are applicable to Class 8 box trucks operating on a line haul cycle. Hybrid, bottoming cycle and advanced integrated aerodynamic options are included in a separate “maximum technology” package, due to their significantly higher incremental costs and uncertain market penetration potential.

Table 3.3F Powertrain and Resistance Reduction Technology Package Fuel Efficiency and Consumption Improvement Potential

Medium-/Long-Term (2030-2050)	Conventional Class 8b MPG (AEO 2030)	Scenario MPG		Fuel Consumption Reduction Range	
		Minimum	Maximum	Minimum	Maximum
“Conventional” Package	7.3	8.1	9.5	10%	23%
Maximum Technology Package	7.3	8.8	10.5	17%	30%

Costs

Incremental costs for powertrain strategies are generally low relative to vehicle costs, with the exception of “maximum technology” options. Cost estimate ranges above

[61] For example a multiplicative interaction between measure A with a 2.0 percent fuel consumption benefit and measure B with a 3.0 percent benefit would come to 4.9 percent (0.98 x 0.97) rather than 5.0 percent (for a purely additive interaction).

[62] Survey of the literature as reported in Lutsey (2008).

conventional diesel HDVs are provided truck class group in Table 3.3L (Frey and Kuo, 2007; Schubert and Kromer, 2008; Vyas et al., 2002; CARB, 2008a; NESCCAF/ICCT, 2009). Unit costs for trailer treatments are multiplied by 2.5 to account for the ratio of trailers to tractors.

Table 3.3G Incremental Costs of HDV Resistance and Powertrain Technologies (Dollars per Vehicle)

	Class 4-7		Class 8	
Technology	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Basic cab aero	750	750	750	750
Enhanced cab aero	800	800	1,500	1,500
Trailer edge curvatures	-	-	1,250	1,250
Advanced integrated aerodynamics	-	-	24,500	24,500
Low-rolling resistance tires & aluminum wheels	1,680	1,680	3,920	3,920
Auxiliary electrification	1,000	1,000	1,000	1,000
Lubricants and bearings	500	500	500	500
Peak cylinder pressure	-	-	1,000	1,000
Improved injection/combustion	2,000	2,000	1,500	1,500
Turbocompounding (mechanical)	-	-	2,650	2,650
Bottoming cycle	-	-	15,100	15,100
Hybridization	20,500	26,000	20,500	26,000
Weight reduction	1,000	2,000	1,000	2,000
Boat tails	-	-	1,250	5,600
Load profile improvement	-	-	0[a]	0[a]
Front fairings	2,000	2,500	2,000	2,500

[a] Does not include operator labor.

Cobenefits

As noted, many of the engine system improvements described above raise combustion temperatures and therefore engine-out NO_x emissions. The increase in NO_x formation is generally more of a limiting factor to increases in engine efficiency than PM emissions. Selective catalytic reduction (SCR) technologies being adopted to meet the upcoming 2010 NO_x standards can be designed to lessen the energy requirements associated with exhaust gas recirculation (EGR) systems by permitting greater engine-out NO_x levels, in turn reducing fuel consumption (Greszler, 2008).

Certain powertrain improvements also can improve engine driveability by increasing available torque at a wide range of engine speeds. Improved fuel injection also can result in reduced formation of NO_x and PM, although reductions in tailpipe PM may be negligible due to the great effectiveness of DPFs in 2007 and later diesels.

Apart from the primary benefits of increased fuel efficiency and reduced GHG emissions, widespread market penetration of HD hybrids is likely to result in marked reduction in both PM and NO_x emissions resulting from reduced diesel fuel consumption. Initial test results for hybrid electric buses, for example, have shown NO_x reduction of 50 to 60 percent, with corresponding PM reduction of greater than 90 percent, relative to pre-2007 diesel engines (ATA, 2006). For 2010 diesel engines, where tailpipe emissions will be just a few percent of uncontrolled levels, the benefit will be much less significant.

Feasibility

The engine and powertrain improvements discussed in this section typically need to be designed into a new vehicle, and therefore are not feasible for retrofit on existing vehicles (unless an entirely new engine is retrofit to a vehicle). As such, policy needs will be somewhat different than for resistance reduction strategies, many of which can be retrofit. One approach is to establish efficiency standards, as currently is being evaluated pursuant to the EISA of 2007. Given that market economics likely play a larger role in vehicle purchase decisions for heavy-duty vehicles relative to light-duty vehicles, due to the high contribution of fuel costs to total operating costs, the adoption of standards may have relatively less impact. On the other hand, as noted in the previous section, there is evidence that trucking companies base their purchasing decisions on low amortization periods of about three years, meaning that even cost-effective strategies will not necessarily be implemented through market forces alone.

Financial incentives such as tax credits or low-interest loans also may play a role in helping to overcome initial capital costs. Such incentives are beginning to emerge at the Federal and State levels to promote the introduction of heavy-duty hybrid technology into the fleet. For example, the Energy Policy Act of 2005 includes tax credits of up to $12,000 based on the fuel efficiency and weight of a particular vehicle. Finally, demonstration projects and information dissemination, as performed under EPA's SmartWay program, may play a role in helping to inform truck owners about the benefits of new technology and encourage purchase of more efficient vehicles. Partnerships with larger fleet operators, for example, may be valuable in bringing a particular technology to scale and reducing costs such that smaller operators also will be willing and able to adopt it.

Many of these strategies face technical hurdles as well. The turbocompounding and fuel injection developments noted above are expected to be developed further and increase their market penetration in the future. They are limited primarily by cost and the development time needed to ensure that they maximize efficiency and pollutant reduction. Bottoming cycle systems face tremendous engineering hurdles involving freeze prevention, vibration, and numerous other factors before they can be considered a viable option for the on-road market. For example, due to the poor transient response of the bottoming cycle, this system may have to be coupled with hybrids to achieve acceptable performance (NESCCAF/ICCT, 2009). Thermoelectrics face cost and durability issues. Additionally, these devices are not yet efficient enough to provide significant electric generation.

Low-viscosity engine and transmission fluids exist that can reduce parasitic driveline losses. Limitations to these fluids include convincing operators to pay for the higher costs as part of their maintenance cycle, and uncertainty regarding long-term effects on component durability (Killian, 2008).

In the case of improvements to fuel injectors, intakes, and turbocharger design, fuel consumption and emissions can often be reduced together. There is a limit to the improvements that allow these two characteristics to move in the same direction, however, and it is estimated that engines could achieve 15-20 percent higher fuel efficiency using today's technology *if* there were no NO_x requirements. Accordingly, fuel efficiency also could be significantly improved with a breakthrough in NO_x aftertreatments which could allow engines to operate at their most efficient levels without regard for engine-out NO_x levels (Greszler, 2006).

As mentioned previously, heavy-duty hybrid market penetration is several years behind the current level in the light-duty marketplace. Many issues exist that present challenges before heavy-duty hybrids can gain a foothold in the market. For example, electrical components such as air-conditioning and steering pumps only exist as expensive prototypes in heavy-duty vehicles—there are no widely available systems yet that can sustain regular heavy-duty duty-cycles. In addition, optimized engines, more advanced combustion schemes, and lighter weight materials are necessary for heavy-duty hybrid technology to reach maturity (ATA, 2006). Finally, battery replacement costs have not been included in the above analysis, and may be substantial, assumed by one source to be required approximately every six years (NESCCAF/ICCT, 2009).

Advanced integrated aerodynamic improvements will require a redesign of the tractor-trailer system in order to minimize overall drag. This strategy is particularly challenging, given the lack of incentive on the part of trailer owners, who would not normally see a monetary benefit associated with their (quite sizable) investment.

3.4 Transit Buses

Buses, including transit buses, school buses, and intercity buses, occupy a small but important niche in the U.S. heavy-duty vehicle sector. Of the different types of buses, the best data is available on transit buses, and the greatest development of alternative fuel or advanced technology powertrains has taken place in this subsector. As of 2006, there were roughly 1,500 transit authorities operating fleets of heavy-duty transit buses. These agencies were responsible for over 80,000 vehicles that traveled over 20 billion passenger-miles, mostly in stop-and-go urban traffic settings. In that same year, these buses consumed more than 525 million gallons of diesel fuel, the fuel for nearly 80 percent of the transit buses on the road (APTA, 2008).

Transit Buses

Per Vehicle GHG Reduction: varies by technology, 10 – 50% for hybrid electric buses

Key Cobenefits and Impacts: **Positive**

Feasibility: **High**

- Some proven technologies

Key Policy Options:

- Financial and policy support for transit agency purchase of efficient/ advanced vehicles, energy-saving

In spite of their visibility, buses actually contribute less than 1 percent of total on-road GHG emissions in the United States.[63] For this reason a full assessment of the costs, benefits, and feasibility of advanced bus technologies is not provided here, although a discussion of the emerging technology options is presented below. In addition, some of the strategies applicable to heavy-duty trucks (Section 3.4) also can be applied to buses, leveraging development resources, increasing market volumes, and reducing unit costs. Furthermore, transit buses are often technology leaders. Predictable service patterns, centralized fueling and maintenance, and available 80 percent Federal capital cost subsidy all make transit buses attractive platforms to introduce new technologies. For example, hybrid powertrains, natural gas fuel, and fuel cell powertrains have all been pioneered in transit buses.

For a range of reasons, a growing number of transit agencies are turning to nonfossil diesel fuels to power some or all of the vehicles in their fleets. Between 1996 and 2007, the use of Compressed and Liquefied Natural Gas (CNG and LNG) grew by a factor of 50 in these fleets; today 15 percent of transit buses use one of these fuel types. Electric or hybrid-electric buses now comprise 2 percent of the total buses in America, increasing 23 times in that same period and making hybrids the third most popular technology used by buses today. Finally, gasoline, propane and “other” sources, consisting of biodiesel, hydrogen, and various blends remain popular in some fleets, but these fuels are collectively used in less than 3 percent of transit buses in America. Over this period, diesel’s share of transit bus fuel dropped substantially (by over 15 percent), and transit buses are now consuming slightly less diesel fuel than they were in 1996, despite a steady growth in U.S. passenger miles taken by transit buses.

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[63] 13.1 mmt CO_2e for transit buses in 2007, compared to 1,568 mmt for all on-road transportation (U.S. EPA 2009).

Fossil Diesel

Despite the growth of alternative fuels and technologies, diesel is still the dominant fuel for the transit bus sector. Because of the high-energy density of diesel fuel and the thermodynamics of compression-ignition engines, diesel-powered vehicles tend to have good fuel efficiency. However, they emit have historically emitted relatively high amounts of certain types of air pollutants, including NO_x and particulate matter. Consequently, Federal regulations have increased emission standards for heavy-duty vehicles and required the use of ultra low-sulfur diesel, both of which increase the capital and operating cost of a transit bus somewhat (Clark et al, 2007). Since 2004, U.S. EPA's National Clean Diesel Campaign has been seeking to improve the environmental performance of diesel engines in many sectors through both regulatory and voluntary measures, and as a result, diesel engines are cleaner than ever (U.S. EPA, 2009b).

Compressed and Liquefied Natural Gas

While natural gas generally combusts more cleanly than diesel and gasoline, there are no clear greenhouse gas-reduction benefits from CNG or LNG buses (Clark et al, 2007) as total GHG emissions are about the same on a per-mile basis as for diesel buses. This is especially true if CNG is mishandled and leaks occur, since CNG is composed of 85-99 percent methane (IEA, 2002) a potent greenhouse gas. CNG has historically been cost-competitive compared to diesel fuel, but transit buses using CNG require an expensive fueling infrastructure consisting of high-pressure storage, compressors, and dispensers. The median costs of modifying CNG/LNG-ready bus depots and building refueling stations have been found to be around $875,000 and $2 million respectively (in 2007 dollars). However, once a fueling infrastructure is established, the operating costs of a CNG/LNG fleet can be lower than for other technologies, due to lower overall fuel and maintenance costs (Clark et al, 2007). However, CNG and LNG have lower energy content than diesel fuels, reducing the total driving range compared to diesel. There were 6,600 CNG and 1,000 LNG transit buses operating in the United States as of January 2005 (CCAP, no date).

Electric and Hybrid-Electric Systems

Electric and hybrid-electric vehicles are steadily growing in popularity across transit bus fleets. Pure electric vehicles, powered by on-board batteries, are quiet and do not directly emit pollutants into the atmosphere, characteristics that make them highly desirable in communities where a premium is placed on local air quality. Hybrid diesel-electric and gasoline-electric vehicles are powered in combination by an internal combustion engine and an electric motor. These buses can obtain 10 to 50 percent better fuel efficiency than their conventional diesel counterparts, with similar reductions in GHG emissions (IEA, 2002; Greene and Schafer, 2003; CCAP, no date). Actual in-service fuel efficiency improvements depend strongly on the duty cycle of the bus; hybrids are most advantageous when used on routes with more stop-start cycles, hills, and time where the bus is at rest (such as in traffic or at passenger stops). While hybrid diesel-electric systems are gaining in popularity, vehicles using this technology are still relatively expensive compared to most other alternatives, with a total unit cost of over $500,000 for a full-size heavy-duty hybrid transit bus, approximately $200,000 more than a conventional diesel bus of similar design. Operating costs of hybrid-electric buses also tend to be higher than other alternatives currently, due to the added expense of battery maintenance and replacement (Clark et al., 2007). Battery technology is advancing rapidly, however, which will likely drive down both the capital and operating costs of hybrid-electric buses while increasing their performance and durability. One study reported cost-effectiveness values for GHG reduction from hybrid transit buses at less than $140/tonne CO_2e (McKinsey, 2009). There were estimated to be approximately 1,100 hybrid buses in operation in the United States in 2006 (CCAP, no date).

Fuel Cells

Like batteries, fuel cells convert chemicals directly into electricity, the key difference being that a fuel cell will continue operating as long as it is supplied with fuel and air (to provide hydrogen and oxygen, respectively), while batteries will operate (on one charge) only as long as it takes to consume their self-contained reactants. Also like batteries, fuel cells are efficient, quiet and have no moving parts. Typically fuel cells are "hybridized" by combining them with batteries. Compared to buses powered by batteries only, vehicles equipped with fuel cells have longer driving range.

Fuel cell systems can be powered directly by hydrogen, which is the approach being pursued by most fuel cell bus developers today. Hydrogen can obtained from a central fueling source, or alternatively by using a reformer on the bus to separate hydrogen from a variety of fuels including natural gas, alcohol, or gasoline, although on-board reforming is not currently favored. Heat and water are the only direct emissions from a hydrogen-powered fuel cell, although the energy consumption and emissions from generating the hydrogen off-board the bus must be considered when comparing the merits of different fuel options. Hydrogen fuel cells, while viewed by many as the propulsion system of the future, will not likely penetrate into vehicle fleets in the numbers and time horizon called for in the Energy Policy Act of 2005 (U.S. DOE, 2009b). While the basic technology behind hydrogen fuel cells is well understood, many technological, institutional, and cost barriers are hindering widespread adoption of hydrogen fuel cells in transit (see Section 2.8 for a discussion of similar barriers to use in light-duty vehicles). On the other hand, the unique characteristics of transit vehicles (such as their once- or twice-daily starts in many cities) may make some fuel cell technologies viable in buses that would not be viable in automobiles. Because fuel cells have not yet become commercially viable, buses employing fuel cell technology are still heavily subsidized (IEA, 2002).

Biofuels

The use of biofuels in bus transit is growing, especially in municipalities that require that a percentage of diesel come from biomass sources (Biodiesel Magazine, 2008). Because the primary difference between buses operating with fossil diesel and biodiesel is simply the fuel used, there is little difference in capital or infrastructure costs. However, fuel costs can be higher for buses using B20, since the cost of B20 has historically been greater than that of conventional diesel (Clark et al., 2007). B20 also has slightly less stored energy compared to conventional diesel fuel, meaning that operating range is slightly reduced for a given tank size.

Other Transit Bus Technologies

Several other options comprise the balance of fuels used by transit authorities in the U.S. For example, propane has gaining been popularity in some areas because it can be less expensive per mile than diesel fuel, although capital costs related to converting buses to run on propane can be upwards of $5,000 (McCann, 2008), and the overall supply of propane is limited (since it is a byproduct of other petroleum product production) and its price tends to closely track gasoline with the exception of some seasonal fluctuations (see Section 2.5). Despite the recent interest in ethanol as a transportation fuel, it has not penetrated the U.S. transit bus sector to date.

Various agencies and departments within the U.S. government are actively promoting the development of advanced transit bus technologies. The FTA supports a grant program that assists transit authorities as they seek to improve the environmental performance of their fleets. DOE supports research and development into advanced transportation technologies through its Advanced Technology Vehicles Manufacturing Loan and Clean Cities programs. EPA manages several programs aimed to advance the development and penetration of advanced transit technologies, such as the above mentioned National Clean Diesel Campaign. Finally, the U.S. Department of Agriculture has been active in providing guidance related to the use of biofuels in their Alternative Fuels and Fleet Efficiency program (USDA, 2009).

3.5 Railroad Technologies

> **Railroad Technologies**
>
> *Per Vehicle GHG Reduction:*
>
> - Common rail injection systems: 5–15%
> - Genset engines: 35–50%
> - Hybrid yard engines: 35–57%
> - Hybrid line-haul operations: 10–15%
> - Light weight railcars, aerodynamics, wheel to rail lubrication: 4–10% individually
> - Improving load configuration for intermodal trains: up to 27%
>
> *Confidence in Estimates*: **Moderate**
>
> - Benefits of some technologies not well-documented
>
> *Key Cobenefits and Impacts*: **Positive**
>
> - Some technologies can significantly reduce pollutant emissions in populated areas
>
> *Feasibility*: **Moderate**
>
> - Mostly limited by railroad operator interest in/ acceptance of new technologies
>
> *Key Policy Options*:
>
> - Financial incentives for purchase of retrofits

Currently, there are approximately 23,000 locomotives operating in the United States (U.S. DOT, 2009; Weatherford, 2008), including line-haul locomotives that move freight over long distances, and yard or switcher engines that operate at or near a rail yard. Yard engines are involved in disassembling and combining freight cars into trains and are equipped with engines between 1,000 and 2,300 horsepower, consuming approximately 50,000 gallons of diesel fuel per year (CARB, 2008b). Yard locomotives with horsepower ratings less than 1,000 are referred to as "industrial locomotives" or "critters" and are expressly exempt from EPA locomotive emissions standards (EPA, 1997). Line-haul locomotives tend to be larger than yard locomotives and over time, are increasing in size to be able to carry more freight efficiently (Weatherford, 2008; Shurgart, 2007). Today's line-haul locomotives have an average horsepower rating of 3,600 (Weatherford, 2008), with the largest engines having a horsepower ratings greater than 6,000 (Stodolsky, 2002). A line-haul locomotive consumes between 250,000 and 500,000 gallons of diesel fuel per year (CARB, 2008b). Most rail fuel consumption and emissions—over 90 percent for Class I railroads that carry most of the freight in the United States—are associated with the operation of line-haul locomotives (Table 3.5A). The Class I railroads consume approximately 4 billion gallons of diesel fuel per year to move 1.8 trillion ton-miles of cargo.[64]

[64] Class I railroads, which currently include the seven largest railroads in the U.S., account for 67 percent of the industry's mileage and 93 percent of its freight revenue. They concentrate largely (but not exclusively) on long-haul, high-density intercity traffic lanes. Class II and III are smaller, regional and local railroads. In addition, switching and terminal (S&T) railroads primarily provide switching and/or terminal services (AAR, 2009).

Table 3.4 Class I Railroad Fuel Usage

Railroad Activity	Total Diesel Fuel Used in 2007 (Million Gallons)
Line-Haul Operations	3,710
Yard Switching	311
Total	4,022

Source: U.S. DOT (2009).

Rail represents one of the most efficient methods of cargo transport, requiring on average less energy and emitting fewer pollutants per ton of cargo moved than most other modes of surface transportation (Kruse et al., 2009; VTPI, 2008). Locomotives have become about 16 percent more efficient over the last decade, and currently emit approximately 24 g CO_2e/ton-mile (Stodolsky, 2002; SmartWay, 2009). Nevertheless, additional improvements can be made. DOE initiated a program in 2002 to improve rail fuel efficiency by 25 percent by 2010 and 50 percent by 2020 (relative to the 2002 base year), on a gallons per revenue ton-mile basis (Stodolsky, 2002). Greenhouse gas emissions also may be reduced by shifting freight from less-efficient trucks to rail; mode shift strategies are discussed in Chapter 5 of this report.

The primary means of railroad energy use and GHG emissions through vehicle technologies is through enhanced, more efficient power systems (Section 3.5.1). Other strategies also can be implemented to reduce weight, improve aerodynamics, and reduce rolling resistance (Section 3.5.2).

Power System Modifications

Overview

The primary technology-based methods for reducing emissions from locomotives involve modifications of the power system. These may include optimization of existing diesel systems, as well as the use of diesel-electric gensets and hybrid powertrains.

With regard to enhancements to existing diesel technologies, locomotive engines equipped with common rail fueling systems have the ability to control and optimize fuel injection which provides smoother, quieter running engines with better performance and greater combustion efficiency. Conventional diesel engines inject pressurized fuel into each cylinder at a rate dependent on the rotational speed of the engine. Common rail injection systems allow for a more controlled fuel injection rate across all engine speeds by storing fuel at high pressures along a common rail connected to each cylinder (MTU, 2008). High injection pressures generate very fine atomization of the fuel yielding more efficient combustion. Furthermore, common rail systems control the point in the engine cycle that fuel is injected into the cylinder and the duration of the injection (WSU, 2004). The largest common rail locomotive engine currently available has a maximum horsepower of 4,000, appropriate for use in yard and line-haul operations.

Genset yard locomotives use multiple smaller (~700 horsepower) diesel engines in conjunction with an electric generator and propulsion motors. Older locomotives can be retrofit with genset engines, which are newer and more efficient than larger conventional yard engines, and are certified to EPA Tier III emission standards. A genset's improved efficiency is due in part to the use of electronic engine controls to better match engine operations with locomotive activities. Electronic engine controls also reduce wheel slippage, which enhances traction. Additional fuel savings result from idle reduction technologies that shut off the engine when not needed. Currently, there are approximately 200 genset locomotives operating in the United States. In 2007, the Class I railway companies reported operating 1,298 yard locomotives. Since many of the Class II and III operators primarily use switch engines, the actual population of yard and switch engines is probably much larger.

Existing yard engines also may be retrofit with hybrid systems for efficiency improvements. These engines are equipped with small (~125–300 hp), highly efficient diesel engines similar to those found in gensets. These engines provide power to banks of long-life, recyclable batteries which run electric motors to turn the wheels. The engines operate only when the batteries need to be recharged (Frey and Kuo, 2007). Additional research is needed to evaluate battery maintenance and disposal. Hybrids are particularly suitable for yard activities as the weight of the batteries (approximately 25–50 tons) enhance traction (RailPower, 2006). Conventional yard locomotives operate in a "stop-go" manner at a variety of engine loads. This type of activity is inefficient as diesel engines have an optimal operating load, outside of which fuel consumption and emissions increase. 'Stop-go' operations also increase engine maintenance activities due to increased wear and tear on engine components. Operating in a "stop-go" manner is not an issue for hybrids, as their diesel engines only operate at a constant, optimal load when battery recharging is needed (CARB, 2006). As of 2006, 54 hybrids were in operation and 13 were on order (TrainWeb, 2006); these do not include a recent order by Union Pacific.

Additional improvements continue to be made in locomotive (and marine) diesel engine design, including use of advanced turbo charging over a wider range of operating conditions; application of turbo compounding which uses heat from engine exhaust to increase power and reduce fuel consumption; and the use of intercooling systems that increase the density of the intake air, which in turn increases the amount of air and fuel entering the cylinder, allowing for more efficient combustion (Bowman, 2004). Turbo charging is fairly common for newly manufactured engines, while turbo compounding and intercooling are relatively new (Stodolsky, 2002), but it is anticipated that new engine designs will regularly include these technologies over the next 10 to 15 years.

Electrification of railroad activities is another potential strategy involving railroad vehicle technology. Since electrification also represents a completely different fuel source, it is discussed in Section 2.9 under low-carbon fuel strategies.

Magnitude and Timing of GHG Reduction

Common rail injection systems are estimated to provide fuel and GHG emission reductions between 5 and 15 percent (CEC, 2008; Union Pacific, 2007). Genset engines can reduce fuel consumption and GHG emissions by 35 to 50 percent (NRE, 2008; Donnelly, 2004), and hybrid yard engine can reduce consumption by 35 to 57 percent (Railpower, 2006). In standard yard service, a single hybrid yard locomotive can reduce GHG emissions by 267 tons per year on average, with greater reductions where heavy-duty switching is carried out continuously (Railpower, 2006). For the most part, hybrid locomotives are primarily used for yard activities, though General Electric (GE) has recently developed a 4,400 horsepower hybrid for line-haul operations providing a 10 to 15 percent reduction in fuel usage and GHG emissions (General Electric, 2009). This equates to 189,000 fewer gallons of lifetime fuel consumption per locomotive compared to conventional diesel engines (GE, 2005; GE, 2006).

Market penetration potential is limited by the typical life of a railroad locomotive (often 30 to 40 years, with major overhauls every 600,000 to 1,000,000 miles (Stodolsky, 2002). On average only 900 new locomotives are manufactured every year (U.S. DOT, 2008; AAR, 2008; Stodolsky, 2002). With approximately 24,000 locomotives currently in operation, it would take at least 25 years for the current fleet to be replaced, without incentives for accelerated replacement. The unusually long fleet turnover time is of particular concern for these strategies, since most of the technologies are only appropriate for newly constructed engines rather than retrofit applications.

Estimates of potential fuel savings and emission reductions for line-haul operations are provided in Table 3.5D. These estimates assume that identified technologies currently are used in a limited capacity, but will achieve full market penetration by 2050. The list of technologies presented in the table is not additive; however, the options listed could essentially be implemented independent of each other, and therefore a maximum combined impact was estimated as the multiplicative percent impact of all strategies (e.g., 10 percent reduction for lightweight cars, then 10 percent of the remainder for aerodynamics). This results in a combined estimate of an 18 to 24 percent fuel savings, or 10.1 to 13.6 mmt CO_2e in 2050. Impacts for 2030 were estimated by assuming 50 percent market penetration of lightweight cars by that time, and 100 percent market penetration of aerodynamic improvements and wheel/rail lubrication systems.

Table 3.5D Projected Impact of Other Rail Fuel Economy Strategies

Technology	Anticipated Fuel Savings	Anticipated Annual Reduction in Fuel Use (Million Gallons)	Anticipated Reduction in GHGs (Million Tons)
Lightweight Cars	5 – 10%	264 – 528	3.0 – 6.0
Aerodynamic Improvements	> 10%	487	5.5
Wheel/Rail Lubrication Systems	4 – 6%	195 – 292	2.2 – 3.3
Combined Impact (2050)	**18 – 24%**		**10.1 – 13.6**

Combined Impact (2030)	**15 – 19%**	**8.7 – 10.8**

Uncertainty in this evaluation largely results from the limited number of applications to date. As such there is little data about how these options will perform under a wide range of operating conditions.

Cost-Effectiveness

The purchase cost of a new locomotive is typically between $1 and $2 million (CARB, 2008b; Railpower, 2006). Older locomotives can be converted to a genset or hybrid configuration at approximately 60 percent of the cost of a new conventional locomotive, and they typically last 20 years before they need to be reconverted. These conversions costs are approximately $600,000 to $1.2 million and are more expensive then an engine replacement using a conventional diesel engine (Railpower, 2006). As noted earlier, the Class I railroads currently are purchasing gensets and hybrids with financial support from States such as California and Texas.

New locomotive power system technologies are seen to be very cost-effective given the current and projected diesel fuel costs. For example, yard locomotives consume approximately 84,000 gallons of fuel per year (U.S. EPA, 2007c, 2009d) which equated to $308,000 per year at a price of $3.67 per gallon (per AEO forecasts for 2030). Assuming a 40 percent reduction in fuel consumption using gensets or hybrid engines (Railpower, 2006; NRE, 2008), a simple assessment of the payback period for a converted yard locomotive would be between five and 10 years, not taking into account discount rates.

The fuel savings associated with diesel locomotive engines with a common rail configuration are less dramatic than the yard engine options, although costs also are lower, leading to a similar payback period. Detroit Diesel manufactures common rail engines with a rating of 1,600 to 3,750 hp at a cost ranging $300,000 to $500,000 (Mangum, 2009). A typical line-haul locomotive uses 150,000 gallons of fuel per year (EPA, 1997) at a cost of $551,000 (at an assumed $3.67/gallon). A 10 percent reduction in fuel provides a cost savings of $55,000 per year, which would equate to a payback period between five and nine years.

Cobenefits

These strategies, particularly genset and hybrid locomotives, can result in significant reductions in air pollutant emissions, since engines can be run at an optimal speed and emission controls optimized for this speed. Potential public health benefits are greatest for applications at rail yards, which are often located in more densely populated urban areas, whereas most line-haul operation takes place in rural areas. In fact, incentive programs have been implemented in California and Texas, where genset and hybrid yard locomotives especially are viewed as a cost-effective means of reducing pollutant emissions (particularly NO_x and PM).

Feasibility

All of the locomotive engine technologies presented here are commercially available, though the hybrid line-haul locomotive is relatively new, with the first models being available in 2010 (GE, 2005; King, 2007). Despite long-term net cost savings to the railroad operator, capital costs represent a primary barrier to adoption of locomotive engine improvements. Hybrid engines are particularly expensive and market penetration for has been largely limited to States such as California and Texas that have programs that help subsidize their implementation through incentive programs. Gensets and common rail systems are less expensive options. Another limiting factor to penetration of these technologies is the slow rate at which the locomotive fleet turns over. Retrofitting existing locomotives with new engines, while less costly than replacing a locomotive, is still an expensive option. Older locomotives are typically passed down from Class 1 railroads to financially strapped short line operators, extending the life of old equipment in shorter distance operation.

The technologies discussed in this section may be encouraged through existing regulatory programs or through financial incentives to help overcome initial capital cost barriers and shorten payback periods. Implementing financial incentives may be more effective at the national level, to ensure that new locomotives and engines are provided to areas of the country that have the most rail traffic and that older, less efficient locomotives are taken out of service. There is some concern that the older locomotives that new genset and hybrid engines replace in California and Texas are not decommissioned, but are shifted to other States, exacerbating their air quality problems. Meanwhile, other States, regional air quality groups, and local governments are finding it difficult to encourage railroad companies to bring the new locomotives to their areas without providing similar funding initiatives.

Technologies also may be introduced through regulatory mechanisms. The EPA has established emission standards for NO_x, HC, CO, PM, and smoke for newly manufactured and remanufactured diesel-powered locomotives and locomotive engines. Three separate sets of emission standards have been adopted, with applicability of the standards dependent on the date a locomotive is first manufactured or when remanufactured (EPA, 1997). Though these standards have been developed relative to available engine and control technologies, similar standards could potentially be promulgated that encourage the use of more efficient engines that emit less greenhouse gases. The ability to do so may depend upon future interpretation of the Clean Air Act or other Federal legislation providing EPA with the authority to regulate greenhouse gases.

Finally, because rail freight operators operate in a competitive marketplace, they tend to have natural (cost saving) incentives to find ways to reduce fuel in the face of high prices, without government intervention. The future price of fuel—whether affected by market forces or government regulation—is likely to have a significant bearing on the adoption of more efficient rail vehicle technology.

Other Rail Fuel Efficiency Strategies

Overview

A number of non-engine-based rail efficiency improvement strategies currently are being implemented to varying degrees. For example, aluminum cars and wheel-to-rail lubrication systems have been commercially available for several years. There also has been some effort to improve the aerodynamics of freight trains, ranging from covering empty cars to shielding.

Aluminum cars were initially pioneered in the railroad industry in the late 1950s. Aluminum is highly durable and considered appropriate for a wide variety of railroad applications. For instance, aluminum offers excellent resistance to corrosion from high-sulfur coal. Furthermore, cars designed with aluminum extrusions require fewer structural components and can be as much as a third lighter than comparable steel cars (Rail Age, 1994). Use of such lightweight materials allows for cars with larger carrying capacity, which in turn allows for more freight to be moved per gallon of fuel (Frey and Kuo, 2007).

Freight trains use a considerable amount of energy to overcome air friction, due to the aerodynamically unfavorable profile of freight trains, unshielded space between cars, and lack of covers on empty cars (Lai, 2007 and Stodolsky, 2002). For example, a locomotive pulling open empty cars consumes more energy than when pulling full freight cars with a better aerodynamic profile. Intermodal trains also tend to have poor aerodynamic characteristics. Both the capacity and the aerodynamics of intermodal freight can be improved by using double-stacked cars (Lai, 2007). However, this approach may require infrastructure changes to ensure sufficient clearance in tunnels and bridges.

In addition to covering empty cars and modifying how intermodal cars are loaded, aerodynamics can be improved by reducing open areas that catch the wind as the cars are moved. For example, the bogie area of freight cars and area between cars are typically uncovered. In order to minimize drag, these areas may be covered with smooth and streamlined surfaces (IUR, 2008).

Energy also is expended by locomotives to overcome wheel-to-rail friction. Reductions in wheel-to-rail resistance can be made via improved lubrication (Stodolsky, 2002). Lubrication systems, such as top-of-rail systems, reduce wheel and rail wear as well as fuel consumption. Newly developed computer controlled systems limit the amount of lubricant applied to reduce excessive applications that lengthen required braking distances (IUR, 2008).

Magnitude and Timing of GHG Reduction

Light weight high-capacity railcars have been introduced by Canadian Pacific Railway, demonstrating a reduction of energy use by 10 percent for coal shipments and by 5 percent for grain shipments (NESCAUM, 2006). Improving the loading configuration for intermodal trains can reduce fuel consumption by as much as 27 percent, or up to 1 gallon/mile per train, although the potential for loading configuration efficiencies also is dependent upon shipper loading practices, including partially loaded boxes and empty-box backhauls. Other aerodynamic improvements can reduce fuel consumption up to 10 percent (Lai, 2007 and Stodolsky, 2002). Based on available field studies and manufacturer data, wheel-to-rail lubrication systems can reduce fuel consumption and GHG emissions between 4 and 10 percent (U.S. DOE, 2006b).

Industry-wide annual railcar production ranges from 17,000 to a peak of nearly 76,000, while aluminum car production ranges from 4,000 to 13,000 (Freight Car America, 2008; Wagner, 2008). Currently, there are approximately 1.3 million freight cars in use in the U.S (U.S. DOT, 2008). At the current rate that aluminum cars are being introduced it will take approximately 100 years to replace the existing population of cars, although this could potentially be accelerated through policy or market incentives. Some aerodynamic improvements, as well as lubrication systems, can be implemented on existing cars, yielding shorter-term GHG reductions.

Cost-Effectiveness

With the exception of lightweight cars, the technologies noted in this section have relatively low capital cost (Wagner, 2007). However, aluminum cars are not only lighter requiring less fuel to move, but can be constructed with higher carrying capacity that increases the amount of revenue cargo transported, such that the pay back period for new cars is approximately two years. Also, aluminum rail cars have high salvage value when their hulks are scrapped (Mangum, 2009).

Cost associated with the purchase of air shields, wheel-to-rail lubrication systems, and drive optimization software are often paid back within a couple of years, or more quickly as diesel prices escalate. It is estimated that using new computer controlled wheel-to-rail systems could save the industry between $500 million and $1.4 billion in fuel costs, increase productivity by allowing for increased speed and train length, and reduce maintenance activities by 25 percent (Mangum, 2009).

Cobenefits

Pollutant emissions should be reduced roughly in proportion to fuel savings and GHG reductions for these strategies. As noted under cost-effectiveness, aluminum cars can increase the amount of revenue cargo transported.

Feasibility

There are few barriers to implementation of these technologies, as they require little or no change in infrastructure and are not restricted by current railroad regulations. Their use may be encouraged through voluntary programs such as the EPA's SmartWay Program, which serves as a clearinghouse for information on environmentally beneficial practices, and offers public relations "branding" for those companies with notable environmental performance. Low-interest loan programs or tax incentives could potentially help overcome concerns about capital investment costs. Higher fuel prices will provide additional incentive for railroad operators to voluntarily implement these technologies.

3.6 Marine Vessel Technologies

Globalization of the economy has lead to increasing marine vessel traffic. For example, in 1970, 2.5 billion metric tons of freight were shipped by sea while in 2006, that value increased to 7.4 billion metric tons (IMO, 2008). Marine traffic includes shipment of raw materials, intermediate and final products around the world; 90 percent of global trade is carried by marine vessels (IMO, 2008). Marine vessels represent one of the most efficient methods of freight transport, as shown in figure 3.9, and furthermore, are the only option for transoceanic shipping, for all but the lightest and highest value goods.

Marine Vessel Technologies

Per Vessel GHG Reduction:

- 4–15% for ship design
- Up to 20% for diesel electric for vessels that change speed or load frequently (cruise ships, harbor tugs, and ferries)

Confidence in Estimates: **Low**

- Considerable range of estimates; benefits of some technologies not well-documented

Key Cobenefits and Impacts: **Positive**

- Some technologies can significantly reduce emissions near populated areas

Feasibility: **Moderate**

- Mostly limited by vessel operator interest in/ acceptance of new technologies and low fleet turnover rates

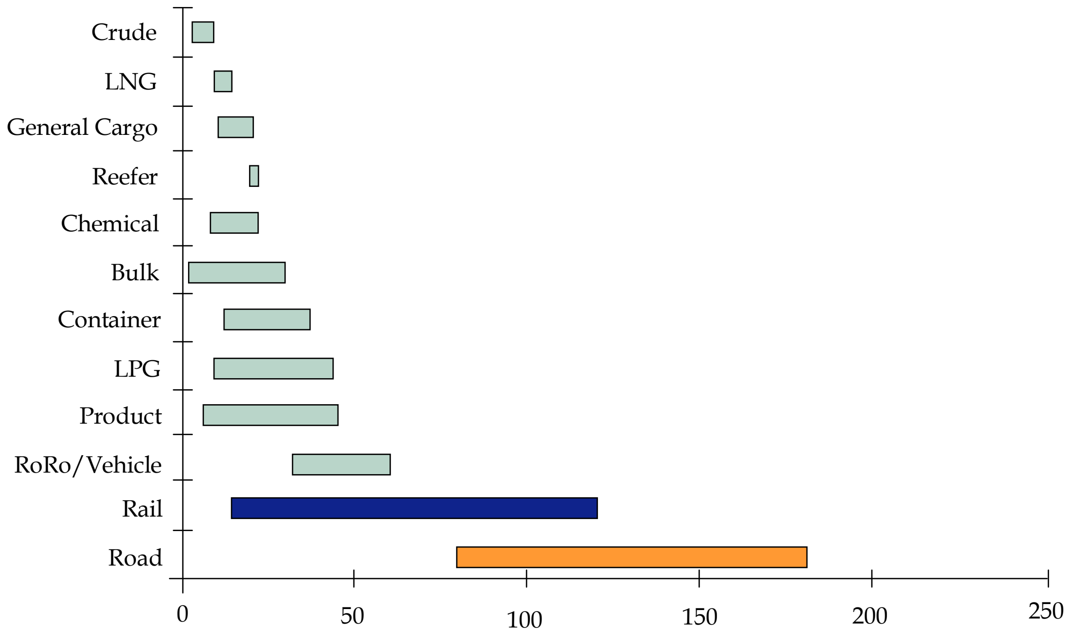
Key Policy Options:

- Work with international marine organizations to adopt technology standards and market and non-market incentives for fuel efficiency improvements
- Work with domestic operators (ports, ferry) to purchase efficient technology
- R&D for advanced technologies

Shipping activities can be split into international and domestic traffic. The international component includes approximately 100,000 vessels; about half of this fleet is involved in cargo shipments, including container ships, tankers, auto carriers, and general cargo vessels (IMO, 2008; Fairplay, 2009). Most of the international cargo fleet is equipped with large engines similar to land-based utility power generating equipment (EPA, 2003). These vessels operate in international, Federal, and coastal State waters, frequenting U.S. deep water ports operating along both coasts and the Gulf of Mexico. Vessels involved in domestic traffic include tugs, bulkers, ferries, offshore support vessels, and harbor craft that operate mostly in coastal and inland waterways. These vessels are equipped with smaller engines approximately the size of a large locomotive (EPA, 2007c).

Different policy channels will be appropriate for the international and domestic fleets. Since ocean-going vessels operating in international and sovereign waters around the world are flagged by many other countries, improvements would need to be encouraged through international agencies such as the United Nations' International Maritime Organization. International banking organizations also can play an important role in expediting the introduction of new technologies. For example, capital financing of vessels favors conventional vessel designs over innovative or "experimental" designs, which may apply to vessels equipped with the first applications of new environmental technologies (Corbett, 2009; Kuznik, 2008). The United States can require certain attributes on international ships entering U.S. waters, but such requirements can inhibit commerce and place U.S. ports at a disadvantage with Canadian and Mexican competitors.

Figure 3.9 Range of Typical CO2 Efficiencies for Various Cargo Carriers, g CO2/tonne-km



Source: Buhaug et al 2008.

Technology changes to the domestic fleet can be encouraged through existing Federal regulations for vessels subject to the Jones Act, U.S. EPA emission and fuel standards, and U.S. Coast Guard rules and regulations. Alternatively, programs such as the U.S. EPA's SmartWay program can be used to encourage voluntary changes to vessel fleets that provide for more efficient freight movement with less emissions (U.S. EPA, 2009d).

Improvements discussed in this report to increase the energy efficiency and reduce GHG emissions from commercial marine vessels include the following:

- Improvements to ship design to reduce hull drag;
- Propulsion system improvements such as diesel-electric hybrid systems;
- Improved propeller designs; and
- Advanced energy technologies such as solar and wind power.

Combined GHG Benefits of Marine Vessel Technologies

Consistent with the scope of this report, benefits are estimated only for the domestic marine fleet and for the portion of international shipping traffic attributed in the AEO's inventory to the U.S. According to the United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines, national totals of GHG emissions should reflect only domestic transport, including the domestic leg of shipments bound for foreign markets (i.e., operations within 200 miles of the coastline); international aviation and marine bunker fuel emissions from fuel sold to ships or aircraft engaged in international transport should be excluded from national totals (UNFCCC, 2006). However, differentiating domestic and international fuel consumption is often difficult, resulting in significant year-to-year variations in the official estimates.

The combined GHG benefits that could be anticipated from marine vessel improvements are estimated as follows. The range of ship design benefits (1-17.9 mmt CO_2e) is added to the range of propulsion system benefits (3.1-7.4 mmt CO_2e). While there may be some overlap between these categories, most of the ship design benefits will be realized for long-distance ships while propulsion benefits will primarily be realized for ships operating near-shore. Some additional benefits could be realized through wind and solar power, but these technologies are still speculative (particularly wind). The combined benefit is estimated to be 4.1 to 25.3 mmt CO_2e in 2050, with about two-thirds of these benefits realized in 2030 depending upon fleet turnover and phase-in of other technologies.

Improvements in Ship Design

Overview

In general larger ships provide efficiencies of scale and are capable of transporting more cargo per gallon of fuel than smaller vessels. This scaling effect has led to an increase in vessel size of about 4 percent per year for newly constructed vessels, with an increase in installed power at rates about 10 percent per year. This is more than twice the rate of growth in seaborne trade and is driven largely by growth in containerized shipping delivering intermodal cargoes to onroad and railway freight shippers (Corbett, 2007). The net growth in fuel use and GHGs is nearly proportional to the growth in cargo volumes. One of the reasons that fuel use trends are not increasing in direct proportion to increased installed power is that new vessels take advantage of improved hull designs and other technologies. These changes in hull design include application of ducktails and interceptor planes which extend the stern of the vessel and enhance propeller efficiency (Wartsila, 2008; Kanerva, 2006; Jaap, 2005).

Vessel efficiency declines when marine plants and animals accumulate on a ship's underwater hull causing fouling. Advances in vessels coatings, such as self-polishing resin systems based on hydrolysable acrylate polymers, inhibit fouling, and provide a smoother surface (Royal Caribbean International, 2008; Kiil, 2001). Similarly, vessel efficiency also can be improved by injecting small amounts of air in the turbulent boundary layer underneath the ship (Wartsila, 2008; Okada, 2008; Technology Demark, 2007; Katsui, 2003). As a result, drag is reduced through the movement of the air bubbles and the formation of a thin film of air along the vessel's hull. This technology has been tested and optimized in a towing tank and currently is being piloted on a 250-foot multipurpose vessel (Technology Denmark, 2007).

In general, the vessel design technologies discussed in this section are commercially available. While hull designs can only be introduced on new vessels, interceptor planes, ducktails, and air injectors can be added as retrofits, though these changes can be made more cost-effectively during new vessel construction. Their application has been limited by the cost for retrofits; for example, interceptor plates with ducktails can cost millions of dollars to install (IMO, 2009).

Magnitude and Timing of GHG Reduction

Use of larger containerships, tankers, and bulk carriers allows for more efficient movement of cargo. Generally a 10 percent increase in ship volume can improve fuel efficiency by 4 to 5 percent in terms of gallons of fuel needed per ton-mile transported (Wartsila, 2008). However, this can vary depending upon the vessel type and operation.

Reducing vessel displacement by increasing the hull width by only 0.25 meters allows for a reduction of 3,000 tons of ballast, reducing propulsion energy requirements by 8.5 percent (Wartsila, 2008). Use of interceptor or trim planes can improve fuel consumption by 1 to 4 percent, or up to 10 percent if the interceptor or trim plane is used in conjunction with a ducktail (Wartsila, 2008; Hansen, 2008; Jaap, 2005). Air lubrication systems can improve fuel efficiency from 3.5 percent for ferry operations to 15 percent for large tankers (Wartsila, 2008; Technology Demark, 2007; Frey and Kuo, 2007; Katsui, 2003).

Given that the lifespan of large commercial vessels is over 35 years, fleet turnover is slow, roughly 2 percent of the fleet per year (EPA, 2002). Accordingly it will take nearly half a century to incorporate current new hull designs into the global fleet.

Estimates of potential fuel savings and emission reductions are provided in Table 3.6A. Information on the efficiency benefits of different technologies is quite limited and can vary significantly depending upon the characteristics of the specific vessel being modified (i.e., long-haul operations such as tankers and containerships, versus vessels whose operations can change frequently such as cruise ships and tugs). As a result, a considerable variation in the range of potential benefits is shown in Table 3.6A. These estimates assume that identified technologies currently are used in a very limited capacity or not at all, but will achieve full market penetration by 2050 if programs to encourage the application of these technologies are put in place in the near future. Combined benefits could potentially range from 1.0 to 18 mmt CO_2e. With a 25- to 40-year turnover cycle typical for marine vessels, benefits in 2030 could be in the range of half to three-quarters of the 2050 benefits, or up to 12 mmt CO_2e assuming a two-thirds turnover. 2030 benefits could potentially be higher if policies and/or market forces lead to accelerated fleet replacement.

Table 3.6A Projected Impact for Ship Design Technology Strategies

Strategy	Ship Types	Anticipated Fuel Savings (Percent)	Anticipated Annual Reduction in Fuel Use (Million Gallons)	Anticipated CO_2 Reduction (Million Tons)
Enhanced Ship Design	Tankers/Bulkers	2 – 35 %	21 – 364	0.23 – 4.11
	Container		42 – 741	0.48 – 8.37
	Roro[a]		9 – 163	0.11 – 1.84
	Passenger		8 – 135	0.09 – 1.52
	Offshort Support Vessels		10 – 180	0.12 – 2.03
Interceptor Planes	Roro	4%	19	0.21
	Ferry		15	0.17
Ducktails	Container	7%	148	1.67
	Roro		33	0.37
	Ferry		27	0.30
Bubble (Air) Lubrication	Tankers/Bulkers	10 – 15%	104 – 156	1.17 – 1.76
	Container		212 – 318	2.39 – 3.59
Combined (2050)	**All Categories**	**2 – 35%**		**1.0 – 17.9**
Combined (2030)		**2 – 24%**		**0.7 – 12.0**

Note: Assuming vessel split obtained from Corbett, Firestone, and Wang (2007) and projected fuel usage based on 2009 AEO data.

[a] Roll-on/roll-off, or ships or ferries designed to carry wheeled cargo

Cost-Effectiveness

The capital cost associated with interceptor planes and ducktails can be a significant barrier to implementation, particularly if the modifications are made to existing vessels rather than applied to vessels that are under construction (Mangum, 2009). The cost associated for installing bubble lubrication systems run from $0.5 to 1.0 million per vessel (Mangum, 2009). The anticipated fuel savings for these modifications often justify the modification costs.

Cobenefits

Minor environmental cobenefits are expected from these strategies, as pollutant emissions should be reduced roughly in proportion to fuel consumption. These benefits will be most significant for domestic vessels operating in near-shore waters, where emissions will result in the greatest population exposure.

Feasibility

The marine vessel technologies presented in this section are all viable and commercially available. Two of the limiting factors to implementation of these technologies are the high cost associated with these changes and the slow fleet turnover rate. Policies that provide incentives for the retrofit of these technologies, or facilitate a more rapid fleet turnover, will accelerate the environmental and economic benefits.

Given the international nature of marine shipping, improvements to the global fleet may need to be encouraged through international agencies and organizations which are involved in regulating vessel operations, fuel usage, and setting vessel construction standards. International insurance and banking agencies also may be recruited to ensure that financing policies facilitate the application of reduced GHG environmental technologies.

Propulsion System Improvements

Overview

Many of the engine improvement technologies discussed in the locomotive section of this report, such as common rail configuration, advanced turbo charging, and turbo compounding, have been applied to newly constructed vessels or during engine retrofit programs over the past decade. For example, Wärtsilä, the leading manufacturer of large marine engines, began marketing a range of slow-, medium-, and high-speed common rail engines in 2001. By 2008, Wärtsilä received orders for over 700 common rail engines.

Typically diesel engines provide power directly to a vessel's propellers. For such vessels, fuel consumption and emissions tend to be higher when the engines are not operating at their optimum speed and load rating. In a diesel-electric configuration, however, a series of diesel generators are run at an optimized level, providing power to an electric motor which in turn drives the vessel's propellers. Similar engine configurations have been used in naval submarines, but it was not until the mid 1990s that this technology was applied to cruise ships (Moretti, 2002; Kanerva, 2006; PJK, 2006). For example the largest cruise ship currently in operation is the Royal Caribbean's *Freedom of the Seas*, which is equipped with 6 Wärtsilä 46 V12 diesel engines that use a common rail fuel injection system (Royal Caribbean, 2009). Each of these engines is rated at 12.6 megawatts, providing a total output of over 100,000 horsepower (Wartsila, 2009).

The advantages in using diesel-electric systems apply to vessels that operate over a wide range of loads such as cruise ships, tugs, and roll-on/roll-off ferries. For vessels that primarily operate at a constant and optimal load such as containerships and tankers, total plant efficiencies with traditional diesel propulsion may be higher than with diesel-electric systems, such that there is little fuel advantage to using this configuration for these long-distance vessels.

Hybrid systems also are being developed that are very similar to diesel-electric systems in that they operate smaller, more efficient diesel engines to power a generator which in turn generates electricity for charging batteries or during periods of high demand, for the propulsion motors. Hybrid technology has been considered for smaller marine vessels such as harbor tugs and ferries which operating under a wide range of transient loading (Foss, 2008; New York City Government, 2008; Workboat, 2008). Additional information is needed to evaluate whether hybrid technologies provide significantly different benefits (i.e., better propulsion plant efficiencies) to marine vessels than diesel electric configured vessels or traditional marine diesel system designs.

Nuclear powered commercial marine vessels could reduce greenhouse gas emissions, but the commercial application of this technology is complicated. Currently, there are 150 nuclear powered vessels operating globally; this vessel population is composed primarily of military vessels (e.g., submarines and aircraft carriers) or government agency ice-breakers. Attempts have been made in the past to development nuclear merchant ships, but these projects have failed for technical, economic, or political reasons. For example, the U.S.-built *NS Savannah* and the German-built *Otto Hahn* were decommissioned because they were too expensive to operate, partly due to safety concerns and insurance issues involving the use of nuclear power in civilian ports (Schmitt, 2009). The Japanese *Mutsu* was dogged by technical and political problems (World Nuclear Association, 2008). Current concerns regarding national security (e.g., piracy and terrorism), complex maintenance issues (e.g., refueling, preventive and scheduled maintenance activities), and longer-term issues concerning disposal of spent rods and decommissioning of vessel reactors, make this technological option more complicated to implement then other technologies presented in this study. For these reasons, this report evaluates implementation only of nonnuclear technologies.

Magnitude and Timing of GHG Reduction

The fuel savings for diesel/electric systems in vessels that frequently change speed or load, such as cruise ships, harbor tugs, and roll-on/roll-off ferries, can be as much as 20 percent, although depending upon operations, actual fuel savings may be less (Wartsila, 2008). Where applications are appropriate for hybrid engines, fuel and emission reductions can be as much as 35 percent (Wartsila, 2008). For marine propulsion application, common rail engines provide a fuel improvement around 1 percent. Wärtsilä has combined the common rail technology with enhancements to turbo charging to providing addition improvement in efficiency of 2 percent (Wilk, 2008).

Early introduction of diesel/electric and hybrid technologies is possible as each option can be applied as a retrofit, though hybrid options are easier to apply on newly constructed vessels. For the purposes of this analysis it is assumed that cruise ships have a diesel/electric configuration and therefore additional penetration of this technology to these vessels is not significant.

Costs

According to the literature cited above, fuel costs savings over the life of the vessel typically outweigh increased, upfront technology costs for these engine technologies. The most effective use of the propulsion technologies discussed in this report are with vessels whose operations vary frequently, such as roll-on/roll-off vessels, harbor ferries, offshore support vessels, and assist tugs. The cost of including diesel/electric configured engine systems into new vessel construction increases the cost of a vessel by approximately 15 percent (Mangum, 2009). There are cases where older cruise ships have been modified to use these systems, but information concerning the retrofit cost is not readily available. Regarding hybrid marine vessel technologies, the limited applications of this technology make it challenging to accurately assess the incremental cost of this option. Estimates of the increased cost of hybrid systems vary from 30 percent (Mangum, 2009) to 85 percent.

Cobenefits

These strategies can result in significant reductions in air pollutant emissions, since engines can be run at an optimal speed and emission controls optimized for this speed. Potential public health benefits are greatest for applications in near-shore activities such as ports, ferries, and inland waterways, which are often located in more densely populated urban areas, whereas most line-haul operation takes place in rural areas. These also are the applications in which fuel savings tend to be greatest. In fact, incentive programs have been implemented in California and Texas, where genset and hybrid marine vessels are eligible for financial incentives if they meet cost-effectiveness criteria for NO_x pollutant emission reductions.

Feasibility

The diesel/electric engine configuration is a technology that has been successfully applied to a variety of marine applications. In contrast, marine electric hybrid technology is relatively new and operating constraints are not fully understood at this time. Since the diesel/electric option is appropriate for vessels involved in international travel such as cruise ships and roll-on/roll-off vessels, it would be necessary to work with international organizations to encourage the application of these technologies in these situations.

For both the diesel/electric and hybrid configurations, a barrier to implementation is the initial capital cost, whether applied to new ship construction or as a retrofit. Other potential barriers include service requirements, operating and maintenance differences, mechanical crew staffing requirements, and space constraints. Increased fuel costs over time should provide greater incentives for the introduction of these technologies.

State and Federal tax incentives could play a significant role in encouraging use of these engines. For example, California and Texas offer incentives to replace or re-engine smaller vessels such as harbor tugs with newer, more efficient engines that emit less pollutants. While these programs target criteria pollutants and precursors rather than greenhouse gases, to the extent that emission reduction technologies are more efficient, GHG benefits also will be realized. Similar programs could be offered on a nationwide basis.

Enhanced Propeller Design

Overview

Conventional fixed-pitch propellers are most efficient at one rotational speed and load condition, with the propeller utilizing the maximum amount of power from the engine. At any other rotational speed or operating load, a fixed-pitch propeller is either "over-pitched" or "under-pitched," which leads to a reduction in fuel efficiency and an increase in emissions. Controllable-pitch propellers have been designed to optimize efficiency for any speed and load condition. As with diesel/electric configurations, the fuel and emission benefits associated with controllable-pitch propellers are most apparent for vessels that frequently change speed or load such as harbor vessels, cruise ships, ferries, and roll-on/roll-off vessels.

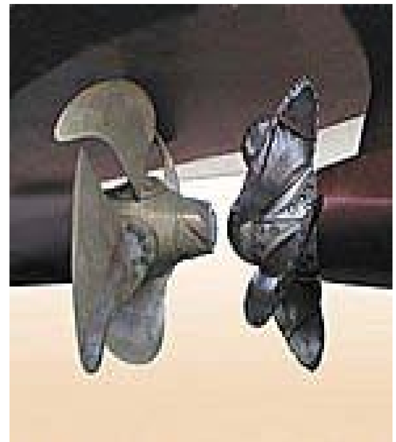


Figure 3.10 Counter-Rotating Propellers

Counter-rotating propellers include a pair of propellers positioned along the same axis as the standard propeller, as shown in Figure 3.10 (Ämmälä, 2006). Counter-rotating propellers can be configured as independent propellers or can be coupled together, but have independent drive shafts that rotate in opposite directions. In this configuration the rear propeller recovers rotational energy from the front propeller, which is used to generate power for the vessel's electrical system (Frey and Kuo, 2007).

Figure 3.11 Nozzles Enclosing Propeller to Reduce Friction Losses

To obtain the maximum thrust for propulsion, a propeller must quickly move large volumes of water. Friction losses occur at the tip of each blade as water escapes from the high pressure to the low-pressure side of the blade, reducing the effectiveness of the propeller. Large nozzles that enclose the propeller (as shown in Figure 3.11) reduce friction loses by restricting water flow to the propeller tips. At the entrance of the nozzle the diameter is greater than at the trailing throat. This design forces the water to accelerate from the front of the nozzle to the rear, increasing the speed of the water as it reaches the propeller, and allowing the propeller to move more water and create more thrust for the same input power and torque (Rice, 2009).

Another approach to reducing friction loss at the tips of propeller blades involves the application of tip winglets (Lumin, 2005; Technical University of Denmark, 2006; European Commission, 2002). This approach is similar to the wing tip devices used for aviation that prevent vortex formation. This technology was initially used in recreational vessels, but has evolved into applications appropriate for larger commercial marine vessels (Technical University of Denmark, 2006) and has been evaluated by the European Commission's BRITE technology program (European Commission, 2002) for larger vessel applications.

The benefits of improved propeller design are maximized when coupled with control systems that optimize engine performance based on vessel speed, propeller torque, and propeller thrust.

Magnitude and Timing of GHG Reduction

Counter-rotating propellers improve fuel efficiency and reduce GHG emissions by 10 to 15 percent (IMO, 2009; Ämmälä, 2006; Wartsila, 2008). Add on devices such as propeller nozzles can improve fuel efficiency by up to 5 percent (Rice, 2009; Hansen, 2008) while propeller winglets can improve propeller efficiency up to 4 percent (Technical University of Denmark, 2006; Lumin, 2005). Because some of these devices address the same drag forces, combinations of these technologies will not necessarily provide an additive reduction in fuel use. These technologies can be retrofit to existing ships, though some configurations of controlled-pitch and counter-rotating propellers are easier to implement for newly constructed vessels. Adding propeller nozzles and using propellers with winglets can be implemented at any time. Because propeller technologies are relatively easy to implement, it is unclear to what extent these technologies are being used in today's fleet, particularly with regard to the domestic U.S. fleet; therefore, quantitative estimates of potential additional GHG reductions are not shown. Counter-rotating propellers are a relatively new technology and it is likely that their use is not as extensive as controlled-pitch propellers, nozzles, or winglets.

Cost-Effectiveness

All of the propeller technologies discussed in this section are cost-effective for most vessel operations due to reduced fuel consumption rates. Some of the lower cost options such as use of propeller nozzles and winglets are particularly attractive to domestic tug and tow boat operations, providing a pay back period less than two years (Ship Propulsion Solutions, 2009). While counter-rotating propeller and controlled-pitch propellers are higher cost options, they also are associated with larger fuel reductions.

Cobenefits

Significant cobenefits are not expected from these strategies, although criteria pollutant emissions may be reduced in proportion to fuel use.

Feasibility

Many of these propeller technologies are relatively inexpensive to implement and therefore require little assistance from policy-makers to encourage their use. These technologies may be promoted through voluntary programs such as the EPA's SmartWay

Program, which serves as a clearinghouse for information on environmentally beneficial practices, and offers public relations “branding” for those companies with notable environmental performance. Increased fuel costs over time should provide greater incentives for the introduction of these technologies.

Future Technologies

Overview

In addition to conventional propulsion system improvements, fuel consumption for larger vessels can be reduced by using wind and solar power. Windpower options include wing-shaped sails made from composite materials (i.e., wing sails) (Cousteau Society, 2003), large kites attached to the bow of the ship (SkySail, 2008), and rotary sails (actually wind turbines) (Enercon, 2009). These have been tested on cargo ships and tankers up to 160 meters in length (SkySail, 2008; Hansen, 2008; USCG, 2009). Currently, wind powered options are being studied by the Technical University of Berlin for different sail types, vessel types, operating speeds and routes.

Flettner rotors (Figure 3.12) are large vertical devices that use the wind to spin rotors to generate electricity, which is either stored in batteries or used directly for propulsion (MarineBuzz.com, 2008). Enercon, a German wind technology company, has recently launched a large vessel equipped with Flettner rotors, which will be put into service in 2009 (Enercon, 2009).

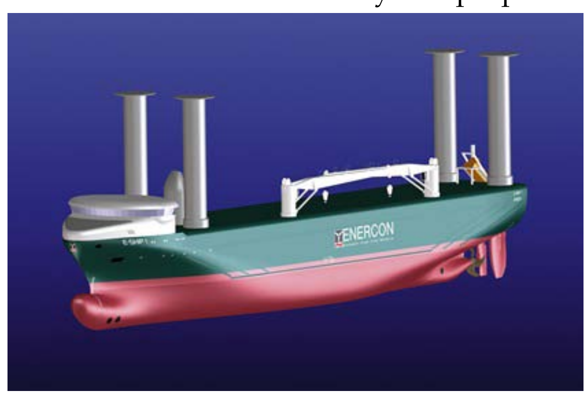


Figure 3.12 Flettner Rotors

Solar panels capable of generating several kilowatts of electricity have been used for years on large vessels to provide power for the crew’s living quarters. Photovoltaic technologies are now being scaled up in pilot studies commissioned by major shipping companies as a way to reduce fuel consumption and GHG emissions associated with propulsion systems. For example, 328 solar panels, each capable of generating 40 kilowatts of electricity, were recently placed on top of a 60,000 tonne car carrier used by Toyota Motor Corp (NYK Line, 2009; Okada, 2008). Hybrid solar/wind systems that use aluminum sails covered with photovoltaic panels have been applied to small ferry operations in Sidney, Australia since 2000 and currently are being considered by San Francisco’s Alcatraz Ferry Service and San Diego’s Harbor Ferry Service (SolarSailor, 2008). In October 2008, China’s COSCO marine transport company commissioned work

Figure 3.13 Solar Wings

to retrofit solar wings to a tanker ship and a bulk carrier (Figure 3.13) to evaluate the potential fuel savings associated with these technologies (Macdonald-Smith, 2008; Transportation and Logistics News, 2008; SolarSailor, 2008).

Magnitude and Timing of GHG Reduction

Solar powered systems, such as that used by Toyota, can provide energy for the demand for electricity to provide lighting for navigation purposes and for quarters, other navigational devices such as radar, weather tracking systems and smaller cargo handling equipment. Such systems have been shown by Toyota and Solar Sailor to reduce energy demand by 5 to 7 percent (NYK Line, 2009; Solarsailor, 2008). Use of wind power has proven to be even more significant, providing a fuel savings and GHG emissions reduction of 20 to 40 percent (reference). Both of these technologies are particularly applicable for larger vessels with extensive surface areas that are involved in long-distance trade.

Cost-Effectiveness

There is limited cost data available for these emerging technologies. Many are in their early stages of development and the costs associated with demonstration projects are considerably higher than anticipated future costs when these systems are fully commercialized. At this time, photovoltaic options are relatively expensive, due primarily to the cost of photovoltaic panels, which currently are not cost-competitive for electricity generation in most applications. The system used in the Toyota auto carrier cost $1.4 million to develop and install (NYK Line, 2009).

Cobenefits

Minor environmental cobenefits may be realized from these strategies, as pollutant emissions should be reduced roughly in proportion to fuel consumption. Solar power may reduce emissions in ports even while the ship is not in transit, which may benefit air quality near the port. Wind power will provide benefits on the open ocean, and therefore the air quality benefits for human population exposure are not likely to be significant.

Feasibility

Though wind and solar powered systems have been in existence for a while (particularly, vessels equipped with sails) their application on large modern vessels should be considered innovative, requiring additional research and development before commercialization can occur. Investments associated with solar and windpower technologies are particularly attractive as many of these options can be applied as retrofits to existing vessels. At this time, the most significant barrier to implementation is the high capital costs. International R&D initiatives may be needed to reduce capital cost for these technology options, especially windpower. Reductions in solar photovoltaic technology costs are likely to be driven by forces in the broader electricity generation sector, rather than marine-specific initiatives. Increased fuel costs over time should provide greater incentives for the introduction of these technologies.

3.7 Aircraft Technologies

> **Aircraft Technologies**
>
> *Per Aircraft GHG Reduction:*
> - Advanced engine technologies: 10 – 30%
> - Conventional airframe / wing retrofit: 1.6 – 10%
> - Blended wing body design: 20 – 40%
>
> Fleet-wide GHG Reduction:
> - Annual reduction of 1.4%-2.3% during 2015-2035 with 2015 as the base year.
>
> *Confidence in Estimates*: **Moderate**
> - Some technologies demonstrated; feasibility of others not yet determined
>
> *Key Cobenefits and Impacts*: **Unknown**
>
> *Feasibility*: **Moderate**
> - Requires long-term commitment and considerable investment for some technologies
> - Blended wing design requires airport infrastructure changes
>
> *Key Policy Options*:
> - R&D for advanced technologies
> - Demonstration programs / partnerships
> - Financial or regulatory incentives to accelerate new technologies

Internationally there are approximately 20,000 commercial aircraft in operation, of which 12 percent are involved in cargo operations (U.S. DOT, 2008; SmartWay, 2009) and the remainder in primarily passenger operations. (Passenger aircraft also often carry cargo.) In the U.S., the commercial air carrier fleet accounts for 7,000 aircraft of which 1,300 (19 percent) are dedicated to freight shipments (U.S. DOT, 2009; SmartWay, 2009). With this large fleet involved in diverse freight and passenger activities, there are a variety of factors that the introduction of new technologies. Some factors include stringent safety standards, aircraft performace demands, extremely high costs of transitioning to newer generation aircraft fleets, and tradeoffs among environmental performance properties such that reducing one environmental impact may increase another.

Incentives are important because costs for developing new large commercial aircraft can be restrictively burdensome (ADL, 2000). For example, Airbus spent $15 billion to develop the new A380 aircraft which currently is selling for approximately $330 million, at which price Airbus will need to sell 420 aircraft to break even (Babka, 2006). Given the expense of large commercial aircraft there are economic drivers to keep a given model in service for as long as profitable (ADL, 2000). For example, the Boeing 747 was initially constructed in 1970 and while there have been significant improvements in performance with each subsequent version of the B747, several of the earliest models are still operating (SmartWay, 2009), such that the average age of the Boeing B747 fleet is approximately 25 years (U.S. DOT, 2009). This means that technology turnover may operate on a longer timeframe than fleet turnover, further slowing the introduction of new technology.

Contrasting the economics of aircraft manufacture, aircraft fuel consumption typically represents 20 to 30 percent of an airline's direct operating costs (ICAO, 2006). Given the significance of aviation fuel costs, the industry has historically been aggressive in pursuing improvements to aircraft engine and airframe design that result in a reduction in fuel consumption and emissions. Commercial aircraft sold today are about 70 percent more fuel efficient per passenger-mile traveled than 40 years ago (ADI, 2007; ICAO, 2006, 2008; ADL, 2000). According to the ICAO, an additional 20 percent improvement in fuel efficiency is targeted by 2020 (ICAO, 2008).

Engine efficiency improvements reduce fuel consumption and also pollutant emissions. Without advances in low NO_x combustor technology, however, NO_x emissions also may increase as engines are made more efficient (Jamin, 2004; Morris, 2009; ADL, 2000), providing a small offsetting GHG disbenefit.

Aircraft efficiency improvements are discussed in two categories: 1) engines, and 2) airframe and wing design. Some airframe and wing technologies are available for retrofit, but in general, the most significant advances to aircraft efficiency will come with the introduction of new aircraft and engine designs.

Advanced Engine Technologies

Overview

Jet engine design has continued to evolve since the introduction of jet engines for commercial applications in the 1950s. Engine efficiency improvements currently are being made by increasing fan bypass ratios, increasing compressor pressure ratios and combustor temperatures, and improved component efficiency (ADI, 2007). This is possible through the application of improved design methods using advanced numerical simulations, and use of high temperature materials and new light weight engine components constructed of powdered metal alloys and carbon fiber composites. These new materials allow for improved engine designs, reducing fuel consumption, and are often more durable, reducing maintenance requirements (GE, 2008).

General Electric recently developed a new line of GEnx jet engines employing new designs and materials that reduce both GHG and criteria pollutant emissions. Currently, these engines are an option for Boeing's new 787 Dreamliner, a mid-sized wide-body jet (Boeing, 2004) and Boeing's new 747-8 aircraft (Boeing, 2006). These improvements in current engine design are anticipated to continue through the Leading Edge Aviation Propulsion (LEAP) 56 program development program (CFM, 2007). Pratt & Whitney has developed a high-bypass geared jet engine (PW1000 G) which currently is being tested for smaller regional jet applications, but also is applicable for larger aircraft such as Boeing's 747- SP and Airbus' A340-600 (Pratt & Whitney, 2008). This geared jet engine allows the engine fan to operate at a slower, more optimal speed while the low-pressure compressor and turbine operate at their optimized higher speed (ADL, 2000).

Several companies such as GE, Rolls Royce, and Pratt & Whitney are working on an open rotor engine where propeller blades are geared to the turbine and mounted outside the casing. Such designs can be lighter and provide higher efficiency. However, there are several factors that may limit the application of open rotor engines. For example, they are too large to be mounted under-wing (of current aircraft), typically are most appropriate for lower cruise speeds, and tend to be louder than shrouded fan configurations.

There also is a significant secondary benefit to improving jet engine efficiency. As less fuel is needed, the total weight of the aircraft is reduced which further reduces fuel consumption and emissions.

Magnitude and Timing of GHG Reduction

GE's GEnx engine design reduces fuel consumption between 10 and 15 percent relative to the engine that it is designed to replace, and further improvements of 10 percent are targeted under the LEAP 56 program. Pratt & Whitney's PW1000 G projects similar fuel savings as the GEnx engine (Pratt & Whitney, 2008). Open rotor engines have been shown to reduce fuel consumption by 10 to 30 percent (Morris, 2009; ICAO, 2008; Flight International, 2007a, 2007b; JHA, 2008; SBAC, 2008).

Cost-Effectiveness

Economics is probably the most important factor encouraging adoption of more fuel efficient aircraft engines. Fuel prices have been volatile in recent years; the price of jet fuel increased significantly since January 2002 when it was approximately 75 cents per gallon to $3.83 in the fall of 2008, but then fell to $1.89 per gallon in June 2009. The new GEnx engine is anticipated to reduce annual fuel costs by over a million dollars per year per aircraft, based on AEO fuel price forecasts of $3.33 per gallon.

Cobenefits

Cobenefits of these strategies may be realized through reduced air pollution in the vicinity of airports, especially with new engines that also are designed to minimize criteria pollutants. For example, GE's GEnx engine design produces fewer emissions than the maximum allowed by 2008 international standards (94 percent fewer hydrocarbon emissions and 57 percent nitrogen emissions), while consuming at least 15 percent less fuel than the engines they replace (e.g., CF6-80C2) (ICAO, 2008; GE, 2009; Gates, 2006). On the other hand, some efficiency improvement technologies, notably high thrust engines that operate at higher temperatures, can potentially increase NO_x emissions. In addition, as noted, open-rotor engines are noisier than current engines, which may create impacts on residential areas near airports.

Feasibility

The engine technologies presented here are all viable, but at different levels of commercialization. For example, the GEnex engines are commercially available, while testing of the geared turbofan was initiated in the summer of 2008. In 2009, GE and NASA began wind tunnel tests on the open rotor engine design.

Fuel prices can be a driver for adopting the engine technologies discussed in this section, but this is offset by the high capital cost of the aircraft which acts as a factor to extend the active life of the aircraft (and engines) as long as possible. The slow rate at which the aircraft fleet turns over, particularly the larger aircraft (20 to 30 years), is an issue at this time when declining air traffic has reduced demand for new aircraft, leading to excess capacity. Policies that encourage replacing older, less fuel efficient engines with new engines could accelerate the environmental and economic benefits associated with these technologies; however, the specific design or potential impact of such policies has not been investigated.

Advanced Airframe/Wing Design

Overview

The airframe is responsible for approximately 50 percent of an aircraft's gross weight. Use of advanced lighter and stronger materials in the structural components of the airframe, such as aluminum or titanium alloy and composite materials, can reduce airframe weight leading to reduced fuel use (Barzega, 2008; ADL, 2000; IPCC, 1999). Such materials are being used increasingly for aviation. For example, composites will make up approximately 50 percent of the airframe structure of the Boeing 787 Dreamliner, a sharp increase from the 9 percent figure for the Boeing 777 (Boeing, 2009). The International Civil Aviation Organization (ICAO) estimates that adoption of these materials can reduce an aircraft's structural weight by 15 percent.

Figure 3.14 Multilayer Panels on Tail Fins

Figure 3.15 Winglet

A large portion of the energy used by an aircraft is to overcome aerodynamic drag, including skin friction and induced drag. As such, drag reduction can significantly improve the fuel efficiency of airplanes and reduce emissions. Efforts to reduce "skin friction" drag include the use of an adhesive-backed film with micro-grooves placed on the exterior surfaces of the wings and the fuselage. However, the lifetime of the micro-groove film is only two to three years, after which it needs to be reapplied. The fact that the film needs to be maintained frequently may limit the viability of this technology as the effectiveness and fuel savings are relatively small and the ongoing maintenance costs are unknown.

Skin friction drag also can be reduced by maximizing laminar flow. Designing the wing with favorable pressure gradients and mechanisms to protect the wing surface from accumulating matter such as insect carcasses can enhance laminar flow. Alternatively, systems have been studied utilizing multilayer panels on the wing surface that allow air to be sucked through pores on the outer layer and vented away from the wing (Barzega, 2008; Reneaux, 2004; ADL, 2000; IPCC, 1999). These designs were demonstrated by Airbus on the tail fin of the A-320 aircraft in 1998 (Barzega, 2008; AeroStrategy, 2005; Schmitt, 2000), shown in Figure 3.14. However, there is considerable concern over the viability of this technology because of the additional weight, complexity and cost of the internal systems and challenges of avoiding fouling of the surfaces (Waitz, 2009).

Vortices are formed at the tips of the wings as high air pressure migrates toward lower air pressure areas. These vortices reduce fuel efficiency by producing induced drag. Induced drag can be reduced by modifying the wing tips. For example, a winglet is a commercially available device mounted at the tip of the wing (see Figure 3.15) to provide a smooth, perpendicular surface that can favorably alter vortex formation (Morris, 2009; USAF, 2007; ADL, 2000). An alternative design, shown in Figure 3.16, employs a spiroid tip which is a loop formed at the end the wing to reduce drag. Spiroid tips have been applied to Gulfstream II aircraft (Ostrower, 2008). Wing tip devices may not be appropriate for all aircraft as it may require an increase in structural weight to support the wing tip offsetting the fuel savings associated with the reduction in drag. This was the case for the Airbus A-320, which at one point included winglets that were later removed because they did not provide the expected reduction in fuel consumption (Kingsley-Jones, 2006). Winglet devices that are better integrated into the wing design may be more beneficial. Spiroid winglets may offer more benefit but additional study is required to validate this technology.

Figure 3.16 Spiroid Wing Tip

Some of these technologies such as drag reducing films and multi layer panels are only now being demonstrated and need further development before they are commercially viable. There are no issues regarding the airworthiness of wing tip technologies, compared with other drag reduction technologies which require additional research.

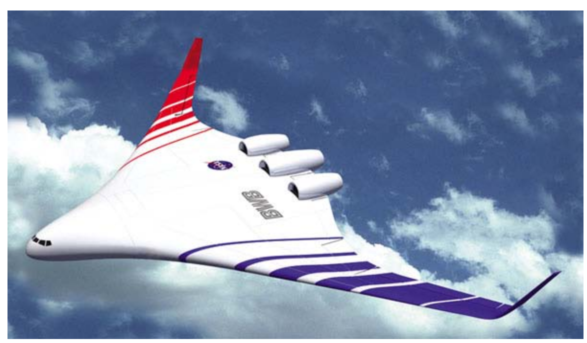


Figure 3.17 Blended Wing

In addition to these existing technologies, Boeing, Airbus and NASA, along with several university research programs, are developing a blended wing body (BWB) design (see Figure 3.17). This approach will significantly improve fuel efficiency as the whole aircraft contributes to the generation of lift, not just the wings as in the current designs. This design has been successfully demonstrated on smaller aircraft designs. Additional research is needed to scale up the design to larger aircraft. This BWB approach may reduce fuel consumption and greenhouse gas emissions by 20 to 40 percent while also reducing noise below current stage 4 standards (Morris, 2009; Warwick, 2007; ADL, 2000; NASA, 1997). BWB aircraft are most attractive for larger applications, e.g., 250-1,000 passengers with a range of over 7,000 miles (IPCC, 1999; NASA, 1997), but smaller variations of the aircraft also are possible. Initially these aircraft will probably provide services to large and distant urban centers that are associated with dense air traffic, such as between New York and London or Los Angeles and Tokyo. Because of the unusual shape of these aircraft, changes in infrastructure will be required to accommodate these aircraft (ADL, 2000).

Magnitude and Timing of GHG Reduction

The application of drag-reducing surface films is anticipated to decrease fuel usage by up to 1.6 percent, while multilayer panels used to reduce surface friction across the wing are expected to reduce fuel consumption and emissions between 6 to 10 percent. Use of wing tip devices can reduce fuel use by 1.7 to 2 percent for blended winglets (Morris, 2009, Reneaux, 2004) and up to 10 percent for spiroid winglets applied to smaller aircraft (Ostrower, 2008). Additional testing is being implemented for larger aircraft to quantify fuel consumption improvements associated with spiroid winglets.

Cost-Effectiveness

As mentioned earlier, the high cost of fuel is anticipated to drive the development and application of these technologies, as they will reduce operating costs, although the cost-effectiveness of each technology may vary. For example, wing tip retrofit kits cost approximately $1 million to install, which would require less than six years to break even based on a fuel cost of $3.33 per gallon. The payback period for other technologies that have yet to be commercialized is uncertain, as cost data are not readily available. Blended wing bodies are anticipated to entail a considerable price premium of $30 to $60 million per aircraft, including development costs.

Cobenefits

Since these devices primarily improve efficiency at high speeds (i.e., high-altitude operation), any benefits in terms of pollutant reduction are not expected to be significant.

Feasibility

Wing tip devices are commercially available and require little assistance from the policy-makers to promote their use. Accelerated adoption of wing tip devices may be encouraged through voluntary programs such as the EPA's SmartWay Program. Grooved adhesives and multi layer panels are likely to be less viable than other technologies presented in this section, due either to short lifetime (adhesives) or uncertain benefits (panels).

Tests of wing design changes that reduce friction through laminar flow have been encouraging, but at this time these designs have yet to be incorporated into commercially available aircraft. Similarly, BWB aircraft have performed well in model tests implemented by NASA, but significant further development is required before this aircraft design is ready for commercialization.

With regard to the BWB aircraft, the large capital investments required to develop the aircraft design and retool manufacturing operations to be able to construct the aircraft is a significant factor for the introduction of this new aircraft. Additionally, airports where these aircraft visit will need to modify passenger and cargo loading infrastructure to service these unusually shaped aircraft (ADL, 2000). Policies and/or incentives may be required (such as agreements to modify airports to accommodate new aircraft designs) in order to minimize financial risk for the manufacturers.

Fleet-wide Aircraft Technology Improvement

On a fleet-wide basis, both aircraft engine and airframe technology improvements could potentially increase efficiency by 1.4-2.3% annually between 2015–2035 relative to 2015 as the base year, according to goals outlined in the National Aeronautics Research and Development Plan developed by the National Science and Technology Council (NSTC 2007).

New Tehcnology Initiative for Civil Aviation

FAA Continuous Lower Energy, Emissions and Noise (CLEEN) Program

In 2009, FAA initiated the CLEEN program to mature and demonstrate engine and airframe technologies by 2015 that will reduce fuel consumption, GHG emissions and noise of current aircraft. CLEEN incorporates a 1:1 cost share with industry and is targeting technologies for use on civil subsonic jet aircraft that could reduce fuel burn by 33%, NOx emissions by 60% (relative to CAEP 6 standards) and noise by 32 EPNdB cumulative (relative to Stage 4 standards). CLEEN also strives to advance alternative fuel development and qualification for aviation use. The FAA is coordinating technology development efforts under CLEEN with stakeholders in NASA and the Air Force Research Laboratory. Contracts will be awarded in early 2010.

3.8 Vehicle Air Conditioning System Measures

Overview

Mobile air conditioning (MAC) systems contribute to GHG emissions in two ways. First, the use of air conditioning increases engine loads and, accordingly, exhaust CO_2 emissions. MAC compressor engine loads can be greater than the power required to move a typical sedan at 35 mph (Farrington and Rugh, 2000). In addition, the current automotive refrigerant, HFC-134a, is a greenhouse gas with a GWP of 1,300 when released into the atmosphere.[65] It is estimated that about 20 percent of the automotive refrigerant in use is released into the atmosphere annually (U.S. EPA, 2007d). Releases are caused by vehicle system leaks, leaks during servicing, and releases during recycling and disposal at vehicle end of life (EOL). It is estimated that 60 percent of MAC refrigerant releases are at EOL and servicing, while 40 percent are from in-use system leaks (Bateman, 2005).

> **Vehicle Air Conditioning Systems**
>
> *GHG Reduction Potential:*
>
> - Mobile air conditioning systems account for 3.5% of U.S. transportation GHG emissions (U.S. EPA, 2009d).
> - Banning "do-it-yourself" refrigerant refills in California was estimated to reduce that State's mobile air conditioner emissions by 66%. (CARB, no date).
> - Changing refrigerant types could reduce mobile air conditioning emissions by 91.3 to 99.9% depending on refrigerant type and mechanical efficiency (U.S. EPA, 2007b).
>
> *Key Cobenefits and Impacts*: **Negative**
>
> - Can ban could affect low-income do-it-yourselfers; change in standards would require industry retooling
>
> *Feasibility*: **Moderate**
>
> - Precedent established
>
> *Key Policy Options*:
>
> - Federal action to phase out existing refrigerants
> - Support for industry/government partnerships to develop new systems standards
> - Modify vehicle certification test procedures to reflect improvements in accessory efficiency

Refrigerant emissions are unique in that, in large part, they are not dependent on how much a vehicle is driven or how efficient it is. Due to the sheer number of units, refrigerant emissions from LDV MAC systems are estimated to account for 80 percent of refrigerant emissions from all transportation modes, with the remaining 20 percent split between HDVs (4 percent), refrigerated railcars (7 percent), and refrigerated commercial marine containers (9 percent).[66] In addition, of new LDVs sold in the U.S., 99 percent are equipped with air

[65]One hundred-year potential (UNFCCC, 1995).

[66]U.S. EPA (2009), Table 2-15.

conditioning, and, as a result, nearly all in-use LDVs are estimated to have a MAC system (Atkinson, 2007). For these reasons the following section focuses on LDV refrigerant control and reduction options, although some of these strategies will have applicability for other modes.

Legislation controls the safety characteristics of refrigerants, certification of service professionals, and service and EOL refrigerant recapture. Currently, professional service stations must use certified personnel, attempt to recover all refrigerant for recycling, and must initiate leak repairs. These requirements do not apply if the vehicle owner performs the work, however. Additional control initiatives are promoted by programs such as the Improved Mobile Air Conditioning (IMAC), which is designed to address all aspects of lifetime MAC performance. IMAC participants include the U.S. EPA, vehicle manufacturers and suppliers, and air conditioning component manufacturers. Their findings are guiding EPA in future MAC-related rulemaking, and manufacturers in the technologies they pursue (U.S. EPA, 2007d).

There are three approaches to reducing GHG emissions associated with MAC system operation:

1. Reduce the leakage of the refrigerant to the atmosphere;

2. Reduce the GWP of the refrigerant itself; and

3. Reduce the engine load (and concomitant CO_2 emissions) associated with running the air conditioning system.

One way to reduce refrigerant leaks is to simply reduce the amount of refrigerant in the system itself. Increases in MAC system efficiencies over time have resulted in a decrease in average charge volumes. Currently, the average vehicle charge size for a light-duty vehicle is 22.3 ounces (SAE, 2008). Reducing charge size limits the releases that can take place from in-use, service, and EOL leakage. Nevertheless, new air conditioning systems will continue to leak a small amount of refrigerant. The many connections among system components and slow seepage through hoses mean that some leakage is inevitable, estimated to be approximately 8–18 grams/year for current LDVs (Sciance, 2005). This leakage rate represents between 1 and 3 percent of a typical new vehicle system charge, so such losses are not likely to be noticed and repaired by vehicle operators.

System designs for new vehicles are continuously being improved to reduce the leakage rates of crimps, fittings, hoses, compressors, and other MAC system components, with many of these improvements based on IMAC findings and guidelines. As MAC systems age, leaks become more severe, but a certain amount of refrigerant can be leaked before degradation in performance is noticed. For this reason, it may be beneficial to implement a method of monitoring MAC system leakage. Monitoring could include a professional system check, for example during a vehicle's regular Inspection and Maintenance (I/M) or safety test. On-board diagnostic-type equipment also could be added to vehicles to monitor system leaks in order to alert the driver to a leak in a manner similar to the check engine light on today's vehicles. Both of these methods may offer long-term benefits, but are likely to require additional regulations and incurred costs.

Another significant source of refrigerant leakage is MAC system servicing. Service leaks occur as a result of the procedures followed before, during, and after repairs. As MAC systems age, refrigerant quantity decreases and system performance degrades, prompting the operator to initiate a repair, either following a do-it-yourself (DIY) procedure, or going to a service facility. Based on refrigerant sales figures, DIY servicing accounts for about 31 percent of the refrigerant consumed each year, including new-vehicle factory fills (SAE, 2008).

DIY methods typically only involve the addition of new refrigerant and do not involve an investigation or repair of leaks, and therefore result in greater releases of refrigerant compared to professional servicing. Additionally, DIY servicing often relies on a single, often inaccurate, pressure measurement to determine system charge levels, which can result in significant over or undercharging. While undercharging can cause compressor damage from oil starvation, overcharging can result in the system's relief valve releasing excess refrigerant into the atmosphere. Once the system is charged, the refrigerant remaining in the fill can, known as the heel, is often released directly into the atmosphere. DIY recharges typically utilize 12-ounce cans which are estimated to have a wide ranging heel size depending on the procedure followed, ranging from 1.4 to 75 percent of the can's original contents (SAE, 2008). CARB estimates that on average, 22 percent of DIY can contents are lost as heel from DIY servicing (CARB, 2008c). The difficulty handling refrigerant without significant leakage and accurately filling the system is part of the reason why the EPA requires a Section 609 certification for professional repair shops (U.S. EPA 2009d).

For the above reasons, the reduction of DIY MAC servicing leaks is receiving attention from regulatory bodies such as the California Air Resources Board as part of their AB-32 initiatives. The most aggressive method of reduction would be to **ban DIY refrigerant refill cans**, although there could still be a small DIY market by allowing parts stores to rent or sell professional grade servicing equipment. A less extreme control method would focus on reducing can heel releases. By offering only improved **self-sealing containers** and implementing a **refill can deposit program**, DIY servicers would be encouraged to return fill cans to have the heel quantity recycled or reused. (Refill cans with self sealing valves currently are available but cost around twice as much as nonsealing containers, and therefore comprise a small percentage of sales; CARB, 2008d). There also is the possibility of levying an **environmental fee** to the sale of DIY refrigerant cans in order to reduce their use and decrease wastefulness.

Service stations are required to investigate sources of leakage from MAC systems before recharging. When a leak is found, the system is typically evacuated, opened for repair, and then recharged. The evacuation is not complete, however, and some refrigerant is still released when the system is opened. Typical service recovery operations are believed to remove about 80 percent of remaining system refrigerant, with used refrigerant recovered for recycling. During recharge, overcharging is possible depending on the quality of the vacuum drawn, as there is no way of knowing how much refrigerant is left in the system. Service stations generally use 30-pound cans which will have approximately a 2 percent heel at the time of disposal (SAE, 2008).

Refrigerant release also takes place at vehicle EOL. When a vehicle is scrapped, all refrigerant will eventually be released into the atmosphere unless an attempt is made to recover it. While recovery is required in the U.S., compliance is not 100 percent and recovery methods do not remove all of the remaining refrigerant. EOL refrigerant recovery is less than 50 percent of the factory charge according to many estimates. Recovery challenges at vehicle EOL are similar to those encountered during servicing, except that conditions after scrappage make recovery more difficult and less effective. Vehicles are almost always outside where cooler ambient conditions limit drawdown efficiency, and in many cases the engine cannot be run to facilitate refrigerant recovery. Additionally, salvage and recycling operations are time-sensitive and extended efforts to recover refrigerant could have a negative effect on scrap operation profitability (U.S. EPA, 2007d).

Both professional servicing and EOL recovery can utilize similar improvements to minimize refrigerant leakage. Changes such as heating the accumulator and increasing vacuum pressures can raise recovery levels substantially. These efforts, along with performing a second drawdown to the system, will increase refrigerant recovery but also will require additional time and equipment. In addition to more robust recovery processes, accurate charging can help reduce refrigerant losses and waste. Charging based on the mass of refrigerant added is the proper method, but is limited in accuracy by the quality of the preceding recovery.

Alternative refrigerants exist that have a lower GWP than HFC-134a. Of the refrigerants that could be substituted for HFC-134a within the next five years, **HFC-1234yf** is one of the leading candidates. **HFC-1234yf** has a GWP of 4 and can operate in systems similar to current designs, with the potential for direct replacement of HFC-134a in existing systems (Yau, 2008). A second refrigerant under evaluation is **HFC-152a**, with a GWP of 124. This refrigerant is more toxic than either HFC-134a or HFC-1234yf, and is unlikely to be used in existing MAC systems, as protection from leakage into the passenger compartment would be required. The third refrigerant commonly considered is **R-744**, which consists of CO_2. This refrigerant is primarily being considered in Europe where R-134a will by phased out starting in 2011. However, CO_2 is less efficient than other refrigerants and its use would require a significant redesign of MAC components (Andersen, 2008). It also is unlikely that CO_2 would be able to provide acceptable levels of cooling in hot or humid environments, and the lower efficiency of these systems means their associated fuel use would be much greater than systems using the other alternatives.

MAC systems are sized to have the capacity to keep the vehicle comfortable on a hot and sunny day. Reducing vehicle cabin temperatures will in turn reduce MAC system capacity requirements and energy demand. **Solar reflective window glazing** can reflect most infrared (IR) light, and still allow acceptable light transmission for visibility. Similarly, **solar reflective paint** can be used on the vehicle's body in order to minimize the amount of heat absorbed from light, especially in the IR spectrum. Technologies to make darker colors (especially black) significantly more reflective do not yet exist, however (CARB, 2009).

Also, the addition of a **secondary loop** can make MAC systems more efficient. While conventional, or primary loop, MAC systems use refrigerant to directly chill the in-cabin heat exchanger, secondary loop systems employ a second fluid to chill the vehicle's interior. This secondary fluid would likely be a water/antifreeze solution. There are three primary benefits to a secondary loop system. In the case of a system with a toxic refrigerant, secondary loop systems isolate passengers from the refrigerant, for example in the event of a rapid leak resulting from a collision. Additionally, these systems can be used to reduce power requirements by allowing the compressor to run primarily during deceleration or at efficient engine operating conditions. The antifreeze itself also could be used as a thermal sink to maintain low temperatures in the time between these operational modes. Another benefit is that these systems allow a reduction in the size of the primary refrigerant circuit and, as a result, a reduction in the required size of the refrigerant charge. It is estimated that the charge size can be reduced by about 50 percent for typical vehicles. Designs and prototypes for these systems exist, but the increased cost and complexity has kept them out of the market so far (U.S. EPA, 2007d).

Even without a secondary loop, changes can be made to component designs and compressor cycling to reduce engine loads. **Improved compressor cycling and control**, similar to that proposed for secondary loop systems, also could be employed to take advantage of efficiency gains possible during vehicle deceleration. It also is possible to allow the system to run at higher temperatures while in defrost mode. These changes, coupled with more efficient heat exchangers, would allow MAC systems to operate with reduced energy requirements. Such enhancements also would help hybrid vehicles maintain their efficiency advantages over conventional vehicles during MAC system operation: the continuous compressor load dramatically reduces the amount of engine-off time that hybrids can utilize, so reducing MAC power requirements can help hybrid vehicles operate even more efficiently.

Magnitude and Timing of GHG Reductions

EPA estimates that in 2007, mobile air conditioner (MAC) emissions accounted for 3.5 percent of total transportation greenhouse gas emissions (U.S. EPA, 2009d). Because the Calilfornia Air Resources Board (CARB) has begun evaluating possible methods of reducing "do-it-yourself" (DIY) MAC servicing in California, much of the available data concerning DIY methods come from that State. DIY refrigerant emissions in California represent about 0.39 percent of GHG emissions from the California transportation sector. It is estimated that a ban of DIY refill cans would reduce refrigerant emissions by 66 percent of this amount (CARB, 2008e). As an alternative to a can ban, adopting a deposit program to recycle can heels is estimated to reduce DIY emissions by about 31 percent. The effect of environmental fees would be dependent on the amount of the fee, with an upper limit near that of the can ban. Because CARB anticipates that the above reductions could be achieved in two years, methods of DIY reductions are considered near-term options (CARB, no date).

The impact of a change in MAC refrigerant type depends primarily on the GWP of the refrigerant and the mechanical efficiency of the system. HFC-1234yf would reduce CO_2-

equivalent leakage emissions by 99.7 percent when HFC-134a is completely phased out. HFC-152 would reduce CO_2 equivalent leakage emissions by 91.3 percent at full phaseout, and R-744 would reduce equivalent leakage emissions by 99.9 percent. Currently, a phaseout of HFC-134a is planned in the EU. This phaseout does not specify a replacement refrigerant, but rather that no new vehicle may be sold after 2011 containing refrigerant with a GWP over 150 (U.S. EPA, 2007d).

Little specific data exist comparing the engine load requirements of the alternative refrigerants. The available data suggest that HFC-1234yf would increase required engine load by 2.3 to 6 percent over HFC-134a. R-744, however, would increase engine load by 70 percent to 100 percent over HFC-134a (Atkinson, 2008). The move to alternative refrigerants represents a long-term option for GHG reduction in the case of HFC-152a and R-744, as inuse vehicles are not likely to be retrofitted with this refrigerant. HFC-1234yf may be used with current vehicles with little to no modification, making it possible that GHG benefits for this refrigerant could be realized in the short term, if research shows that direct substitution into current R-134a systems is feasible.

In addition, according to a 2004 report, it was estimated that mechanical loads from LDV MAC system use increases fleetwide gasoline consumption by 7 billion gallons per year (U.S. EPA, 2009d), or approximately 5 percent of total LDV consumption in 2010. Reduction of vehicle cooling loads can reduce these emissions. Solar reflective glazings and paints can reduce MAC fuel use by up to 30 percent (Rugh et al., 2006). If new vehicles adopted secondary loop systems, a reduction in fuel use also could be realized. It is estimated that a small car operating with a secondary loop system with HFC-152a refrigerant would have 21 percent lower MAC-related fuel usage than a similar vehicle with a conventional MAC system. The implementation of improved compressor cycling and control, coupled with more efficient compressors and heat exchangers, also could result in fuel consumption reductions of up to 30 percent.[67] It is expected that these technologies could enter the market in the next few years but would likely only affect new vehicles sold, resulting in these reductions only being realized in the medium term (U.S. EPA, 2007e).

Cost-Effectiveness

Cost estimates for DIY MAC service restrictions are taken from California ARB estimates. The increased cost of a DIY "can ban" comes primarily from the increased cost of professional vehicle servicing. It is estimated that the cost increase, borne primarily by consumers that had previously performed DIY service on their own vehicles, would be \$135 per tonne CO_2e. Implementing a deposit program also would create additional costs for the consumer. It is estimated that this type of program to reduce heel emissions would cost between \$9 and \$19 per tonne CO_2e, largely paid for by consumers in the form of more costly containers and shipping logistics. The cost-effectiveness of adding an

[67] Personal communication with Dr. Stephen Andersen, U.S. EPA.

environmental fee is highly dependent upon the fee level and whether the fees collected are applied to other GHG mitigation strategies. High fee levels could obtain reductions at similar cost-effectiveness to a can ban, but the cost-effectiveness of lower fees would depend strongly on the cost-effectiveness of the mitigation strategy to which the fees would be applied (CARB, 2008c).

Alternative refrigerant cost estimates are not frequently cited in the literature. Based on current estimates, refrigerant costs for HFC-1234yf will likely be the highest of the three alternatives discussed above, but the complete systems for this refrigerant will be very similar or interchangeable with current designs, so the system costs will likely be the lowest. HFC-1234yf systems may cost around $40 more per vehicle than current systems. HFC-152a will have greater system costs than HFC-1234yf due to toxicity mitigation, resulting in an estimated cost of around $50 more per vehicle. R-744 will have the highest costs due to requiring larger components that are much different than those in current use, resulting in systems that could cost $200 more than current systems.[68] R-744 systems may be more feasible in heavy-duty applications where the physical size requirements and system cost can be more easily managed.

Secondary loop systems will add cost and complexity to vehicles. While specific cost estimates were not found in the literature, estimates imply that the cost increase would be low enough to easily be paid back by fuel savings in climates where air conditioning is used often (U.S. EPA, 2007d). Further cost and benefit analysis for secondary loop systems and other methods of reducing MAC system load are not performed due to lack of sufficient cost data in the literature.

Cobenefits

To the extent that engine loads are reduced, reductions in exhaust criteria pollutants may result. It is estimated that MAC compressor use can increase emissions of NO_x and carbon monoxide by 70 to 80 percent, and increase hydrocarbon emissions by 30 percent (Farrington and Rugh, 2007). In addition, as system integrity and leak prevention become higher priorities, overall reliability increases, resulting in lower maintenance requirements. After the change from CFC-12 to HFC-134a, reliability increased due to the attention given to connections and leakage. The IMAC program is likely to result in similar improvements.

Feasibility

Of the methods identified to reduce MAC system leakage from DIY servicing, a can ban has the most significant barriers to implementation. Such a ban would completely eliminate the small can refrigerant business. However, the economic impact would be

[68] Andersen (2008); Personal communication with Dr. Stephen Andersen, U.S. EPA.

offset to some degree by an increase in the demand for professional MAC service. This type of legislation is meeting resistance in California because it may disproportionately target low-income citizens as these individuals make up a significant percentage of the DIY market. In addition, there would be an overall loss of utility as some people would choose to go without air conditioning. A refill deposit program would have fewer barriers to implementation, although it would likely be somewhat less effective. In this case, refrigerant suppliers would need to expand their delivery logistics to include the reclamation of used containers from retail outlets that receive their products.

Environmental fees on DIY small cans would have primarily legislative barriers to implementation (CARB, 2008c). California has chosen a refill can deposit program in which cans must be self sealing, and an $11 deposit is added to the purchase price of the can and refunded when the container is returned intact. According to CARB, this strategy has the most favorable cost/benefit ratio and avoids the issue of unfairly targeting lower-income motorists. In addition, strategies that target servicing and EOL emissions also can impact reductions substantially in the near term, unlike those measures involving MAC system modifications which require time for new vehicles to penetrate the fleet.

The feasibility of alternative refrigerants is based on their safety, efficiency, and cost characteristics. While HFC-1234yf has a low GWP and its associated system is efficient, it does have a high material cost and is flammable. HFC-152a also is flammable, and it is more toxic than HFC-1234yf and HFC-134a. Currently, many States prohibit toxic or flammable refrigerants. However, renewed interest in these refrigerants is prompting a review of these requirements. The automotive community is working on designs to minimize the risks of toxicity and flammability, and the literature suggests a consensus that these problems can be overcome. R-744, or CO_2, can be toxic to passengers in the case of a sudden system depressurization, and requires significant and expensive changes to the designs of MAC systems. This is because these systems will not use gas-to-liquid phase change as is typically the case in conventional refrigeration cycles. Because of this, R-744 systems are not as effective in warm climates and they are not as efficient, resulting in higher fuel consumption for cooling (Andersen, 2008). Finally, as discussed above, the CO_2 emissions associated with MAC-related engine loads are comparable to, or even more significant than, the actual refrigerant impacts. As such, evaluations of alternative refrigerant options must include a careful evaluation of differential engine load impacts before settling on a preferred strategy.

The move to an alternative refrigerant could take place in a manner similar to the change from R-12 to HFC-134a that occurred in the early 1990s. It is estimated that the conversion to HFC-134a cost automotive manufacturers and the service industry $8.5 billion, while the next change to a new refrigerant could cost over $40 billion. It is important that this conversion is performed at least at the national-level, and possibly at the international-level in order to keep costs to industry reasonable. According to the literature, the choice of refrigerant does not appear to be driven by cost. Each refrigerant's advantages and disadvantages are significant enough to outweigh cost differences among them. The EU set a date for HFC-134a phase out before there was agreement on which refrigerant would be the best alternative. While the EU assumes that a new refrigerant will have any remaining technical issues resolved by this time, determining the preferred refrigerant in advance may facilitate integration of refrigerant production, MAC system manufacturing, and system servicing requirements, even if it requires a longer timeframe.

Adoption of alternative refrigerant systems has additional uncertainties that could have significant impacts on net GHG reduction potential. For instance, different refrigerant systems may have different baseline leak rates, possibly due to different system pressures and/or charge capacities. In addition, given the sensitivity of GHG emissions to AC-induced engine load (estimated to be between 2.5 and 7.5 percent of total vehicle energy consumption; IPCC, 2007 page 339), changes in compressor sizing and engine load from adoption of alternate systems could prove important as well.

Solar reflective paints and glazings are being developed and tested for longevity, appearance, and IR efficiency. Cost is another limit to feasibility. Secondary loop systems also encounter barriers because of their increased cost, weight, and complexity, but as small vehicle efficiency gains become more important, these barriers may become less significant. In addition, an industry-wide changeover to a toxic refrigerant could encourage the move to secondary loop systems for safety reasons, although they can make systems using *any* refrigerant more efficient.

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4.0 System Efficiency

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4.1 Summary

System efficiency encompasses a diverse set of strategies that are focused on ways to optimize the use of the transportation network by improving the efficiency of transportation operations. These strategies seek to improve the operation of the transportation system through reduced vehicle travel time, improved traffic flow, decreased idling, and other efficiency of operations—improvements that can also result in lower energy use and GHG emissions. System efficiency strategies discussed in this report include:

- **Highway operations and management** strategies, including Intelligent Transportation Systems (ITS) and other strategies that reduce congestion or otherwise keep vehicles moving at their most energy-efficient speeds (Section 4.2);
- **Truck operations and management** strategies that reduce the emissions per unit of goods moved by truck (Section 4.3);
- Improvements to the efficiency of **rail and marine freight systems**, including ports and intermodal terminals, that reduce energy use per unit of goods moved by these modes or shift freight movements from truck to those more efficient modes (Section 4.4);
- **Aviation** operations practices, both at airports and en-route, that reduce fuel use and GHG emissions from aircraft (Section 4.5); and
- Improvements in materials and methods that reduce GHG emissions generated during the **construction and maintenance** of transportation infrastructure (Section 4.6).

These strategies are described in detail in the sidebar on p. 4-2. Various strategies that improve vehicle utilization (see sidebar on p. 4-12) may also be considered forms of improving system efficiency. For example, roadway operational improvements such as signal priority for transit vehicles can help buses travel faster and avoid congestion, making transit operations more efficient and encouraging travelers to shift to transit. Ridesharing and vanpooling programs can encourage more efficient utilization of vehicles and road space. Strategies that improve efficiency by affecting travelers' behavior and increasing vehicle occupancies are discussed in Section 5.0, Reduce Carbon Intensive Travel Activity.

System Efficiency Strategies

Highway Operations and Management

- **Traffic Management –** Technologies and practices to reduce congestion and smooth traffic flow through improved traffic operations and management, such as signal coordination, faster clearance of incidents, and freeway ramp metering.
- **Real-Time Traveler Information –** Provision of up-to-date information to travelers and truckers on traffic conditions, incidents, and expected delays; the availability of public transportation and other travel alternatives; weather conditions; road construction; and special events.
- **Bottleneck Relief –** Increased capacity at "bottlenecks" (specific points on the transportation network where demand exceeds capacity), such as interchanges, intersections, and lane drops.
- **Reduced Speed Limits –** Reduced speed limits on high speed facilities, including the InterState system, other limited access highways, and possibly high speed rural major arterials, to no more than 55 or 60 mph.

Truck Operations and Management

- **Truck Idle Reduction –** Education, laws, and/or incentives to introduce technology (such as electrical hook-ups at truck stops or on-board auxiliary power supplies) to reduce long-duration idling of heavy vehicles.
- **Truck Size and Weight Limits –** Changes to Federal law to allow vehicles exceeding 80,000 pounds to operate on InterState highways; and/or to allow longer (53') trailers or double or triple trailers in all States.
- **Urban Consolidation Centers –** Freight facilities where deliveries (retail, office, or residential) can be consolidated for subsequent delivery into the urban area in an appropriate vehicle with a high level of load utilization.

Freight Rail, Marine, and Aviation Operations

- **Rail and Marine Modal Diversion –** Infrastructure improvements to encourage shippers to shift freight traffic to modes that are more energy- and carbon-efficient (generally from trucking to rail or marine), through reductions in the time and cost of shipping or increased reliability by these modes; financial incentives or disincentives that encourage different shipping patterns; and other policy and regulatory actions.
- **Rail and Intermodal Terminal Operations –** Reducing or eliminating chokepoints in the rail intermodal system to eliminate existing rail traffic friction, increase rail throughput potential, decrease variability in travel time, and decrease overall travel time; thus reducing emissions associated with vehicle delay and low-speed operations.
- **Ports and Marine Operations –** Land-side and marine-side strategies to increase the energy efficiency of operations at ports and reduce GHG emissions, such as reducing truck idling and VMT within the terminal, rail service to inland distribution centers, and shore-side power for ships.
- **Aviation Operations –** Operational procedures to reduce delays and GHG emissions from aircraft, such as improvements in airport efficiency, direct routing of flights, reduced separation, and continuous descents.

Infrastructure Construction and Maintenance

- **Construction Materials –** Use of less energy-intensive construction materials by State and local highway departments and other transportation agencies, such as recycled material in cement and asphalt that is prepared at a lower temperature.
- **Other Transportation Agency Activities –** Other transportation agency operating practices to reduce GHG emissions, such as alternative fuel fleet and construction vehicles, energy efficient buildings, and work zone management to reduce traffic congestion.

Summary of Impacts

Highway operations and management strategies include **traffic management** (signal coordination, ramp metering, faster clearance of incidents), **real-time traveler information**, and **highway bottleneck relief**. These strategies have an emission reduction effect by reducing congestion and smoothing traffic flow, thus reducing inefficient vehicle operation. However, the improved conditions they create also result in some amount of additional travel and thus additional emissions through a phenomenon known as induced demand (see section 4.1.4 and Appendix A). Whether the emission-increasing effect of induced demand outweighs the emission reducing effect of congestion reduction and traffic smoothing depends on the amount of induced demand and on the particulars of the strategy. Quantifying the magnitude of induced travel demand and the impact of this extra traffic on travel speeds and traffic flow is particularly challenging, and further research is needed.[1] An additional source of uncertainty relates to the vehicle technology or fuels used by future vehicles, which could further reduce any benefits from congestion reductions strategies.[2] Because of these uncertainties, numerical estimates are not included for highway operations and management strategies in Volume 1 of this report, though outside estimates are included here in Volume 2 both in this summary section (directly below) and in the more detailed Section 4.2. The estimates presented in this section are taken from outside studies and should be considered illustrative. Despite these uncertainties, it is worth noting that congestion relief strategies yield significant cobenefits by reducing the time travelers spend on the road due to congestion and delay. **Traffic management** strategies are technologies and practices to reduce congestion and smooth traffic flow through improved traffic operations and management, such as signal coordination, faster clearance of incidents, and freeway ramp metering. Outside studies have incorporated simplified assumptions regarding induced demand to estimate the GHG impacts of highway operations and management strategies. Analysis for the *Moving Cooler* study (Cambridge Systematics, 2009) suggests that widespread deployment of traffic management strategies would reduce transportation GHG emissions by a modest[3] amount, 0.5 percent or less in 2030. The study found that in 2050, there would still be net emission reductions.

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[1] U.S. DOT is designing research to provide a better understanding of the role of induced demand in offsetting GHG improvements from congestion reduction strategies.

[2] If vehicle technology evolves to rely heavily on electric-drivetrain technology (such as hybrids, battery-electrics, or fuel-cell vehicles), the energy and GHG benefits of congestion reduction will be greatly reduced or disappear altogether. Because the efficiency of these vehicles typically is not reduced at lower speeds, their emission levels stay relatively constant even under congested conditions. In addition, for any highway operations strategy, future improvements in fuel efficiency or reductions in the carbon content of fuels beyond the baseline assumed in this report will lead to lower absolute benefits from any of these strategies.

[3] In this report, when referring to individual strategy effects, "modest" refers to reductions in CO_2e emissions of less than 0.5 percent of total transportation emissions, or 12 mmt in 2030; "moderate" to reductions in the range of 0.5 to 2.5 percent of total transportation emissions, or 12 to 60 mmt in

(Footnote continued on next page...)

Bottleneck Relief strategies increase capacity at "bottlenecks" (specific points on the transportation network where demand exceeds capacity), such as interchanges, intersections, and lane drops. The *Moving Cooler* study examined GHG reduction from projects to reduce congestion at the top 200 bottlenecks, suggesting a potential to reduce GHG emissions by 0.3 percent in 2030, assuming that these projects were fully financed by increased user fees, which would moderately suppress travel demand. However, the analysis also indicated that any short- to mid-term gains of bottleneck relief projects would be negated over the long term, and that there would be no net benefit over the 2010 to 2050 time period. Emissions would in fact be an estimated 0.6% higher in 2050. It is also important to note that this analysis did not include estimates of GHG emissions from construction activities or additional delay during construction.

Real-Time Traveler Information strategies provide of up-to-date information to travelers and truckers on traffic conditions, incidents, and expected delays; the availability of public transportation and other travel alternatives; weather conditions; road construction; and special events. *Moving Cooler* found that these strategies would result in emission reductions of 0.2% or less in 2030, with continued emission reductions in 2050. **Reducing speed limits** from 70 or 65 mph to 60 or 55 mph could lead to a moderate reduction in transportation GHG emissions—between 1.6 to 2.4 percent in 2030, or 30 to 40 mmt CO_2e. Achieving these benefits assumes adequate enforcement of the reduced speed limits. Reducing speed limits will not have induced demand effects and may, in fact, lead to slight decreases in highway travel due to longer travel times.

Truck operations and management strategies will provide modest GHG benefits—up to 6 mmt CO_2e, or 0.2 percent of transportation emissions in 2030. Of these strategies, truck idle reduction has the greatest potential to reduce GHG emissions, while also reducing criteria pollutants and saving vehicle operators money. Increasing truck size and weight limits has modest potential to increase the efficiency of truck transport; however increasing the loads that can be carried by trucks also could encourage shippers to divert goods from rail to truck – thereby increasing GHG emissions. Therefore increases in size and weight limits would need to be applied only in very specific markets where trucks and rail do not compete. Urban consolidation centers (which consolidate goods for more efficient distribution in cities) have been applied experimentally in Europe and Japan but not the U.S.; their viability in the U.S. is unproven but overall GHG benefits are likely to be small (less than 1 mmt CO_2e).

Improvements to **rail and marine modes**, such as capital investment to relieve chokepoints in the network, may have two distinct effects on GHG emissions. The first is improving the energy efficiency for freight already moving by these modes. The second is encouraging freight to shift from truck to more efficient rail or marine modes. Neither effect has been reliably quantified, but the net impact of mode shifting is expected to be modest—less than 10 mmt CO_2e in 2030, or 0.4 percent of transportation emissions. Mode shift impacts could in theory be significant, since it is much more efficient to move a ton of goods a mile by rail, ship, or barge than by truck—about three to four times more efficient.

2030; and "significant" to reductions of greater than 2.5 percent of transportation emissions or 60 mmt in 2030.

In practice, however, the potential for mode-shifting appears limited. Due to handling costs, rail and marine are generally only competitive for long-haul movements (at least 500 to 1,000 miles), and for relatively low-value goods for which speed and reliability are less of a concern. Furthermore, most of the energy efficiency benefits are lost for shorter movements due to the need to transfer goods to truck at one or both ends of the journey.

Operational improvements in the **aviation sector** show moderate potential for GHG reductions. Air traffic modernization measures that are underway or planned through the Federal Aviation Administration's NextGen program (for example, allowing airplanes to fly on more direct routes) could potentially reduce annual GHG emissions from aircraft by 2.5 to 6 percent through 2035. Additional benefits of up to 10 mmt CO_2e annually could potentially be achieved by measures to reduce aircraft delay at airports, and 2-3 mmt CO_2e annually through more efficient or alternative fuel airport equipment and operations. Improvements may also make air travel faster and less expensive, representing a benefit to travelers. Overall demand for air travel is forecast to increase, offsetting at least some of the GHG reduction benefits. The magnitude of this offset has not been estimated.

Transportation infrastructure construction and maintenance practices also show potential for modest to moderate reductions in GHG emissions. Perhaps the most significant currently available strategy is the use of fly ash or other recycled materials in cement, a proven technology that has the potential to reduce GHG by an additional 15 mmt CO_2e annually. Use of warm- and cold-mix asphalt has the potential to reduce GHG by about 3 mmt CO_2e annually, but research on the application of these technologies in the U.S. is still in progress. Other actions by transportation agencies also have the potential to contribute modestly to GHG reductions. These include the use of alternative fuels in transportation agency vehicles and equipment, reduced idling of construction equipment, and increased energy efficiency in transportation agency buildings. These actions are estimated to provide benefits of about 2-3 mmt CO_2e per year.

Cumulative Benefits

The effects of the individual strategies presented in this report are generally independent of each other, and therefore can be added together to provide a rough estimate of cumulative savings from these strategies. Benefits are shown (see Table 4.1) separately for highway modes and for non-highway modes (air, rail, and marine). Highway strategies include trucks and construction practices, as well as general roadway management and operations. Combined benefits of all strategies are estimated to range from 2.9 to 5.7 percent of total transportation emissions in 2030, with the majority of the benefits from the highway sectors. Separate benefits estimates for 2050 are not presented, as these strategies can generally be fully implemented by 2030.

Table 4.1 Combined System Efficiency Strategy Benefits (2030)

	GHG Reduction from Baseline, mmt CO_2e		Percent of All Transportation Emissions	
Year	Low	High	Low	High
Highway and Truck Strategies	44	78	2.0%	3.6%
Air, Rail, and Marine Strategies	12	37	0.6%	1.7%
All Strategies	**63**	**131**	**2.9%**	**6.1%**

Policy Implications

The level of implementation of some of these strategies is constrained by funding. Highway improvements, in particular, are traditionally funded through the Federal-aid process as well as by State and local governments. Broader deployment of traffic management and information has few barriers aside from funding availability; these strategies can generally be implemented at modest cost compared to traditional capacity expansion strategies, and these improvements are generally not controversial. Bottleneck relief projects also can be accelerated through funding but are more likely to raise community or environmental concerns in some locations. Federal funding also could accelerate aviation avionics equipage and rail infrastructure improvements beyond current levels of private sector investment; this would require a significantly greater level of Federal involvement compared to current practice. Funding for system efficiency initiatives could be provided through existing or new programs in the form of broad support for the general types of projects that reduce GHG, or awarded on a performance basis for specific projects that meet demonstrated levels of GHG reduction cost-effectiveness.

Other strategies may require regulatory changes for implementation. Speed limit reductions could be implemented through a uniform national speed limit, combined with requirements or incentives for strict enforcement by States. Federal implementation of a uniform anti-idling law, combined with incentives to defray up-front costs for vehicle owners, would encourage adoption of this technology for trucks. Requirements or voluntary agreements also could be developed with railroads and port operators to implement idling reduction and other GHG reduction practices in rail yards, ports, and intermodal terminals.

Research and development activities could advance other strategies that rely on yet unproven technologies. Examples of efficiency strategies that require further R&D include advancement of warm-mix asphalt and demonstration of the viability of urban consolidation centers. Further improvements to aviation system efficiency require both research as well as funding for deployment.

Finally, planning requirements and/or technical assistance can support some strategies. For example, State and metropolitan transportation agencies could be required to assess the GHG emission impacts of transportation plans or projects and to identify and incorporate GHG reduction strategies in their transportation plans, including system efficiency improvements. GHG reduction practices also could be required in construction and maintenance activities. Ports and airports could be required to conduct GHG inventories and/or develop reduction plans. The U.S. DOT could provide technical assistance (e.g., inventory and assessment tools, best practices guidance), either to support these requirements or as a stand-alone measure to encourage transportation agencies to address GHG emissions. Planning and regulatory strategies are discussed in more detail in Section 8.0.

Summary Evaluation

Table 4.2 summarizes the strategies discussed in this section and presents an assessment of each strategy's effectiveness, cost-effectiveness, and cobenefits, as well as a summary of key Federal policy initiatives that would be needed to implement the strategy beyond current levels. The factors presented in the table are rated according to the following metrics:

- **Effectiveness**: Low = < 0.5 percent of transportation GHG emissions in 2030 (12 mmt CO_2e; Moderate = 0.5-2.5 percent (12-60 mmt CO_2e); High = > 2.5 percent (60 mmt CO_2e).

- **Costs**: Cost is measured as "net included cost" per metric ton (tonne) of CO_2e reduced. A positive number represents increased costs, while a negative number represents a net savings. High Cost = > $200 per tonne CO_2e reduced; Moderate Cost = $20-$200 CO_2e reduced; Low Cost = < $20/tonne CO_2e reduced; Net Savings = < $0/tonne CO_2e reduced. Costs for system efficiency strategies are presented in two ways:

  – Direct costs (implementation costs only) per tonne of CO_2e reduced; and

  – "Net included costs" (which includes both direct costs and any reported cost savings, usually vehicle operating costs). A discussion of how costs are calculated and presented in this report is presented in Appendix A.

- **Cobenefits**: Plus (+) = significant positive cobenefits; minus (–) = significant negative cobenefits; plus/minus (+/-) = both significant positive and negative cobenefits; zero (0) = modest or negligible cobenefits.

Table 4.2 System Efficiency Strategies
Summary Evaluation

Strategy	GHG Reduction (2030)[a]	Direct Cost per Tonne	Net Included Cost per Tonne	Co-benefits	Key Federal Policy Options
4.2 Highway Operations and Management					
4.2.1 Traffic Management	Low <0.1-0.5%	Moderate – High	Net Savings to High	+	Funding for project implementation, technical support, and institutional coordination
4.2.2 Real-Time Traveler Information	Low <0.1%	High	Low to High	+	
4.2.3 Bottleneck Relief	Low <0.1-0.3% [b]	N/A	N/A	+/-	Project funding
4.2.4 Reduced Speed Limits	Moderate 1.1-1.8%	Low	Net Savings	-	Federal speed limit policy, funding incentives for enforcement
4.3 Truck Operations and Management					
4.3.1 Truck Idling Reduction	Low 0.1-0.2%	Moderate	Net Savings	+	Federal anti-idling law
4.3.2 Truck Size and Weight Limits	Low <0.1%	Low	Net Savings	0	Revise Federal policy re: truck size and weight limits
4.3.3 Urban Consolidation Centers	Low <0.1%	Moderate	Net Savings	+	Feasibility studies/demonstration projects
4.4 Freight Rail and Marine Operations					
4.4.1 Freight Modal Diversion	Low <0.1-0.2%	High	Net Savings – Moderate	0	Funding for rail and intermodal capacity improvements
4.4.2 Marine Modal Diversion	Low <0.1%	High	High	0	Capital investment in inland waterways Subsidies for short-sea shipping
4.4.3 Rail and Intermodal Terminal Operations	Low <0.1%	Unknown	Unknown	+	Funding for rail and intermodal capacity improvements
4.4.4 Ports and Marine Operations	Low <0.1%	Unknown	Unknown	+	Tools to assist in GHG assessment; regulations or voluntary partnerships to promote GHG reduction practices
4.5 Air Traffic Operations					
Combined NAS strategies	Moderate 2.5-6%[c]	Unknown	Unknown	+	Continued funding and institutional support for NextGen program Requirements or incentives for GHG reductions
4.6 Infrastructure Construction and Maintenance					
4.6.1 Construction Materials	Moderate 0.7%	Unknown	Unknown	0	Continue R&D on warm-mix asphalt and recycled materials Construction material requirements
4.6.2 Other Transportation Agency Activities	Low 0.1%	Unknown	Unknown	0	Model practices and assessment tools; regulations to reduce GHG in construction; funding incentives for GHG reduction
Combined Benefits	2.9-6.1%				

[a] The estimated benefits of traffic management, traveler information, and bottleneck relief all reflect offsetting effects of induced demand. Increased demand resulting from improved travel conditions is not reflected in other strategies where it may be significant, such as aviation operations.

[b] Does not include emissions from construction activities or from additional delay during construction.

[c] Through 2035. Does not account for induced travel demand, which would reduce emissions benefits.

Cobenefits and Implications for Other Key Transportation Goals and Objectives

System efficiency strategies have a number of common cobenefits, implications for DOT goals and objectives, and implications for infrastructure finance, as described below. Some strategies also have unique cobenefits and impacts that are described in their respective subsections. They can be evaluated against the five strategic goals of the U.S. DOT (identified in the U.S. DOT's Strategic Plan), as well as other key objectives established for transportation by the Obama Administration:

- **Safety –** Strategies that reduce congestion may increase safety by reducing the number and/or severity of crashes. There is a documented link between speed differentials (which result from increased congestion) and greater frequency of crashes (TRB, 1984); however, crashes are likely to be less severe under congested conditions because they occur at lower speeds. Evidence of the net effect of congestion reduction on the social costs of crashes is inconclusive.

- **Reduced Congestion/Increased Mobility –** Strategies that reduce roadway congestion or make travel by other passenger modes quicker will generally improve mobility as will better traveler information. Speed limit reductions will decrease mobility by increasing travel times. Other modal and intermodal strategies (rail, ports, intermodal terminals, aviation) will support the DOT's objective of "reducing impediments to the efficient movement of freight over the transportation network" and meeting new and growing demands for freight transportation.

- **Global Connectivity –** System efficiency strategies focused on ports, border crossings, and intermodal terminals (or infrastructure in the vicinity of these facilities) would improve global connectivity by enhancing the speed and reliability of connections between modes and across national borders. Information technologies also can streamline the movement of goods and people across borders.

- **Environmental Stewardship –** Most efficiency strategies would result in reductions in other air pollutants as well as GHG emissions as a result of burning less fuel. These pollutants include ozone precursors (volatile organic compounds and oxides of nitrogen), particulate matter, carbon monoxide, sulfur dioxide, and air toxics. While reductions in air pollutant emissions will often correspond to reductions in energy consumption and GHG emissions, impacts will not always be in direct proportion; emissions may be higher under acceleration and at particularly low or high speeds. Freight modal shifts also can result in different emissions impacts depending upon the mode, vehicle technology, and operating conditions. Furthermore, specific strategies may provide air quality benefits disproportionate to total emission reductions if the reductions are concentrated in areas of high population exposure. Strategies that involve infrastructure construction, especially those pertaining to highway and rail bottleneck relief, may have localized environmental and community impacts that are either positive or negative.

- **Security –** System efficiency strategies may benefit national security by reducing dependence upon foreign oil. The reduction in oil use will be in direct proportion to GHG reductions for each strategy. In addition, strategies that reduce roadway congestion would improve the response times for emergency services (police, fire, and medical), thereby supporting security. Traveler information technologies will improve the ability to respond to emergencies, including disruptions from natural disasters, terrorists, and criminal attacks. Some of the technologies used for traffic management, such as observation cameras, may benefit security by providing a means of observing roadways and providing information for law enforcement officials to aid them in responding to crimes.

- **Livability –** The freight- and aviation-oriented strategies may support livability in neighborhoods adjacent to ports, rail yards, airports, and intermodal terminals by reducing truck operations on local roadways and by reducing noise and emissions from trucks, ships, locomotives, aircraft, and airport equipment. Major capital investment projects, such as bottleneck relief or rail infrastructure investment, could potentially have negative localized impacts if takings are required. Otherwise, most of these strategies are not anticipated to significantly affect livability.

- **Economic Vitality –** To the extent that these strategies reduce congestion or reduce shipping costs, they will generally improve economic vitality by reducing business and consumer costs and increasing business productivity. For example, research on the trucking industry has shown that shippers and carriers value transit time in the range of $25 to $200 per hour, depending on the product being carried. The cost of unexpected delay can add another 20 percent to 250 percent (FHWA, 2005).

Effects on Infrastructure Funding

All system efficiency strategies will result in varying demands on infrastructure funding sources depending upon their costs. Regulatory strategies such as anti-idling, speed limits, and truck size and weight restrictions are inexpensive to implement; enforcement is the primary cost. Technology for traffic operations, management, and traveler information has modest to moderate costs, while infrastructure construction generally entails high capital costs (in the tens to hundreds of millions per project).

Improvements in highway and truck system efficiency will lead to proportionate reductions in motor fuel sales, and therefore reduced revenue for transportation programs under the current finance structure. The Federal Highway Trust Fund was established in 1957 as a dedicated, user-funded source of revenue for the United States highway system, and is the source of revenue for the Federal-aid Highway Program. Net receipts in

FY 2007 were $34.3 billion to the Highway Account and $5.0 billion to the Mass Transit Account (FHWA, 2008f).

The on-road system efficiency strategies analyzed in this report will reduce total Federal Highway Trust Fund revenues in rough proportion to fuel savings and GHG reductions. Under the 2030 combined scenario described above, the net impact on revenues could range from about $0.9 to $1.5 billion annually.[4] Strategies focused on heavy-duty vehicles will have a somewhat greater relative impact than those focused on light-duty vehicles because of the higher tax rate on diesel fuel (24.4 vs. 18.4 cents per gallon).

This analysis describes potential impacts to Federal highway revenues under the current finance scenario. Funding shortfalls could be mitigated or avoided in the future through shifts in tax structures or through alternative infrastructure funding mechanisms.

Induced Demand

An important consideration in estimating the greenhouse gas and other benefits of system efficiency and travel activity GHG reduction strategies is "induced demand," where improvements in travel conditions lead to increases in travel that may offset the GHG reduction benefits of the improvements. The magnitude of the induced demand from reduced travel times or travel costs is a source of considerable uncertainty and further research is needed.[5] While induced demand does offset some of the GHG benefits of certain strategies, it also reflects an increase in mobility due to the lower cost of travel and in this way reflects a benefit to society. A more detailed discussion of how induced demand works is included in Appendix A. Induced demand effects are reflected in most of the GHG reduction and cost-effectiveness estimates presented in this report for traffic management, traveler information, and bottleneck relief strategies, so the benefits of these strategies are lower than they would be without consideration of induced demand. Induced demand effects are also reflected in a number of the strategies for reducing carbon-intensive travel activity, as discussed in Section 5.0. A related concept, the "rebound effect" (increased travel as a result of lower fuel costs due to more fuel-efficient vehicles), affects the vehicle fuel efficiency strategies as discussed in Section 3.0.

Induced demand has the potential to affect GHG emissions, fuel savings, and air pollution benefits of the following system efficiency strategies in particular:

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[4] Based on a total fuel savings of 4.6 to 7.2 million gallons and a tax rate of 20.3 cents per gallon (gasoline at 18.4 cents weighted 69 percent, and diesel at 24.4 cents weighted 31 percent).

[5] U.S. DOT is designing research to provide a better understanding of the role of induced demand in offsetting GHG improvements from congestion reduction strategies.

- **Traveler information, traffic management, and bottleneck relief –** Any improvement in highway capacity, reduction in congestion, or reduction in travel times should lead to some induced demand. This induced travel generates GHG emissions through additional VMT; this additional traffic also reduces the initial improvements in travel speed, traffic flow, and energy consumption, further reducing GHG benefits. The effects will increase over time as people adapt their travel in response to transportation system changes. Collectively, these factors will at least partially and perhaps completely offset the initial GHG benefits of these strategies. Estimating the net effect of these factors is outside the scope of this report. However, GHG benefits will still be realized through strategies that make traffic flow more *efficiently* (e.g., fewer stops and starts or hard accelerations) without decreasing overall travel times. Moreover, use of "congestion pricing" in connection with bottleneck relief strategies may limit offsets from induced demand.

- **Freight–specific strategies (ports and intermodal terminals, marine, rail, truck size, and weight limits) –** Improvements that reduce costs for shippers also should reduce costs to consumers, leading to some additional demand for goods. The magnitude of the offset will depend upon the relative contribution of transportation costs to the overall costs of the good, as well as the extent to which cost reductions are passed along to consumers (instead of supporting greater profits). For example, if the consumer price elasticity of a good is -1.0, but transportation costs represent only 5 percent of the good's total costs, then a 10 percent reduction in the shipper's travel time/cost will result in an 0.5 percent increase in the consumption of the good. Reduced transport costs also encourage supply chain managers to move distribution centers to distant, cheaper land, which increases truck travel. On the other hand, if costs are reduced *only* for the least GHG-intensive freight modes (rail and marine), GHG emissions could be reduced because of the shift from more intensive modes, particularly truck.

- **Speed limit reductions –** This strategy could result in "negative" induced demand (i.e., less travel). Since reducing speed limits increases travel times, some travelers may choose to forgo trips or make shorter trips because they cannot get somewhere as quickly.[6] There also may be mode-shifting effects to either more efficient (rail) or less efficient (air) modes. The impact will be larger for long distance trucking, for which travel time impacts will be greatest and which also have the greatest potential for modal diversion.

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[6] The effect is likely to be modest for most trips; reducing speed from 65 mph to 55 mph only reduces travel time by two minutes for a typical 12-mile trip.

Improving System Efficiency by Improving Utilization

System efficiency has many facets, but perhaps the most important element in system efficiency is the system's load factor, sometimes called capacity factor or system utilization. When a transit agency dispatches a 50-passenger transit bus on a route, the cost of the bus, the driver, the maintenance/repair back-up, and fuel/emissions are all essentially fixed. If there is only one passenger, the transit bus is a poor investment from the point-of-view of both economics and the environment. On the other hand, if the bus is full or nearly full, there is a reasonable prospect that fares can pay the costs of the run, while the emissions savings from removing 40 or 50 cars off the road are immense.

Put another way, if there is excess capacity, the economic and emissions cost of adding an extra passenger is essentially zero. This same phenomenon applies to both freight and passenger modes, and (because of high operating costs) is particularly important to aviation. Available data suggests that system efficiency for aviation and freight rail is high and has been improving rapidly in recent years. For example, according to data from the Bureau of Transportation Statistics (BTS, 2009), freight rail energy efficiency (measured per ton-mile) improved by an average of 3.4 percent annually in the 1980s, and 1.5 percent annually since then—even though locomotive technology has changed little. For domestic air travel, energy efficiency per passenger-mile has improved by 2.9 percent annually since 1990*, due to increased passenger load factors, increased fuel efficiency, and improved technologies and operational procedures to reduce fuel burn and emissions. Improvements in these privately-operated modes have been driven by economic pressures. However, due to saturation in improvement that can be maximally attained, this trend will likely continue but at the lower pace. Operational gains estimated through 2035 range between 2.5 and 6 percent.

System efficiency for passenger rail and personal automobiles, on the other hand, has been low and stagnating. Transit energy efficiency per passenger-mile declined in the 1980s and increased by only 0.8 percent annually since then; Amtrak efficiency has not changed since 1990. Automobile efficiency has increased by only 0.5 percent annually since 1990 (BTS, 2009). Average vehicle occupancies have continued to decline (and are only slightly higher than 1.0 for work trips. The implication is that there is considerable scope for improvement in the efficiency of surface passenger transportation modes, and that improvements could potentially generate large increases in transportation services without increases in emissions.

System efficiency strategies that improve freight utilization are considered in various subsections of this section. Strategies that improve passenger vehicle utilization, such as transit and ridesharing, are discussed in Section 5.0, Reducing Carbon-intensive Travel Activity.

*Calculated from data in Volume 1 Section 2.2.

4.2 Highway Operations and Management

Highway operations and management strategies seek to reduce congestion or otherwise keep vehicles moving at their most energy-efficient speeds. Strategies discussed in this report include traffic management systems to maintain efficient traffic flow; traveler information to avoid congested routes and times; bottleneck relief to reduce congestion; and speed limit reductions. These strategies also have the potential to result induced travel in response to improved travel conditions. Because of the complexities in calculating the impact these strategies have on travel demand, travel speeds, and traffic flow, the GHG impact of these strategies was not calculated for this report. The estimates presented below are taken from outside studies and should be considered illustrative.

Traffic Management

Description

Fuel consumption by today's motor vehicles varies by speed, as shown in Figure 4.1. Fuel use is highest at low speeds (under 30 mph), high speeds (over 60 mph), and in driving conditions with much acceleration and deceleration. Conversely, fuel consumption is lower—more efficient—when vehicles are driven at steady and moderate speeds. Traffic management strategies are aimed at reducing congestion, thus leading to more efficient vehicle operation (smoother, moderate-speed traffic flow) and reduced fuel consumption. Most management measures are based on an information infrastructure ("intelligent transportation systems," or ITS) that provides real-time traffic information to system operators and/or users; however some, such as traffic signal optimization, can be done without extensive information systems.

Traffic Management

Benefits: **Low**: 1-10 mmt CO_2e in 2030

- Based on widespread deployment of both proven and experimental technologies
- Estimates reflect induced demand effects

Direct Costs: **Low to High**: $40 to >$2,000 per tonne

Net Included Costs: **Net Savings to High**: -$120 to >$2,000 per tonne

- Costs vary significantly by strategy

Confidence in Estimates: **Moderate**

- Benefits may be reduced depending upon pace of vehicle technology advancements
- Magnitude of induced demand effects is uncertain

Key Co-Benefits and Impacts: **Positive**

- Significant travel time savings

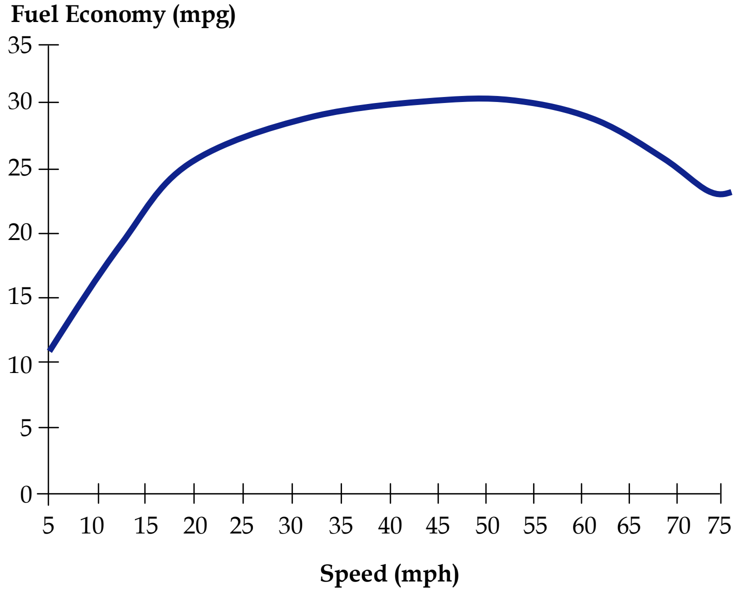
Feasibility: Moderate to High

- Primary barrier is funding

Key Policy Options:

- Targeted funding

Figure 4.1 Example MPG/Speed Relationship for Light-Duty Gasoline Vehicles



Source: http://www.fueleconomy.gov.

Traffic management strategies include:

- Signal optimization and coordination (retiming signals to reduce intersection delay, and coordinating control of traffic signals along a corridor or network);
- Adaptive signal control (use of advanced software that continuously updates signal timing based on demand);
- Incident management (identifying incidents more quickly, improving response times, and managing incident scenes more effectively);
- Ramp metering (placing a stoplight on freeway on-ramps to "meter" or space out traffic during periods of high demand);
- Integrated corridor management (coordination among multiple strategies);
- Active traffic management (emerging strategies to squeeze extra capacity out of the system and prevent flow breakdown, such as lane control, speed harmonization, and queue warning); and
- Vehicle Infrastructure Integration (providing a communications link between vehicles on the road and roadside infrastructure, to provide for safer and more efficient operations).

These strategies are at different stages of development and implementation in the U.S.; some are relatively well established techniques that can be readily expanded; others are in the early stages of research and development and have yet to be broadly deployed.

Traffic management agencies throughout the U.S. vary in their attention to optimization and coordination of traffic signals. According to the 2007 National Traffic Signal Report Card, 72 percent of agencies reported strong or outstanding procedures for updating signal timing parameters when performing a timing update and 62 percent reported conducting a comprehensive review of areawide or corridor signal timings at least every three years (NTOC, 2007). On the other hand, the Institute of Transportation Engineers estimates that over 75 percent of the 300,000 traffic signals in the U.S. could be improved by updating equipment or by simply adjusting and updating the timing plans (ITE, 2009).

Freeway incident management systems are relatively common; they are implemented in a majority of major metropolitan areas, although they still cover only the minority of freeway mileage. Arterial incident management systems are present in only a minority of major metropolitan areas, covering a small fraction of lane-mileage.[7] Ramp metering is also implemented in only a minority of metro areas, covering less than one-third of all freeway miles in 25 major U.S. cities (TTI, 2007).

Integrated Corridor Management (ICM) and Active Traffic Management (ATM) are in their infancy in the U.S. The U.S. DOT's ITS program includes ICM Systems as one of nine major initiatives. The DOT is supporting ICM programs in eight locations throughout the U.S., working with partnerships among State DOTs, regional agencies (MPOs and transit), and local jurisdictions in each area (U.S. DOT, 2009). Active Traffic Management has primarily been deployed in European countries. Vehicle Infrastructure Integration is still in the research and development phase.

The successful implementation of traffic management strategies relies upon the cooperation of a number of actors at different levels of government. State DOTs are typically responsible for traffic operations on freeways, and in some cases on other arterial roadways. Local governments in most States are responsible for signal timing as well as other operations on arterial and local roadways. Toll roads may be operated by a quasi-public or private entity. Incident response also requires the cooperation of emergency responders and law enforcement.

[7] As of 2006, 72 of 106 metro areas surveyed operate one or more traffic management centers. Sixty-three of 100 areas had some amount of their freeway system under surveillance, covering an average of 38 percent of lane miles. Seventy-three areas surveyed had service patrols on freeways, covering 46 percent of lane miles. Arterial incident management systems were implemented in 38 of 106 metro areas, covering 11 percent of lane miles (Cambridge Systematics, Inc., 2008, based on data from U.S. DOT's ITS Deployment Database).

Magnitude and Timing of GHG Reductions

Reducing travel delay has the potential to reduce fuel consumption by reducing idling and inefficient low-speed and stop-and-go operation.[8] Congestion relief strategies also result in some amount of induced travel demand. Induced travel generates GHG emissions through additional VMT; this additional traffic also reduces the initial improvements in travel speed, traffic flow, and energy consumption. The magnitude of induced demand associated with these measures is a source of considerable uncertainty, as is the impact of this traffic on travel speed and traffic flow. Relationships between delay reductions and fuel savings also are subject to some uncertainty.

Analysis performed for the *Moving Cooler* study estimated GHG reductions in the year 2030 – without considering induced demand—on the order of 3–5 mmt CO_2e from ramp metering, 5-7 mmt from incident management, 0-2 mmt from signal control management, <1 mmt from road weather management, up to 6 mmt each from Active Traffic Management and Integrated Corridor Management, and about 6 mmt from Vehicle Infrastructure Integration. The combined benefits of all of these strategies would therefore range from about 24-34 mmt CO_2e. The ranges of potential reductions reflects different levels of aggressiveness in deployment, beyond current levels. The low end assumes deployment of strategies along an additional 200 miles of freeway and 500 miles of arterial annually on an ongoing basis, while the high end assumes deployment of strategies along 400 miles of freeway and 1,000 miles of arterial annually.[9] Considering induced demand, however, significantly reduces the benefits in 2030 – reducing combined benefits from *all* traffic management strategies to in the range of 1 to 10 mmt CO_2e.[10,11]

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[8] Based on work done for FHWA using microscopic traffic simulation, for every hour of vehicle delay reduced, 0.620 gallons of fuel are saved by autos and 1.934 gallons are saved by large trucks (SAIC, 1993). Additional reductions may be achieved through reduced acceleration and deceleration or increasing average operating speeds into the most efficient range of 30 to 60 mph. Traffic signal coordination and control strategies have resulted in fuel use (and corresponding GHG) reductions in the range of 8 to 15 percent in corridors or areas for which the improvements are implemented, not accounting for any changes in traffic volume. Impacts on a regional scale are diluted to perhaps 1 to 4 percent (EEA and Cambridge Systematics, Inc., 1999).

[9] This represents about 3.7 percent of freeways and 1.6 percent of major arterials in U.S. urban areas, based on data from FHWA's 2006 Highway Statistics.

[10] The *Moving Cooler* study (Cambridge Systematics, 2009) examined the GHG impacts and cost effectiveness of a wide range of strategies directed at reducing VMT and improving transportation system efficiency. The study used FHWA's Highway Economic Requirements System (HERS) model to estimate the delay reduction and travel demand effects of bottleneck relief strategies, and analysis methods based on HERS model data to estimate the impacts of traffic management strategies. HERS accounts for induced demand using elasticities of travel demand with respect to general travel costs, which include travel time, fuel costs, maintenance costs, and other out-of-pocket expenses. The HERS model uses an elasticity of travel with respect to total vehicle operating cost equivalent to -0.4 for the first five years and an additional -0.4

(Footnote continued on next page...)

An alternative "bottom-up" approach to estimating GHG benefits from signal optimization can be developed based on a signal timing evaluation conducted in Portland, Oregon. This study estimated that approximately 50 metric tons of CO_2 were saved each year per traffic signal retimed in the city, although the study did not account for induced demand effects. With approximately 3,300 traffic signals in the State, of which 70 percent could benefit from retiming, the potential Statewide CO_2 savings would be 115,000 metric tons in one year (Peters, McCourt, and Hurtado, 2009). Further extrapolating these results to the entire United States, based on ITE's estimate of 300,000 traffic signals, provides an estimated benefit of 11 mmt CO_2e annually. This is somewhat higher than the top-down nationwide estimate for developed for *Moving Cooler*, which assumed phased implementation over time and a lower benefit per signal and accounted for induced demand.[12]

Another important consideration is that the future effectiveness of traffic management strategies will depend upon vehicle technology. With hybrid and electric-drive vehicles, driving cycles have a much lesser impact on fuel consumption and emissions. For example, today's hybrid-electric vehicles have urban fuel economy ratings that typically exceed highway fuel economy ratings. All of the benefits estimates cited above assume current vehicle technology, albeit with improved fuel economy under the baseline assumptions described in Appendix A of this report.

As previously noted, State and local agencies are at varying stages of deploying traffic management technologies. Some technologies (such as signal coordination and incident management) are well-developed, and further widespread implementation could occur within the next 5 to 10 years if financial, institutional, and political barriers are overcome

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thereafter, for a total long-run elasticity of -0.8 (see Appendix A). An elasticity of -0.8 means that a 1 percent decrease in total travel costs will result in a 0.8 percent increase in VMT.

[11] The 10 mmt figure reflects an adjustment to the *Moving Cooler* study results to account for the fact that the induced demand effect may have been overstated compared to the estimates for capacity expansion and bottleneck relief strategies, which were based on different parameters. The *Moving Cooler* study estimated that 93 to 95 percent of the 2030 benefits of traffic management strategies would be offset by induced demand, but only 70 to 80 percent of capacity expansion and bottleneck relief strategies. The difference appears to be at least in part due to the fact that induced demand parameters for traffic operations strategies were not updated to be consistent with the final parameters used for capacity expansion and bottleneck relief strategies. Therefore, a range of induced demand effects is shown here, and the range of GHG benefits for the "with induced demand" case is adjusted to show a maximum benefit that reflects only a 70 percent reduction compared to the "without induced demand" case.

[12] The *Moving Cooler* benefits for signal control management are based strictly on type of signal control, in increasing order of sophistication: pre-timed/actuated, central control, and real time traffic adaptive. Signals are assumed to be upgraded one level, with a coverage rate of up to 2,000 miles of roadway per year. Delay savings per signal without induced demand are estimated to be in the range of 5 to 12 percent, much smaller than the 15 to 40 percent reported in the Portland study. These smaller delay savings account for the fact that at high levels of delay (as the entire intersection approaches exceeds capacity), improved signal timing will not result in GHG benefits because delay is controlled by capacity, rather than signal timing.

(see "feasibility"). Other strategies, such as Active Traffic Management, are still in the development phases and could take 10 to 20 years or more to reach full deployment even with aggressive funding and implementation activities. To maintain the benefits of operational improvements over time, signal timing must be readjusted regularly as traffic conditions change; the Institute of Transportation Engineers suggests reviewing signal timing annually (ITE, 2009).

Cost-Effectiveness

Costs of traffic management strategies vary greatly. Costs range from as low as $2,500 to $3,100 to retime individual intersections, to on the order of $5 to $10 million for establishing an Emergency Response Center or a Transportation Management Center for a large metropolitan area, plus $0.5 to $1.5 million annually in operating costs (ITS Unit Costs Database, reported in Cambridge Systematics, 2008). If implemented on a nationwide basis, ramp metering is estimated to cost between $1.3 and $7.5 billion; signal control management between $2.5 and $17 billion; and incident management between $2.2 and $13 billion, depending upon the extent of the metropolitan highway system covered. The costs of deploying Active Traffic Management or Integrated Corridor Management nationwide are estimated to range from $11 to $26 billion, again depending upon the extent of the highway system covered (Cambridge Systematics, 2009). Costs for traffic management strategies will typically be borne by public sector transportation agencies (or toll facility operators) and financed through State, regional, and local transportation funding sources.

The cost-effectiveness of traffic management strategies depends strongly upon whether induced demand effects are considered in estimating the benefits. Without induced demand effects, the cost-effectiveness of traffic signal retiming (measured in terms of GHG reductions) is estimated to be quite good – about $12 per tonne CO_2e reduced considering implementation costs only.[13] More advanced traffic management strategies have varying levels of cost-effectiveness. Ramp metering and incident management strategies appear to be among the more cost-effective with estimates in the range of $10-40 per tonne GHG reduced over the 2010 to 2050 timeframe. Active Traffic Management and Integrated Corridor management are somewhat less cost-effective (in the range of $100 per tonne) as is signal control management (in the range of $200 per tonne) (Cambridge Systematics, 2009). Including benefits to travelers in the form of vehicle operating-cost savings, cost-effectiveness is estimated to be in the range of -$150-170 per tonne GHG reduced over the 2010 to 2050 timeframe, with Active Traffic Management and Integrated Corridor management in the range of -$90-140 per tonne and signal control management in the range of -$40 to +$50 per tonne. Vehicle Infrastructure Integration is estimated to range from $130 to $160 per tonne for implementation costs only, or -$20 to -$40 per tonne considering operating cost savings to travelers. These estimates do not include the value of time savings.

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[13] This estimate applies the benefits extrapolated from the previously referenced Portland study, and assumes costs of $3,000 per retiming annualized over five years.

Including induced demand effects changes the estimates significantly. Ramp metering and incident management have moderate cost-effectiveness, ranging from $40-90 per tonne for ramp metering and $40 to $170 per tonne for incident management (considering implementation costs only); both strategies show net savings when vehicle operating costs savings are included (up to -$120 per tonne for ramp metering and incident management and lower deployment levels). All other strategies have direct costs of over $200 per tonne (and in a few cases over $2,000 per tonne for road weather management and vehicle infrastructure integration and maximum deployment levels), and show a net cost even when vehicle operating cost savings are included (Cambridge Systematics, 2009).

Cobenefits

Traffic management strategies can have significant benefits in terms of delay reduction for travelers and goods movement. For example, a review of various case studies of preset-timing traffic signal coordination suggests that travel-time reductions in the range of 8 to 25 percent are possible along a particular corridor. Studies of actuated traffic signal coordination have found observed or simulated reductions in travel times from 8 percent to as high as 41 percent, with delay reductions ranging from 14 to 44 percent compared to baseline delay where the improvements have been applied (Cambridge Systematics, no date). The Texas Transportation Institute reports that ramp metering in 25 cities reduces delay by 29.4 million person hours, or approximately 2.4 percent of freeway delay (TTI 2007). Incident management practices have been estimated to reduce incident duration by 39 to 51 percent.[14] Various European countries have experienced a 3 to 7 percent increase in peak period throughput and a 3 to 22 percent capacity increase along highway corridors in which Active Traffic Management is applied (FHWA, 2007a).

Improved safety also is likely to be a by-product of some strategies; for example, crashes may be reduced if motorists are informed of upcoming congestion or if stop-and-go traffic is reduced. Incident management practices that decrease response time can save lives by getting victims medical attention more quickly. Active Traffic Management has been credited with significant reductions in incidents (up to 50 percent) in European applications (FHWA, 2007a).

Traffic management strategies also should result in air quality benefits. Traffic actuated signalization along corridors in three cities reduced hydrocarbon and carbon monoxide emissions by 4 to 12 percent, although oxides of nitrogen increased slightly (by 4 percent) in one location. An evaluation of preset ramp metering in Denver found a reduction in emissions of 24 percent (Mitretek, 2005). These benefits are based on current vehicle technologies and may be reduced in the future, especially if electric-drivetrain vehicles are widely adopted. These estimates of air quality benefits also do not include any additional emissions resulting from induced demand.

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[14]FHWA's IDAS model provides default values of a 39 percent delay reduction for improved incident response/management procedures alone, and 51 percent for combined incident detection and response/management procedures.

Feasibility

Traffic management strategies already are being widely deployed. Funding and institutional issues represent the largest barriers to more comprehensive deployment; these strategies require redirection of scarce resources as well as effective coordination among State, regional, and local agencies. For example, an assessment of the efforts in Oakland, California as part of the ICM initiative found that while technical and operational challenges are relatively easy to deal with, institutional challenges, involving many disparate stakeholders, are the most difficult (LaPlante, 2007). Many traffic signals are under the control of smaller local jurisdictions, which may not have the technical resources to retime and optimize signals on a regular basis, let alone coordinate signals across a corridor or network. One significant action the Federal government could take to speed deployment of traffic management strategies is to provide additional funding to cover the capital and operating costs of regional traffic management systems. Funding and technical support for local jurisdictions (e.g., to support ongoing signal retiming) and interjurisdictional coordination efforts also would likely go far in improving traffic management practices.

Some strategies also have political barriers. For example, ramp metering has proven effective and inexpensive, but is not widely implemented in some areas because of equity concerns regarding who benefits and who is impacted. These concerns led to a shutdown of the Minneapolis–St. Paul ramp metering system in 2001, and its subsequent reinstatement (after traffic conditions worsened considerably) with modified metering patterns to reduce queuing.

Real-Time Traveler Information

Description

Traveler information strategies provide motorists and truckers with up-to-date information on traffic conditions and incidents, and expected delays; the availability of public transportation and other travel alternatives; weather conditions; road construction; and special events. GHG reductions result when better informed travelers and truckers plan trips to avoid congestion by taking alternative routes, forego unnecessary trips, delay travel, or take alternative modes. Traveler information systems therefore achieve GHG reductions

Real-Time Traveler Information

Benefits: **Low**: <0.5 mmt CO_2e (2030)

Direct Costs: **Moderate to High**: $160 to >$600 per tonne

Net Included Costs: **Low to High**: $0 to >$500 per tonne

Confidence in Estimates: **Low**

- Limited evidence on highway traveler information benefits; almost no evidence on information for other modes

Key Co-Benefits and Impacts: **Positive**

- Traveler awareness/satisfaction

Feasibility: **High**

- Public and private sector initiatives in progress

Key Policy Options:

- Targeted funding

both by improving efficiency (e.g., avoiding congestion) and reducing VMT. In some cases, however, better information can have mixed effects. For example, if travelers take a longer route to avoid an incident on their usual route, their VMT will increase, potentially offsetting the GHG reduction from avoiding travel in congested conditions.

Traveler information can take a variety of forms:

- Road status information systems that provide information on roadway traffic conditions and congestion, including travel times and major incidents or delays;
- Information on public transit, including real-time information on expected arrival times, travel times, delays, etc., as well as systems to help people plan trips;
- Carpool information systems that provide advance or real-time information regarding commuters or other travelers destined to the same area and willing to carpool;
- Multimodal information systems that provide travelers with information on the various alternatives they have to get from point A to point B, considering different modes of travel;
- Parking guidance and information systems that provide drivers with dynamic information on parking within controlled areas and assist in searching for vacant parking spaces; and
- Freight route management systems that help carriers make more efficient routing and scheduling decisions in order to avoid congestion, reduce freight vehicle mileage, and increase load factors (e.g., avoiding empty backhauls).

Traveler information is disseminated through a variety of mechanisms, including Internet sites, 511 telephone information systems, auto texting and e-mails to mobile devices, in-vehicle GPS equipment, television public service announcements, radio announcements, public information kiosks, and dynamic (changeable) signs.

Highway traveler information has traditionally relied on the same information infrastructure that supports intelligent traffic management through monitoring of traffic conditions. Various levels of highway traveler information are present in most major U.S. metropolitan areas. As of 2006, 63 of 100 surveyed metropolitan areas conducted real-time traffic data collection on freeways, covering 38 percent of lane miles (Cambridge Systematics, 2008). As of February 2008, 30 States had established 511 information systems.

The private sector is taking a strong role in traveler information services. There is much private sector activity underway to provide customized delivery of traveler information to individual travelers via handheld and in-vehicle devices. Anonymous location tracking using global positioning system (GPS)-enabled mobile phones is providing much more comprehensive real-time information than older monitoring technologies such as loop detectors, cameras, and probe vehicles. Private providers of real-time information such as NavTeq/Traffic.com and Inrix cover many metropolitan areas – INRIX has real-time traffic information available in 126 metropolitan areas as of April 2009 (INRIX, 2009), and one can view traffic speeds in over 60 U.S. cities on Google maps.

Real-time traveler information programs for transit systems are in somewhat less advanced stages of deployment. Many U.S. rail transit systems provide real-time information on train arrivals, but real-time information for buses is less common. The technology exists, however, and has been demonstrated through applications such as NextBus, which combines GPS data with predictive software to give passengers, either on the Internet or at the stop, arrival times for the next few vehicles. NextBus technology has been applied in a number of locations, including Arlington, Virginia; Delaware; San Francisco; and Toronto.[15] Transit agencies are increasingly adopting web-based trip planners that give travelers detailed information on their alternatives given an origin, destination, and start or end time. Private services such as Google and SmarTraveler also have ventured into the realm of providing transit information, but to date have been limited by the availability of underlying data provided by transit agencies.

Worksite-based carpool matching programs have long been a staple of transportation demand management (TDM) initiatives. Only very recently, however, has technology evolved to the point of allowing "real-time" formation of carpools, including for nonwork and irregularly scheduled trips; we are now witnessing rapid innovations is this area. For example, NuRide runs a free, on-line, ridematching service as part of a larger incentive-based program that rewards members for "green trips"; the service had nearly 40,000 members as of February 2009.[16] GoLoco is a Facebook-based ridematching service in which travelers split costs. PickupPal, a free on-line ridesharing service based in Ontario and launched in early 2008, had 100,000 users in 60 countries around the world as of September 2008.[17] The service focuses on casual carpooling for special events; users can enter their start and end point and be matched with other users with similar itineraries. At least nine national on-line ridesharing sites were operating as of February 2009, in addition to numerous regional sites.[18]

Parking guidance systems also are in their infancy in the U.S. One example of parking guidance and reservations is the advanced parking system at Baltimore Washington International (BWI) Airport. Travelers can reserve a parking space at specific facilities or be guided to open floors and stalls by means of ultrasound detection. These techniques have been applied somewhat more widely in Europe, where central business districts often have information signs indicating parking availability and directing drivers to available spots (Figure 4.2).

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[15] http://www.nextbus.com.

[16] http://www.nuride.com.

[17] Urban Transportation Monitor, September 5, 2008.

[18] http://www.rideshare-directory.com/.

Freight route management information is in common use in the private sector. Carriers use GPS systems to track truck locations, provide weather and traffic information, and identify alternative routes. The state-of-the-art with GPS is to incorporate real-time traffic data into the routing algorithms. These are available on consumer GPS, both as original equipment manufacturer (OEM) installations on vehicles as well as aftermarket devices. In addition, most carriers use routing and dispatching programs that plot and optimize truck routes based on pick up and delivery points, refueling stations, etc. UPS and FedEx both have in-house proprietary systems that do dynamic routing.

Figure 4.2 Parking Information System in Freiburg, Germany

Source: Christopher Porter, Cambridge Systematics, Inc.

A few States have explored 511, weather, and traffic congestion information systems for truckers, but few have done much that is sufficiently targeted or timely enough to be as good or better than motor carriers' own systems. One exception is the Washington State DOT's proactive road condition and weather/emergency closure notification program. Additional demonstration projects currently are being funded by some public agencies. For example, the Kansas City Cross-Town Improvement Project, funded in part by FHWA's Office of Freight Management and Operations, is designing a system that would allow trucks to dynamically change routes due to traffic congestion/incidents. The FleetForward test, funded by the I-95 Corridor Coalition, integrated real-time traffic information into carrier routing decisions/software. The Pennsylvania DOT and the I-95 Corridor Coalition currently are looking at the operational benefits of integrating real-time parking availability data into motor carrier routing decisions.

Magnitude and Timing of GHG Reductions

Most of the research quantifying the VMT and potential GHG benefits of traveler information systems has examined highway and transit traveler information systems. Even so, the evidence on the benefits of these strategies is quite limited as it has generally been difficult to measure and quantify specific impacts. The diffuse nature of impacts (spread across the transportation network) and the many ways in which travelers may acquire and respond to information makes it especially challenging to evaluate the impacts of improved information. Furthermore, some traveler responses, such as taking longer routes to avoid congestion, may actually increase VMT and GHG.

Available literature suggests that road status information programs may cause an increase in VMT that roughly offsets the benefits from reduced delay on the mainline (FHWA, no date). However, the literature has been primarily qualitative rather than quantitative, with the exception of one simulation study that predicted a statistically insignificant (0.1 percent) systemwide reduction in VMT from advanced traveler information system strategies and similarly insignificant (0.1 to 0.3 percent) reductions in emissions, compared to a 1.5 percent reduction in overall vehicle-hours of delay (Wunderlich, Bunch, and Larkin, 1999). On the other hand, another study using a computer simulation model concluded that providing motorists in Seattle, Washington, with information about traffic incidents and congestion could lead to a 1.8 percent reduction in average vehicle delay and a 2 percent reduction in vehicle emissions for morning peak periods, as better informed travelers were able to choose the most efficient mode and route to their destination (Jensen et al., 2000).

The *Moving Cooler* study estimated that very modest net GHG reduction benefits would accrue from traveler information systems, including 511 systems, a Web site, and personalized information. The study assumed a 1 percent delay reduction for the lowest level (511 and Web sites only) and 2.5 percent for more aggressive deployment, including personalized information, but also accounts for increased GHG over the long run due to induced demand effects from reduced delay. The overall magnitude of GHG reductions that might be expected from further deployment of traveler information was estimated at 0.6 to 1.8 mmt CO_2e in 2030, or only 0.1 to 0.5 mmt considering induced demand effects (Cambridge Systematics, 2009).[19] Because these estimates were based on professional judgment regarding delay reduction and because no assumptions on diversion were used, they are subject to some uncertainty.

The impact of transit traveler information on mode shifting from auto to transit, and therefore on reduced VMT and GHG emissions, has not been comprehensively studied. Similarly, no reliable evidence yet exists on the potential benefits of real-time carpool and

[19] The lower scenario assumes 511 and Web site only, and deployment along highway segments with peak-period volume-to-capacity ratios greater than 1.05; the more aggressive scenario includes personalized information and deployment along all highways with peak period volume-to-capacity ratios greater than 0.95. The induced demand effects include the same adjustment described in footnotes 5 and 7 under Section 4.2.1.

parking information systems, because these systems are in their infancy. NuRide claims to have reduced 2.4 million car trips and 26.8 tons of emissions as of February 2009, although it is not clear to what extent this includes transit, walk, and bike trips registered by members in addition to carpool trips through the site. Studies around the world have found that between 8 and 74 percent of the traffic present in some congested business districts is due to cruising for parking (Shoup, 2005); while this has not been extrapolated to a nationwide basis, parking search VMT is likely to be only a small fraction of total personal vehicle travel in the U.S.

The limited evaluation data on freight route management systems has not been able to quantify a VMT, fuel savings, or GHG benefit. In an operational test of the FleetForward program by the I-95 Corridor Coalition, carriers generally did not believe that the technology reduced operating costs (of which fuel consumption is one component) and the study was unable to identify any impact on congestion (Cambridge Systematics and SAIC, 2000).

Real-time traveler information should become increasingly widespread over the next 5 to 10 years. Almost all States already have developed and implemented Statewide Web sites for distributing traveler information, according to the most recently available survey data (U.S. DOT, 2007). Many other States and regions are in the process of developing 511 systems (FHWA, 2008). Within 5 years, most of the top 75 urban areas are expected to have detailed traveler information available for at least their freeways, and all States are expected to have Statewide 511 systems in place. Deployment of private sector-based traveler information systems is in its early stages, but significant penetration of private sector traveler information is expected to be achieved in 5 to 7 years. As of 2008, 78 percent of American adults owned a cellular telephone and 13 percent owned a Blackberry, Palm, or other personal digital assistant, and adoption is increasing rapidly (Pew Internet and American Life Project, 2008). As web-enabled cell phone and PDA technology expands, the ability of travelers to access and utilize real-time information will increase significantly.

Cost-Effectiveness

The cost of developing and deploying traveler information strategies varies widely. Average costs for developing Statewide and metropolitan 511 traveler information systems, for example, have ranged from $133,000 to $1,028,000, with an average cost of $416,000. Roadside equipment costs, such as dynamic message signs and highway advisor radios constitute significant expenses. Capital costs for dynamic message signs range from $47,000 to $117,000 and annual operations and maintenance costs range from $2,300 to $6,000 per sign. Capital costs for highway advisory radio range from $15,000 up to $35,000, in additional to $600 to $1,000 annual operations and maintenance expenses (U.S. DOT, 2007). Although these expenditures are not trivial, there is evidence that the benefits of traveler information strategies significantly outweigh the costs when pursuing multiple transportation objectives. For example, in California, it is estimated that every $1.00 invested in Statewide traveler information strategies will yield $100 in benefits (e.g., reduced travel times and vehicle operating costs) over the next 20 years (U.S. DOT, 2007).

The *Moving Cooler* study estimated the cost per tonne of GHG reduction from these types of traveler information strategies to be in the range of $80 to $170 per tonne including direct costs only, or from -$20 to -$110 per tonne (a net savings) considering vehicle operating cost savings, but without induced demand effects. Including induced demand effects increases the direct cost per tonne to $160 to over $600, and the net included cost per tonne to $0 to over $500. These estimates are based on nationwide deployment costs in the range of $2 to $12 billion, depending upon the extent of deployment.

The use of cellular telephones and probe vehicles (e.g., taxis, delivery trucks, or buses outfitted with monitoring devices) for monitoring travel times has reduced the need for costly investment in monitoring infrastructure. Increasingly, private sector companies are providing traffic information to operating agencies for a fee, and/or providing traffic information for customers at no cost to public agencies.

No reliable evidence yet exists on the potential cost-effectiveness of real-time transit, carpool, parking, or freight information systems in reducing GHG emissions. The increasing adoption of web-enabled mobile devices, however, is providing a mechanism to disseminate information without the need for public-sector capital investment in signs, radio, and other infrastructure.

Cobenefits

Traveler information helps travelers adapt to congested conditions by changing routes, departure times, modes, or being able to alert others to schedule changes. A review of existing literature by FHWA estimated that Highway Advisory Radio can save 0.7 percent of nonrecurring vehicle hours of delay, and Variable Message Signs 4.2 percent (FHWA, no date).[20] Improved safety also is likely to be a by-product of some strategies; for example, crashes may be reduced if motorists are informed of upcoming congestion. In addition, many States that have deployed 511 phone systems and other traveler information systems have begun placing AMBER Alerts and homeland security alerts on their systems (511 Deployment Commission, 2004). In some States, traveler information systems may be used to facilitate large scale evacuations due to extreme weather events.

Computerized truck routing and dispatching systems have, as previously noted, been widely adopted by the private sector and generally have been very cost effective for carriers as a result of time and fuel savings. Truck highway information systems also have been found to be beneficial; in an operational test of the FleetForward program by the I-95 Corridor Coalition, 75 percent of carriers believed it was a valuable tool to identify congestion and 33 percent believed that on-time delivery and/or estimated time of arrival improved (Cambridge Systematics and SAIC, 2000).

[20]Nonrecurring congestion does not occur every day, but results from incidents, bad weather, work zones, or special events. FHWA estimates that about half of all congestion is nonrecurring.

Feasibility

Roadway-based information strategies already are being widely deployed. One key barrier to more comprehensive deployment is institutional; widespread deployment and use of information infrastructure requires effective coordination among State, regional, and local agencies and potentially private entities. As with traffic management, which relies on a common information infrastructure, perhaps the most significant action the Federal government could take to speed deployment of traveler information strategies is to provide additional funding to cover the design, construction, and operation of information collection and dissemination systems, as well as to specifically support interagency and interjurisdictional coordination efforts.

There is significant potential for the private sector to enter the traveler information market. The degree to which the private sector will participate with publicly sponsored traveler information systems is not yet known. It also is conceivable that the private sector will offer an increasingly comprehensive set of traveler information services, thus reducing or even eliminating the need for public sector involvement in some types of services.

Greater provision of transit traveler information is limited by fiscal and resource constraints at transit agencies with limited operating budgets. Funding to support the deployment of the required hardware and software data management systems could help overcome this barrier. Carpool matching systems are being tested by the private sector, but traveler interest/acceptance remains a significant unknown. The willingness of travelers to lose a small amount of travel time and travel with a stranger is likely to depend greatly on the price of fuel and therefore the monetary benefits of doing so. Parking guidance systems currently are most feasible at large, centrally operated parking facilities; concepts are emerging for providing parking information where parking is decentralized (such as business districts) but their feasibility is unknown.

Bottleneck Relief

Description

Bottlenecks are specific points on the transportation network where demand exceeds capacity, thereby creating traffic delays and leading to wasted fuel and excess GHG emissions. Major physical bottlenecks have been the focus of transportation improvements—and of travelers' concerns—for many years. On much of the urban highway system, there are specific points that are notorious for causing congestion on a daily basis. These locations—which can be a single interchange (usually freeway-to-freeway), a series of closely spaced interchanges, or lane-drops—are focal points for congestion in corridors; major bottlenecks tend to dominate congestion in corridors where they exist.

Bottleneck Relief

Benefits: **Low**: 1-6 mmt CO_2e in 2030

- Low benefits reflect induced demand effects, but assume that all capacity improvements would be fully financed by user fees, which would partly mitigate these effects
- Estimates do not include GHG emissions from construction activities or delay during construction

Direct Costs: **Not available**

Net Included Costs: **Not available**

Confidence in Estimates: **Low**

- Significant uncertainty over induced demand effects

Key Co-Benefits and Impacts: **Positive**

- Significant time savings to travelers

Feasibility: **Moderate - High**

- Established transportation project development process. Some projects may encounter environmental constraints

Key Policy Options:

- Funding

The severity of congestion at a bottleneck is related to its physical design. Some facilities were originally constructed many years ago using designs that were appropriate when they were built, but are now considered antiquated. Others have been built to extremely high design specifications and are simply overwhelmed by traffic.

The costs of reducing bottlenecks vary considerably. In many cases, bottleneck relief can occur through relatively low-cost strategies such as: hard shoulder running (using a shoulder as a through lane during peak or emergency periods); restriping to increase the number of lanes; paved shoulders; or median barrier treatments (e.g., cables, Jersey barriers). Somewhat higher-cost strategies include auxiliary lanes, especially between two closely spaced interchanges; collector-distributor roads; and added lanes. In some cases, major reconstruction of interchanges – at high cost – is necessary. Traffic management strategies such as ramp metering and active traffic management (lane control, speed harmonization, and queue warning), which are considered elsewhere in this report, also can be considered to be bottleneck relief strategies. Many major bottleneck fixes include "packages" of improvements, which combine major reconstruction, low-cost treatments, transit service, and improved operations. Improvements at one location are often done in conjunction with other improvements across an entire corridor. Specific bottlenecks may be under the jurisdiction of either State or local transportation agencies and subject to improvement through the transportation planning and programming process.

Magnitude and Timing of GHG Reductions

Bottlenecks are the source of recurring congestion. Though occurring at specific locations, they can influence many miles of highways as queuing occurs because of the traffic flow breakdown at the bottleneck points. Therefore, bottleneck relief reduces congestion delays and changes drive cycles (both acceleration/deceleration profiles as well as average speeds), potentially improving fuel efficiency and reducing GHG emissions.[21] However, bottleneck relief strategies also result in some amount of induced travel. This

[21] Impacts are specific to each site. Based on work done for FHWA using microscopic traffic simulation, for every hour of vehicle delay reduced, on average 0.62 gallons of fuel are saved by autos and 1.94 gallons are saved by large trucks (SAIC, 1993).

additional VMT results in additional fuel consumption and GHG emissions; it also reduces the initial travel speed and traffic flow benefits of these strategies. The magnitude of the induced demand is subject to considerable uncertainty, as is its impact on delay reductions and fuel savings. Bottleneck relief projects also involve GHG emissions from construction activities and delay during construction, which further offset any GHG reductions, although these effects have also not been rigorously analyzed.

The *Moving Cooler* study estimated that, not considering induced demand effects or construction emissions, improving the top 100 bottleneck locations in the country could reduce GHG emissions by 6 mmt CO_2e in 2030, while improving the top 200 locations could reduce emissions by 14 mmt (Cambridge Systematics, 2009).[22] The benefits of bottleneck improvements, however, may be substantially reduced through induced demand effects, as more travel occurs in response to improved highway conditions (see Appendix A). Using assumptions consistent with FHWA's 2008 *Conditions and Performance Report* (FHWA, 2008d), the *Moving Cooler* study estimated that the GHG benefits of bottleneck relief would be reduced to 1 to 6 mmt CO_2e in 2030 if induced demand effects were included;[23] this analysis assumed (consistent with the *Conditions and Performance Report* methodology and current highway funding practice) that projects would be fully financed by increased fuel taxes, which would partly dampen the induced demand from lower congestion levels. The study further concluded that as increased travel outweighed the efficiency gains in later years, the entire cumulative GHG reductions from bottleneck improvements over the 2010 to 2050 period could potentially be offset by induced demand (Cambridge Systematics, 2009).

Cost-Effectiveness

The costs of individual bottleneck relief projects vary widely, but typically range on the order of a few million dollars on the low end, to tens—or even hundreds – of million dollars for construction projects such as interchange construction/reconstruction or lane additions on short segments. Improving the top 100 bottleneck locations in the country is estimated to cost $28.8 billion, or about $280 million per location (AHUA, 2004). Since these are the locations where delay is greatest, they also are locations where investment costs are likely to be greatest. Not including induced demand effects, the *Moving Cooler* study estimated the cost per tonne of GHG reduction of improving the top 100 bottleneck locations in the country to be $90 per tonne GHG, or $130 per tonne for the top 200 bottlenecks, considering direct costs alone. If vehicle operating-cost savings are taken into

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[22]Bottlenecks were identified based on a study for the American Highway Users Alliance (AHUA, 2004) and were defined in this study as a "severe traffic chokepoint" at which drivers spend at least 700,000 hours per year in congestion. Most of these bottlenecks are single interchanges (usually freeway-to-freeway), a series of closely spaced interchanges, or lane drops on freeways.

[23] As described in Footnote 12, the travel demand impacts (including induced demand) were calculated using FHWA's HERS model, which estimates demand as a function of total user costs, with a short-term elasticity (first five years) of roughly -0.4 and a long-term elasticity of roughly -0.8.

account, cost-effectiveness is estimated to range from -$40 to -$80 per tonne (Cambridge Systematics, 2009). Since there was no net benefit from bottleneck relief over the 2010-2050 period once induced demand was included, cost per tonne could not be calculated in this scenario.

Cobenefits

Bottleneck relief will have strong cobenefits in terms of reduced delay (time savings) for passenger and freight travelers and reduced vehicle operating costs. These time and cost savings for travel are then passed along as benefits to the larger economy. Low-cost bottleneck treatments have proven to be highly cost effective, even when travel time savings is the only criterion used. For example, three low-cost bottleneck projects in the Minneapolis–St. Paul area (ranging from $2.6 to $10.5 million) produced delay reductions of 87,000 to over 1 million hours annually, resulting in a benefit/cost ratio of between 3:1 and 13:1 (FHWA, 2007b). This study did not consider induced demand effects.

With the exception of oxides of nitrogen (NO_x), other major categories of automobile emissions will be reduced with the reduction in congestion. Also, because crash history is generally addressed when major interchanges are redesigned, there will be safety benefits as well. All of these benefits accrue over multiple years after improvements are made. The American Highway Users Alliance estimated the total benefits in several categories from improving the top 223 bottlenecks in the country (Table 4.3). These benefits are assumed to accumulate over the course of 20 years after improvements are made, and are for all vehicles moving through the bottlenecks' areas of influence, which was assumed to extend for five miles (two and one-half miles in each direction from the bottleneck). Again, this study did not consider any offsetting reductions in benefits as a result of induced demand.

Table 4.3 Total Benefits from Improving the Nation's Worst Traffic Bottlenecks (223 Locations)

Benefit Type	Reduction Due to Improvement (Over 20 Years of Project Life)	Percentage Change Over Five-Mile Segment
Carbon Monoxide (million tons)	**27.1**	**-54%**
Volatile Organic Compounds (million tons)	**2.7**	**-50%**
Carbon Dioxide (million tons)	**390**	**-77%**
Total Delay (million hours)	**48,100**	**-77%**
Total Fuel Savings (million gallons)	**40,011,800**	**-77%**
Total Crashes	**449,600**	**N/A**

Source: AHUA, 2004.

Bottleneck relief projects that involve major reconstruction (such as interchange reconfiguration or lane additions) could result in property takings or other community and environmental impacts. Any project that receives Federal funding is required to go through the environmental review process which may result in actions to reduce or mitigate any impacts.

Feasibility

Bottleneck relief projects continue to be implemented throughout the nation. The feasibility of any particular project depends upon its costs and other impacts. Because of their capital-intensive nature, the ability to undertake major bottleneck relief projects is limited by the availability of Federal, State, and local funding for transportation projects; the most significant action the Federal government could take to increase the rate at which bottlenecks are improved is simply to provide more funding. Major reconstruction projects also may encounter local opposition if community and/or environmental impacts are significant. Some transportation agencies may have operational, safety, or other concerns about applying strategies such as hard-shoulder running or restriping that narrows lane widths.

Reduced Speed Limits

Description

This strategy would reduce speed limits on high speed facilities to maximize fuel efficiency. These limits would be implemented on the Interstate system, other limited access highways, and possibly on high speed rural major arterials (in general, potentially up to all facilities currently posted over 55 mph). Automotive fuel efficiency varies with vehicle speed, with peak efficiencies usually being achieved between 30 and 60 miles per hour, depending upon vehicle type and weight, aerodynamics, tire type, engine size, and other factors (GAO, 2008). A representative fuel economy curve for gasoline powered light-duty vehicles is shown in Figure 4.1, with maximum efficiency occurring between 50 and 55 mph. Similar relationships are seen with other passenger vehicles and heavy-duty diesel vehicles as well, although optimal operating speeds vary.

Reduced Speed Limits

Benefits: **Moderate**: 27-43 mmt CO_2e in 2030

Direct Costs: **Low**: $10 per tonne

Net Included Costs: **Net Savings**: -$320 per tonne

Confidence in Estimates: **Moderate**

- Depends upon level of enforcement

Key Co-Benefits and Impacts: **Mixed**

- Safety benefits; increased travel times

Feasibility: Moderate-high

- Past experience; but widespread resistance and poor compliance

Key Policy Options:

- National uniform speed limit; incentives for enforcement

As seen in the figure, conventional vehicles suffer significant degradation in fuel efficiency at high speeds, primarily due to rapidly increasing wind resistance and other sources of friction. For this reason highway speed limit reductions have been considered as a means of reducing fuel consumption across the country. The Emergency Highway Energy Conservation Act of 1974 first instituted a nationwide speed limit of 55 mph with the goal of reducing total on-road fuel consumption by two percent. However, the law was met with widespread resistance and poor overall compliance, and was ultimately repealed in 1995. Since that time several States have raised their speed limits to pre-1974 levels, while others have retained the lower speeds. An analysis of the 1974 speed limit concluded that it did result in savings of about two percent of annual gasoline consumption while in effect (TRB, 1984).

Speed limit reduction programs are again under consideration, largely in response to climate change concerns, as well as rising gasoline and diesel prices. The economic value of speed control has been recognized in the heavy-duty truck sector, with the American Trucking Association (ATA) reporting that 77 percent of its members have adopted on-board speed limiters restricting operation to 68 mph or less (Lavelle, 2008). In support of climate action plans, States, including Arizona, Arkansas, California, Minnesota, New Mexico, New York, and Utah also have conducted preliminary evaluations of the potential fuel consumption and CO_2 benefit associated with lowering average heavy-duty truck speeds to 60 or 55 mph, lowering the maximum speed limit for all vehicles, and/or through improved enforcement of speed limits.[24] Recent Congressional inquiries and proposed legislation have prompted similar investigations for light-duty passenger vehicles as well as heavy-duty vehicles (Coile, 2008).

The amount of fuel consumption benefits resulting from speed limit reductions will depend largely on the effectiveness of enforcement. For example, noncompliance rates on New York Interstates following the first national speed limit initiative were found to be extremely high, with 83 percent of all vehicles traveling at speeds greater than 55 mph (Coile, 2008). Another study also seems to indicate substantial tolerance on the part of law enforcement, with only one percent of all speeding citations issued to vehicles traveling less than 10 mph over the posted limit (Houston Chronicle, November 24, 2002).

Speed cameras are an available technology that can prove quite effective. Advanced speed enforcement strategies such as Intelligent Speed Adaptation (ISA), which relies on on-board determination of site-specific speed limits using GPS technology, may result in improved compliance in the future. ISA systems may be implemented in varying degrees, from simply notifying the driver of the speed limit violation to fully automatic governance of vehicle speed. Even without considering driver acceptance, however, such systems may be difficult to deploy in the near future due to high costs. For example, a recent ISA pilot program in Sweden instrumented and maintained approximately 5,000 vehicles at a cost of $12.7 million, or $2,500 per vehicle (FHWA, 2005b).

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[24] Maximum posted speeds for trucks range from 55 to 75 miles per hour, and are 5 to 15 miles per hour lower than the maximum posted speed for cars in some States (FHWA, 2008e, Table 3-8).

Magnitude and Timing of Greenhouse Gas Reductions

Optimal operating speeds vary depending on a number of factors. An evaluation of 11 different light-duty gasoline makes and models found their optimal speed ranged from 25 to 55 mph (GAO, 2008). Accordingly, the benefit of establishing a uniform speed limit will vary from vehicle to vehicle. In addition, the fuel consumption benefit also varies depending upon the initial baseline speed of the vehicle. For example, using EPA's Physical Emission Rate Estimator (PERE) model, a 2009 Toyota Camry is estimated to improve its fuel efficiency by approximately 2.4 mpg when slowing from 60 to 55 mph. A larger reduction from 70 to 55 mph will result in a 6.1 mpg improvement (U.S. EPA, 2005a). Heavy-duty diesel vehicles are estimated to obtain a 0.1 mpg improvement (approximately 1.5 percent improvement) on average per one mph of speed reduction at highway speeds (U.S. EPA, 2004).

Special Report 204: 55: A Decade of Experience, published in 1984 by the Transportation Research Board, evaluated the national 55 miles per hour speed limit imposed in 1974 and concluded that it resulted in savings of about two percent of annual gasoline consumption while in effect (TRB, 1984).

A recent DOE evaluation estimated that a 55 mph speed limit implemented at the national level could result in a fuel consumption savings between 175,000 and 275,000 barrels of oil per day, or about 27 to 43 mmt CO_2e per year, which represents about 1.6 to 2.4 percent of on-road vehicle fuel consumption and emissions. For this assessment DOE assumed that 35 percent of all on-road mileage would be impacted by the reduced speed limit, along with a 50 percent compliance rate (GAO, 2008). The non-compliance rate ranged from 49% to 54% of traffic exceeding 55 mph on all highways marked at 55 mph for the period 1980 to 1983, according to speed data reported by the States to the Federal government from automated devices embedded in pavements (TRB, 1984). Future compliance rates would depend on enforcement and public acceptance.

An International Energy Agency study using a mechanical engineering equation of fuel efficiency by speed found that comprehensive enforcement of a 55 mph speed limit could generate a reduction of up to 3.2 percent in fuel consumption and thus GHG emissions in the U.S. (IEA, 2005), or about 56 mmt CO_2e per year.

The benefits will be lower if vehicle fuel efficiency improves beyond the baseline levels assumed in this analysis. Changes in vehicle technology also could affect the magnitude of benefits from speed limit reductions. For example, hybrids are expected to constitute an increasing fraction of the light-duty fleet over time. Fuel consumption in light-duty hybrid gasoline vehicles rises disproportionately quickly above 50 mph, compared with conventional vehicles. To illustrate, the PERE model predicts a 9.5 mpg improvement in fuel economy for hybrid vehicles slowing from 70 to 55 mph, compared to just 6.1 mpg for comparable conventional gasoline vehicles. The higher baseline fuel economy makes total fuel consumption impacts lower in absolute terms, however. A European study found that GHG emissions from modern vehicles tend to show much less dependence on vehicle speeds (at least at highway speeds) compared with older vehicles (Carsten et al., 2008).

Reduced speed limits can be implemented very quickly, limited only by the time required for re-signage and public notification, as well as the implementation time required to upgrade enforcement levels in order to reach full benefits.

Cost-Effectiveness

The immediate costs associated with implementing speed limit reductions are relatively small, including new signage and public outreach and education effort. Ongoing enforcement costs will be more significant. Public outreach program costs can vary substantially depending upon media selection, frequency, and duration of messaging, and other factors. The IEA (2005) study estimated a $3 million cost for a basic national public information campaign, assuming no advertising cost for public service announcements; paid advertising could increase this cost substantially. Incremental enforcement efforts or citation costs above those already in place were estimated in the IEA report at $200,000 per additional officer and $26,000 per speed camera. Estimated national costs would be approximately $600 million annually for personnel, or $800 million initially for speed camera deployment (not including operations and maintenance/replacement costs, which were not estimated).

Considering annual enforcement personnel costs alone produces a cost-effectiveness estimate of about $11 per tonne CO_2e reduced, using IEA's benefit estimates. However, the IEA study concluded that these enforcement costs were effectively canceled out by fuel-cost savings. Both fuel-cost savings and enforcement costs would accrue to drivers, assuming that enforcement costs were fully recovered through fines. The study did not consider increased travel time costs. Cost and GHG reduction data from the Moving Cooler study suggest a cost-effectiveness of -$320 per tonne, considering vehicle operating cost savings but not travel time costs.

State analyses for climate action plans have produced varying estimates of cost-effectiveness, from $-200 to $55 per tonne of CO_2 reduced. These proposals included both increased enforcement and lowered limits, and several applied only to heavy-duty trucks. Some also included vehicle operating cost savings.

Cobenefits

Speed limit reductions would result in fuel savings and other vehicle operating-cost savings, but also increased travel time costs. Tradeoffs between fuel-cost savings and travel time costs can especially factor into freight transporters' practices; for example, in March 2008 one major trucking firm announced that it was limiting speeds to 62 mph in order to reduce fuel consumption (Marketwire, 2008), suggesting that the travel time savings above that speed were of less value than the increased fuel costs.

Speed limit reductions also would have safety benefits. A National Academy of Sciences analysis estimated that 4,000 traffic fatalities were averted per year as a result of the previous national speed limit (TRB, 1984), which translates into $24.4 billion using the U.S. EPA, Science Advisory Board $6.1 million "value for a statistical life."

Speed reductions may result in reductions of some criteria pollutants and precursors. NO_x in particular increases significantly at higher speeds and so should see the greatest reduction; the EPA's MOBILE6 emission factor model predicts that NO_x emissions are about 10 percent lower at 60 mph compared to 65 mph, or 17 percent lower at 55 mph versus 65 mph. Maintenance requirements also are expected to decrease for heavy-duty diesel trucks as a result of less engine and brake wear (EPA, 2004).

Feasibility

With the exception of the enhanced enforcement options discussed above, barriers to speed limit reductions are social and political rather than technical. The previous national speed limit initiative met with substantial resistance across the country and was limited in its effectiveness by inconsistent enforcement. Enhanced enforcement options that rely on speed cameras or GPS also are likely to encounter significant public resistance. This strategy would therefore require political leadership and a significant public education initiative regarding the climate change benefits of reduced speed limits to achieve support.

■ 4.3 Truck Operations and Management

Truck operations and management strategies are directed at utilizing and operating vehicles more efficiently in order to reduce GHG emissions per ton-mile of freight moved. Strategies discussed in this report include:

- Implementing idle reduction technologies and regulations to reduce long-duration idling;
- Allowing longer and/or heavier vehicles which use less fuel per ton-mile of goods carried; and
- Establishing urban consolidation centers on the fringes of cities to consolidate goods into loads that can be distributed by fewer and more efficient vehicles.

One strategy that is not directly addressed in this report is improved efficiency in freight logistics patterns, or "green logistics." Examples include load matching to reduce empty backhauls, use of routing and scheduling software to reduce distances traveled, and flexible loading and receiving schedules to allow drivers to avoid congestion (EPA, 2002). These strategies are primarily under the control of the private sector. However, the U.S. EPA has undertaken outreach efforts through its SmartWay program to encourage businesses and shipping companies to improve freight logistics to reduce GHG emissions, and has developed software to assist companies in calculating the GHG implications of their logistics decisions. Pricing measures that increase the cost of carbon emissions will encourage private companies to adopt more efficient practices by internalizing the costs of the carbon emissions related to goods movement.

Truck Idling Reduction

Description

Truck idling reduction strategies include education, laws, technology, and land use decisions to reduce long-duration idling of heavy vehicles. Heavy vehicle operators often leave their engines idling for extended periods in order to provide cab heat or air conditioning, storage cooling, and electrical power while they are stationary. Examples of idle reduction technologies include: providing electrical hookups at truck parking spaces; automatic shut-down/start-up systems for engines; heating and air-conditioning powered by on-board batteries or diesel generators (auxiliary power units or APUs); and Statewide anti-idling laws to require or encourage adoption of anti-idling

Truck Idling Reduction

Benefits: **Low**: 1.3-6.1 mmt CO_2e in 2030

- Low estimate – truck stop electrification; high estimate – idle reduction equipment on all sleeper cabs

Direct Costs: **Moderate**: $20 to $50 per tonne

Net Included Costs: **Net Savings**: -$480 to -$180 per tonne

Confidence in Estimates: **High**

Key Co-Benefits and Impacts: **Positive**

- Reduced air pollutant emissions; long-term cost savings to truck owners

Feasibility: **High**

- Some initiatives in progress

Key Policy Options:

- Uniform anti-idling law

technology. Truck-stop electrification is only one component of idle reduction because many truckers idle at decentralized locations (rest areas, roadsides, other parking areas) which cannot be efficiently electrified.

Idle reduction technologies and laws have been implemented to varying degrees throughout the country. Of the nation's 5,000 truck stops, 136 stops in 34 States were electrified as of October 2008 (U.S. DOE, 2008); all or part of 25 States have implemented anti-idling laws (ATRI, 2009); and 36 percent of trucks with sleeper cabs currently have on-board idle reduction technologies (ATRI, 2006).

Most idle-reducing technologies require equipment on-board the vehicle. So-called "single system" electrified parking spaces at truck stops require an attachment for the truck window through which all services are delivered, and/or components for the truck to connect to the electrical grid. On-board technologies have an upfront cost for vehicle owners associated with purchase and installation, but financing and tax relief programs are available to help users afford idle reduction technology.

While the carbon benefits of this strategy to the transportation sector as a whole are relatively small (0.3%), truck idle reduction provides net cost savings to trucking companies, with a short payback period of two to three years. Although the fuel savings are small compared to the transportation sector as a whole, they are significant to individual trucking companies.

This truck idling section addresses two particular anti-idling strategies: installation of heating and cooling systems on sleeper cabs and truck stop electrification. These strategies are non-additive, since trucks would typically use only one system or the other when parked. Of the two measures, the on-board systems have a much larger impact since they have the potential to be used regardless of where a truck is parked, while truck stop electrification applies only to the use of electrified parking spaces at the nation's 5000 truck stops. As a result, the high-end GHG estimate for idle reduction strategies (6.1 mmt in 2030) reflects the maximum deployment assumption for on-board systems. The low-end estimate (1.3 mmt) corresponds with a 100 percent deployment assumption for truck stop electrification.[25]

Magnitude and Timing of Greenhouse Gas Reductions

There are about 666,000 combination tractor trailer trucks with sleeper cabs registered in the United States, according to the 2002 Vehicle Inventory and Use Survey (VIUS). Sleeper cab trucks idle, on average, for about five hours a day while consuming about 1 gallon per hour while idling (Perrot et al., 2003). In comparison, an APU consumes about 0.3 gallons per hour and a battery the equivalent of 0.05 gallons per hour (BusinessWire, 2008a and 2008b).

[25] While one would not expect to achieve 100 percent deployment, the calculation provides a useful bar. Changing the deployment assumption to less than 100 percent would make a difference of less than a tenth of a percent in the transportation sector-wide GHG reduction estimate, since the current estimate is 0.1%.

The *Moving Cooler* study estimated nationwide GHG reductions of 6.1 mmt in 2030 from installation of heating and cooling systems in all sleeper cabs, and between 0.4 and 1.3 mmt from truck-stop electrification depending upon the extent of deployment (ranging from 1,500 to all 5,000 truck stops in the U.S.). The heating/cooling system benefits cannot be added to the truck-stop electrification benefits since trucks would typically only use one or the other (Cambridge Systematics, 2009).

On-board idle reduction technology and truck-stop electrification are market-ready and are relatively simple and fast measures to implement. The rate of deployment, however, is likely to depend upon the specific incentives provided for implementation. As the trucking fleet turns over and on-board technologies are installed on more new vehicles, the use of on-board technologies will expand. Some on-board technologies, such as APUs, can be installed in trucks currently in operation but are most likely to be installed only in class A sleeper trucks that are less than four years old due to capital investment requirements (Gereffi and Dubay, 2008). Additional incentives and/or regulations may be required to achieve more immediate adoption throughout the vehicle fleet, beyond that which would occur through normal fleet turnover.

Cost-Effectiveness

The *Moving Cooler* study (draft work in progress) estimated an overall cost of $16 to $18 per tonne GHG reduced for heating and cooling systems in sleeper cabs, and $45 to $52 per tonne for truck-stop electrification, considering direct costs only. Including fuel and operating-cost savings to carriers, the cost-effectiveness is estimated to be -$420 to -$480 for heating and cooling systems in sleeper cabs, and -$180 to -$210 for truck-stop electrification (net cost savings for both technologies).

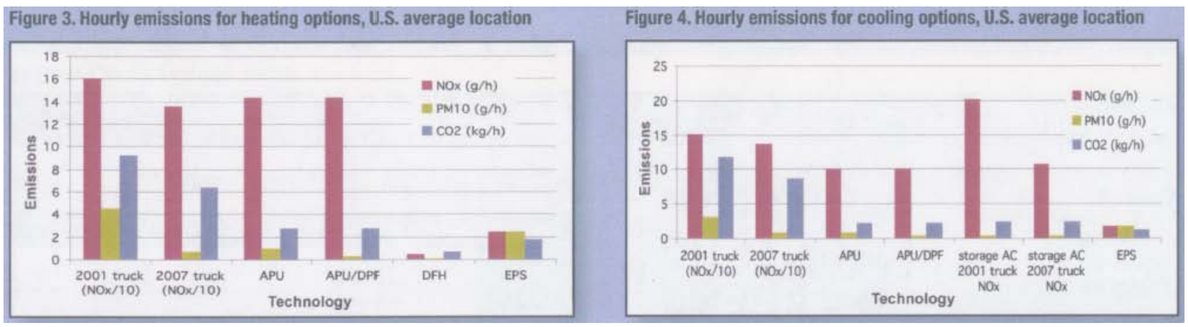
Both the costs and cost savings for these technologies generally accrue to the truck owner (although truck-stop electrification requires an initial investment by the equipment vendor or property owner, which is recouped through user fees). The average one-time cost of implementing on-board idle reduction technologies is around $6,000 per truck (ATRI, 2006). Truck owners' investment will generally be paid back in two years or less at a diesel cost of $4 per gallon, or within three years at $3 per gallon. However, in California, where diesel particulate filters are required on APUs, the added cost of the filter leads to a slight net loss for truck owners with this technology. The most cost-effective approach also will depend upon the amount of idling; trucks must idle at least 20 to 30 hours per week to make on-board equipment cost-effective for truckers (Gaines et al., 2009).

For electrified truck parking spaces, there is an additional infrastructure cost for parking space construction that varies between $6,000 and $17,000, depending on the type of electrification service offered that is born by the property owner. The cost of installation is born by the vendor at no cost to the land owner. The truck owner will see no up-front cost (for single-system hookups), but will pay an hourly fee of between $2.50 and $3.00 for use of the system. Because of the operating-cost savings from this strategy, the truck owner would see net savings in the range of approximately $1,000 to $4,000 annually with electrified parking spaces (Gaines et al., 2009).

Cobenefits

As shown in Figure 4.3, most idle reduction technologies will reduce air pollution, at least for older trucks, with benefits concentrated in the vicinity of truck stops and other truck layover areas. For newer trucks, the magnitude of the emission benefits depends upon the APU option – whether it has after-treatment, and whether it is diesel-fueled, battery, or thermal. Electrified truck stops and diesel-fired heaters will generally reduce NO_x emissions, although APUs provide no NO_x benefits for heating and only modest benefits for cooling. Air pollution benefits also will vary depending upon the local electricity generation mix. Electrified truck stops in regions that rely heavily on coal may see net increases in PM emissions, although these primarily occur in rural areas, leading to low population exposure (Gaines et al., 2009).

Figure 3.3 Emissions Benefits of Idle Reduction Technologies



Source: Gaines et al. (2009).

APU = auxiliary power unit; **DPF =** diesel particulate filter (required on APUs on 2007 and newer trucks in California); **DFH =** diesel-fired heater; EPS = electrified parking space.

Feasibility

Although 300,000 truck parking spots are eligible for electrification, it will not be feasible to electrify the vast majority of truck parking spots, which are often dispersed (e.g., highway shoulders). As a result, the most significant gains from reduced idling will need to result from on-board technologies such as diesel fired heaters and storage cooling air conditioning units. From a truck owner's perspective, the primary barriers to implementation of anti-idling technologies include initial startup cost, low fuel prices, and information dissemination. The added weight of APUs also may pose a barrier; APUs can weigh a few hundred pounds, and therefore would allow truckers to carry incrementally less payload considering a given State or Federal weight limit.

A combination of regulatory reforms, price incentives, and outreach programs can help to combat these barriers. Some price incentives and education/outreach programs already exist; for example, the EPA's SmartWay program offers a variety of financing programs for the purchase or lease of idle reduction technologies approved by SmartWay or California Air Resources Board, and the Energy Improvement and Extension Act of 2008 eliminated the 12 percent excise tax on idle reduction devices for new trucks as a financial incentive to retrofit trucks with such devices.

A uniform national anti-idling law would help to unify the existing patchwork of State laws and encourage more widespread adoption of idle reduction technology.[26] It is currently a State-by-State decision to exempt APUs from a truck's total weight; a national standard could potentially help promote the technology by eliminating the current patchwork of regulations. In addition, EPA has issued State implementation plan guidance to encourage States to incorporate truck idle reduction projects into their air quality planning.

Adoption of idle reduction technology is likely to be faster among large fleet operators than among small fleet operators and independent truckers who are less able to afford the capital investment required for such equipment. In 2002, 55 percent of heavy trucks with sleeper cabs were privately owned (used for internal company business), 27 percent were motor carrier owned, and 11 percent were owned as independent truckers owner/operator, according to the 2002 VIUS. According to the American Transportation Research Institute (ATRI, 2006), only 26 percent of sleeper cab truck owners without anti-idling technology are likely or very likely to purchase idle reducing technologies. This suggests that additional incentives will be required to achieve near-universal adoption of these technologies and realize the GHG benefit estimates cited above.

Increased Truck Size and Weight Limits

Description

Increased truck size and weight limits allow truck operators to carry more goods per truck, using heavier or longer trucks than are currently allowed. This basic improvement in productivity per truck translates to fewer trucks on the road, reduced fuel consumption, and reduced greenhouse gas emissions. For example, a 129,000-pound longer combination vehicle (LCV) consisting of a truck towing two 33-foot trailers can carry a payload that is 60 percent higher than a conventional five-axle semi while using only 31 percent more fuel (derived from data in Jack Faucett Associates, 1991).

Increased Truck Size and Weight Limits

Benefits: **Low**: 0.6 mmt CO_2e in 2030

Direct Costs: **Low**: minimal direct costs

Net Included Costs: **Net savings**: -$1,200/tonne

Confidence in Estimates: **Moderate**

- Contingent upon limiting to markets not competitive with rail

Key Co-Benefits and Impacts: **Uncertain**

- Unclear whether positive or negative safety impacts
- Cost savings to shippers

Feasibility: **Moderate**

- Primary political concern is over safety

Key Policy Options:

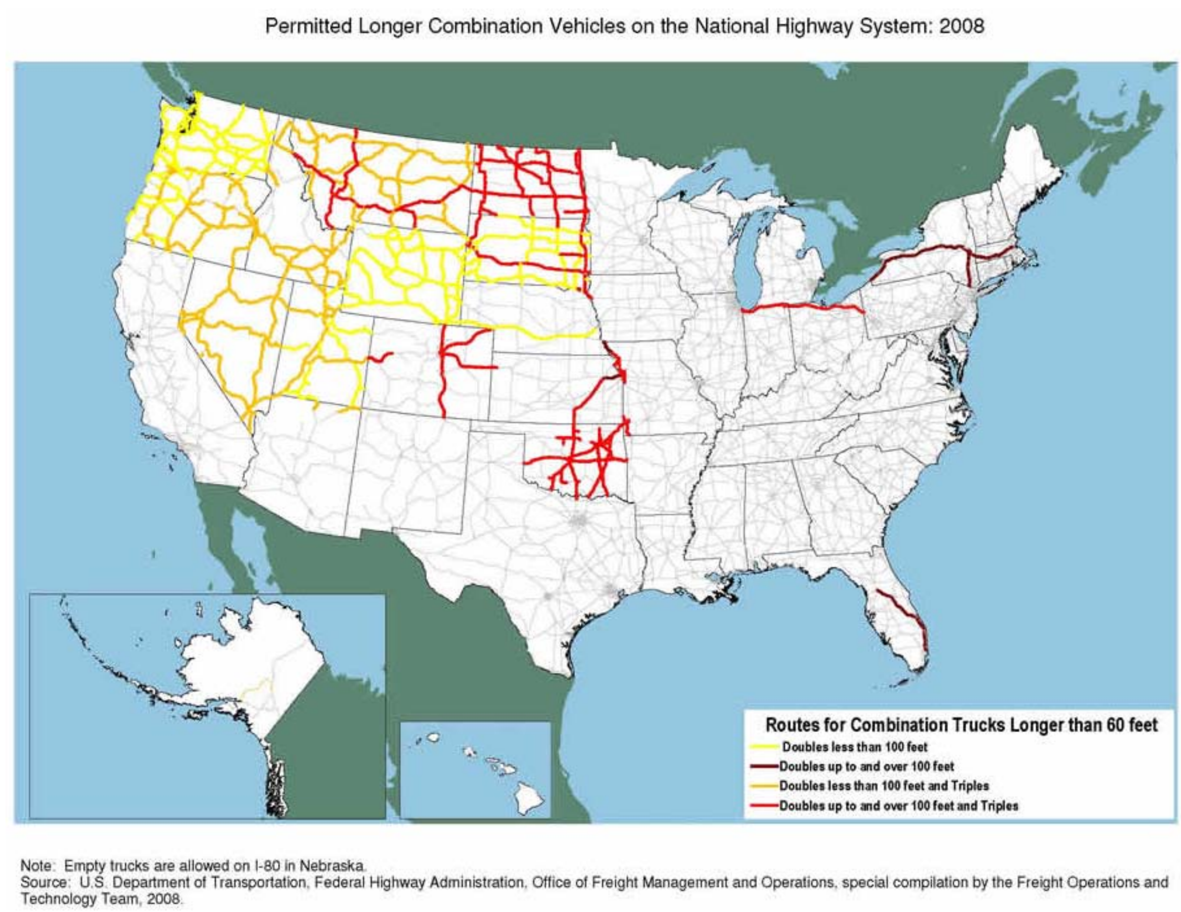
- Federal policy change to increase size and weight limits

[26] EPA SmartWay's Model State Idling Law, EPA420-S-06-001, April, 2006, incorporated broad stakeholder input into its recommendations for a uniform approach to idle reduction policy.

Federal law establishes a gross vehicle weight (GVW) limit of 80,000 pounds on Interstate Highways, subject to the Bridge Formula which may require lower weights depending on number and spacing of axles. Under Federal law, States may allow larger and heavier loads under special permits for nondivisible commodities or international containers. Regarding vehicle lengths and configurations, Federal law requires States to allow singe 48-foot trailers and twin 28-foot trailers on the National Network. Many States allow 53-foot single trailers; due to a series of legislation adopted between 1956 and 1991, nearly half of the States in the U.S. allow heavy and/or long trucks to drive on their roads with GVW up to 164,000 pounds and lengths up to 115 feet. Increased size and weight limits have primarily been adopted in States where commodities that would benefit most from bulk transport (such as natural resources) are an important part of the economy, and in areas of lower population density where traffic density and therefore potential safety concerns are less significant. Both double and triple-trailer LCVs are permitted in most States of the Great Plains and Rocky Mountain West, while doubles also are permitted on a few access-controlled highways in Florida, Indiana, Massachusetts, New York, Ohio, and Washington (Figure 4.4).

Figure 4.4 Long-Combination Vehicles

State Operations



Source: FHWA (2008).

However, the GHG reduction potential for heavy trucks or LCVs could be offset by its impact on freight mode use. If the trucking industry is permitted to use heavier or long-combination vehicles, the industry is likely to capitalize on its shorter, more direct, more reliable, and faster routes between origins and destinations to capture 10 to 15 percent of the current rail market (Martland, 2007). Rail is a more fuel efficient mode, so any diversion from freight rail to truck would represent a negative GHG benefit.

To preclude the potential diversion from rail to truck, heavy or LCVs would need to be allowed with specific restrictions to limit potential competition between truck and rail. In general, a shipping container makes the long portion of its intermodal trip on a train and is carried to the final destination on a truck. A dray move made by a truck that carries a container from an intermodal facility or port to its final destination is not rail competitive. In addition, natural resources can only be sourced on-location; a coal mine is the only place to collect coal. There are specific natural resource sources that are only accessible by truck via State highways and other truck routes.

Recognizing these factors, States could realize GHG emissions reductions in truck dominant markets with little risk of rail competition by carefully structuring size and weight permits to allow LCV trucks carrying natural resources in trucks that weigh up to 138,000 pounds on designated non-Interstate truck routes (to preclude long-distance travel). In addition, Federal policy already allows overweight containers under special permit, which can provide for trucks carrying shipping containers for distances less than 250 miles and weights up to a gross vehicle weight of 110,000 pounds (to improve port and intermodal terminal access).

Magnitude and Timing of Greenhouse Gas Reductions

No comprehensive research has been conducted to evaluate the GHG reductions that might be achieved from heavy trucks and LCVs. However, *Moving Cooler* developed some order-of-magnitude estimates. Allowing trucks traveling on non-Interstate truck routes to carry heavy natural resources in longer and heavier trucks (increasing the gross vehicle weight to 138,000 pounds) would save about 40 million gallons of fuel or 0.4 mmt CO_2e.[27] Some benefits already may be occurring since virtually every State allows overweight/oversize trucks as long as the trucker pays the permit fee; allowing dray trucks to carry heavier shipping containers from intermodal terminals and ports is estimated to produce annual savings of 24 million gallons of fuel, or 0.2 mmt CO_2e (Cambridge Systematics, 2009).

The benefits of lifting truck size and weight restrictions would likely accrue in two increments. The first benefits would accrue very rapidly as the existing tractor trailer fleet that already is able to haul heavy trailers is permitted and allowed to do so. The second benefits would accrue over time as the remaining existing tractor trailer fleet—already not able to haul heavy trailers—turns over and is permitted; the turnover rate for these trucks is approximately 10 years.

[27] The calculation reflects an 85 percent increase in productivity, and assumes that 25 percent of the 6.57 billion natural resource ton-miles would be carried by permitted heavy trucks.

Cost-Effectiveness

While increasing truck size and weight limits would involve only modest administrative costs, heavy trucks cause more damage to the nation's infrastructure than do lighter vehicles and would therefore more significantly increase infrastructure maintenance costs. However, vehicle owners and shippers would benefit significantly from reduced vehicle operating costs, and therefore, fees could be charged to recover the added infrastructure costs. The *Moving Cooler* study estimated the cost-effectiveness of increased size and weight permits to be about -$1,200 per tonne CO_2e reduced—reflecting a net cost savings (Cambridge Systematics, 2009).

Estimates of total pavement costs and the State cost responsibility from the Federal pavement cost responsibility from the Federal Highway Cost Allocation Study (FHWA, 2000) suggest that it would cost $399 million ($0.1875 per new VMT) to cover the maintenance costs from allowing dray trucks to carry heavier containers and $432 million ($0.481 per new VMT) to cover the costs of allowing heavier natural resource vehicles.

Safety Impacts of Heavy and Long Combination Vehicles

While heavy and long-combination trucks have generally been opposed due to safety concerns, the literature on this topic is inconclusive. A literature review by the Canada Safety Council (2003) found mixed evidence on the safety impacts of long combination vehicles (LCV). Some studies suggest that LCVs tend to crash more than single trailer trucks, while others suggest that they tend to crash less often. The picture is muddied by the inability of researchers to compare the two modes with "all else being equal." That is, the truckers who drive LCVs are generally more highly skilled than the average tractor trailer driver, they are restricted to the safest roads, and can only operate in the safest weather conditions. The risk exposure is different for LCV operations than it is for normal truck operations. Analysts have arrived at differing conclusions depending upon how they account for these risk factors.

Furthermore, crash severity is a concern as well as crash frequency. A 1999 FHWA report suggests that LCV crashes tend to be marginally more severe than normal trucks, with a slightly higher injury rate (31.28 per million VMT for multiples compared to 28.01 for singles) but no significant difference in fatality rates (2.44 per million VMT for multiples compared to 2.43 for single trailers).

The same literature review (Canada Safety Council, 2003) found no research about the safety record of heavy vehicles of normal size. They will likely follow a similar pattern of crash rates to LCVs due to decreased maneuverability.

To the extent that LCVs and heavy trucks reduce overall truck VMT, they have the potential to reduce crashes even if crash rates (on a per-mile basis) are similar. A study by the Transportation Research Board (TRB 2002) found that differences in crash involvement rates among different truck types are smaller than the differences in vehicle capacity and the vehicles they would replace, so involvement rates per unit of truck services should decline. This finding suggests that increased use of heavy trucks and LCVs should have a net safety benefit, assuming that regulations are implemented in such a way as to reduce overall truck VMT (as required to achieve greenhouse gas reductions). If LCV and heavy truck use were expanded to more urbanized areas with higher traffic volumes and congestion levels, however, it is possible that the overall safety impacts could be different.

Heavier and longer trucks mean fewer trucks and lower vehicle operating costs, due to both fuel and labor savings. Allowing heavier natural resource vehicles is estimated to reduce overall vehicle and driver operating costs by $800 million, accounting for nearly twice the permit price (if the price is set to recover infrastructure maintenance costs). Allowing heavier containers will reduce overall vehicle and driver operating costs by $174 million, offsetting only half of the permit cost for heavy container trucks. If truck *owners* are responsible for permitting costs, then shipping heavy containers will increase the cost to shippers. However, *shippers* save $2.2 billion (above and beyond vehicle operating costs) by shipping goods in heavier containers. Therefore the increased truck shipping cost of $225 million will be covered in full plus the shipper will net nearly $2 billion in savings (Cambridge Systematics, 2009).

Cobenefits

Cobenefits include cost savings to shippers (as described above, and which are partially offset by increased infrastructure maintenance costs); as well as reductions in fuel consumption and emissions, assuming that policies are implemented in such a way as to minimize modal diversion from rail. Air pollutant emissions benefits have not been comprehensively estimated. Heavy and long-combination trucks have most often been opposed due to safety concerns; the existing research on this subject has not produced any definitive findings to validate or invalidate these concerns (see sidebar, page 4-43).

Feasibility

Increased truck size and weight limits can be implemented through changes to Federal policy. Past attempts at increasing these limits, however, have encountered strong resistance because of the perception that having longer, heavier vehicles on the road is less safe, especially in urban or hilly conditions. Study results are mixed but heavier and longer trucks will not gain political footing unless conclusive safety evidence can be developed. Safety concerns could potentially be alleviated through the widespread implementation of truck-only lanes. It may only be possible to increase size and weight limits on certain routes due to engineering issues (most bridges in the U.S. are only rated for a maximum 91,000 lb. load). Further implementation of increased size and weight limits also could face political resistance both from the rail industry, which will be protective of its market share; and from truckers' unions, who may be interested in protecting jobs. It is possible, however, that conflicts with the rail industry can be avoided by expanding truck size and weight regulations in noncompetitive markets.

Urban Consolidation Centers

Description

Urban consolidation centers (UCC) are freight facilities where deliveries (retail, office, or residential) can be consolidated for subsequent delivery into the urban area in a low-emissions, efficient, appropriately sized vehicle with a high level of load utilization. UCCs have two linked objectives: first, to reduce or eliminate the number of large trucks operating on urban streets; and second, to avoid the need for vehicles to deliver partial loads into urban centers. The center can be developed outside a city center, an airport, or another appropriate location with either private or public support. While the UCC concept is new to the U.S., a total of 67 UCC schemes with evidence of detailed research or in-place operations have been identified in Europe and also in Japan (Woodburn et al., 2005).

Urban Consolidation Centers

Benefits: **Low**: <1 mmt CO_2e in 2030

Direct Costs: **Moderate**: $30 to $60 per tonne

Net Included Costs: **Net savings**: -$300 per tonne

Confidence in Estimates: **Low**

Key Co-Benefits and Impacts: **Mostly positive**

- Reduced truck volume and emissions in urban areas; increased local truck traffic around center

Feasibility: **Unknown**

- Concept unproven in U.S.

Key Policy Options:

- Feasibility studies/demonstration projects

UCCs are likely better suited to some types of goods and vehicle movements than others. They are unlikely to be suited to perishable and highly time-sensitive products (such as fresh food) and goods with specific distribution and handling requirements. In addition, vehicles that already are carrying full loads for a single destination will not benefit from a UCC. From the evidence available, UCCs are most likely to be successful in situations where urban centers are undergoing growth in retail, suffering from delivery truck traffic congestion or quality of life related impacts, or conducting major construction projects where a consolidation center could reduce costs and organize deliveries (Woodburn et al., 2005).

Urban consolidation centers could result in three primary outcomes that could reduce GHG emissions:

- Reduced road freight traffic levels (i.e., reducing goods vehicle movements in the urban area through improved consolidation or modal shift);
- Improved efficiency and thus reducing fuel consumption per ton of urban freight transportation operations (through improved load factors and the need for fewer deliveries); and
- Greater use of environmentally friendly vehicles.

Magnitude and Timing of Greenhouse Gas Reductions

A 2005 University of Westminster study focused on data from 17 urban consolidation centers successfully implemented in Europe and Japan. Reductions in urban truck VMT from these centers ranged from 30 to 45 percent for the shipments served (Woodburn et al., 2005).

The *Moving Cooler* study evaluated a hypothetical scenario of developing consolidation centers on the periphery of large urbanized areas in the U.S. (*Moving Cooler*, draft in progress). The focus is on less-than-truckload carriers, which collect freight from various shippers and consolidate that freight onto enclosed trailers for linehaul shipment to the delivering terminal or to a hub terminal. These carriers represent 8.6 percent of total urban truck miles. Using VMT percent reduction estimates from the European examples, this analysis found that a GHG reduction in 2030 of 0.2 to 0.3 mmt CO_2e could be achieved, depending upon the total number of regions where UCCs are applied.

Assuming that the UCC concept was proven viable in the U.S., UCCs could be implemented within a few years. The primary requirements are to establish suitable sites as well as a revised distribution structure, working with private shippers.

Cost-Effectiveness

The general European consensus is that in the long-term UCCs must be financially successful in their own right, and that subsidies are not a viable solution. This means they would pay for themselves through reductions in shippers' operating costs, and therefore have zero (or negative) cost per tonne of GHG reduced. However, the European studies also recognize that without some initial funding from central or local government to pay for research work and pilot studies, UCCs are unlikely to be developed, let alone succeed. The *Moving Cooler* study U.S. assumes development costs of $5 million per 1 million population. This results in a net cost-effectiveness of $30 to $60 per tonne CO_2 reduced over the 2010 to 2050 period, including investment costs only, or savings of about $300 per tonne CO_2e, including reduced shipping costs (Cambridge Systematics, 2009).

Cobenefits

Consolidation of goods has additional economic and environmental benefits. From an economic perspective consolidation can help to increase the volume of goods carried on vehicles entering a given urban area, thereby reducing the unit costs of transportation for the final delivery stage, as well as reduce the number of deliveries that have to be received at a location, thereby reducing the disruption and labor requirements associated with receiving multiple deliveries. From an environmental and quality of life perspective, consolidation can help to reduce fuel consumption and total truck volumes in urban areas, thereby reducing criteria air pollutant emissions, as well as improve quality of life in urban areas by removing delivery trucks from city streets.

Reductions in criteria pollutant emissions will depend upon the emissions characteristics and VMT of the specific types of vehicles utilized. Quantitative estimates of emissions reductions have not been developed. Some negative impacts may be realized in the immediate vicinity of the center due to the increased concentration of truck traffic at the center. Careful siting will be important to minimize impacts on residential neighborhoods.

Feasibility

UCCs have seen varying levels of success in Europe, and there are a number of unknowns regarding costs and the willingness of shipping companies to support development. Siting of the centers is likely to be a challenge due to potential neighborhood opposition to the concentrated truck traffic. A comprehensive study and successful pilot projects would need to be completed in the U.S. in order to demonstrate the potential for GHG reduction benefits from this strategy.

■ 4.4 Freight Rail and Marine Operations

Improvements to the operating efficiency of rail and marine freight systems, including ports and truck-rail intermodal terminals, can reduce energy use per unit of movement by these modes. Furthermore, these improvements also can encourage shippers to shift freight movements from truck to the more energy-efficient rail and marine modes. The effects of rail and marine improvements are discussed separately as follows:

- Rail modal diversion – shifting freight from truck to rail;
- Marine modal diversion – shifting freight from truck or rail to marine vessels;
- Operating efficiency improvements on the rail system and at truck-rail intermodal terminals; and
- Operating efficiency improvements at ports and in marine operations.

Modal diversions from truck to rail or marine are not the only potential freight mode-shifts with GHG benefits, although they are the ones that have received the most attention. There also may be potential for GHG benefits from shifting air cargo to truck. Domestic air cargo shipments are quite sensitive to fuel prices and airline equipment configuration. Shipments designated "air cargo" for overnight services may move by truck, especially between city pairs that are relatively close together. Moreover, the increase in fuel prices in 2008 compelled airlines to cut plane capacity and frequency of service along lower demand routes. Fewer flights carrying more passengers and their baggage left less belly cargo capacity (both weight and volume) for freight, forcing an increasing volume of freight to trucks. This shift is more pronounced on domestic routes than on international routes. Public-sector initiatives could shift cargo from air to truck if they affected revenue or cost (e.g., fuel taxation), but the potential GHG benefits of doing so have not been estimated.

Pipelines are the safest and most efficient method for transporting large volumes liquid and gaseous substances, and may be useful for transporting alternative fuels such as ethanol or hydrogen if these fuels come into widespread use. Again, it is not clear that policy actions could achieve additional GHG reduction benefits beyond current level of commodity transport by pipelines. Moreover, a life-cycle assessment would be needed to consider the new construction of alternative networks for pipeline transport versus conversion of existing networks. Therefore these strategies are not analyzed further in this report.

Rail Modal Diversion

Description

Greenhouse gas emissions from freight transport may be reduced by shifting freight traffic to modes that are more energy- and carbon-efficient – generally from trucking to rail or marine. Such shifts may be encouraged through infrastructure improvements that reduce the time and cost of shipping or increase reliability by these modes; by financial incentives or disincentives that encourage different shipping patterns; and through other policy and regulatory actions.

> **Rail Modal Diversion**
>
> *Benefits:* **Low**: 0.2-4.7 mmt CO_2e in 2030
>
> *Direct Costs:* **High**: $370 to $450 per tonne
>
> *Net Included Costs:* **Net Savings to Moderate:** -$50 to +$70 per tonne
>
> *Confidence in Estimates:* **Low**
>
> - No reliable estimates of potential for rail modal diversion – estimates are aspirational
>
> Key Co-Benefits and Impacts: **Positive**
>
> - Safety, congestion, and air quality benefits from reduced truck traffic
>
> *Feasibility:* **Moderate**
>
> - Most "easy" rail capacity improvements already implemented; some investments will be made by private sector
>
> *Key Policy Options:*
>
> - Investment in rail and intermodal infrastructure

Examples of strategies to achieve modal diversion to rail include:

- **System Investment –** Investing in rail lines, intermodal terminals, and their operations to eliminate chokepoints, reduce delays, and improve the speed and reliability of rail freight transport, or to expand the reach of the rail network (see sidebar on page 4-50). A study for the American Association of Railroads (AAR) projected that the private sector will be unable to invest the full amount necessary to relieve capacity constraints in the nation's rail network. As a result, additional public sector investment may be needed if rail is to enhance its competitiveness and carry more goods. Many States have rail/economic development programs to pay for rehabilitation of rail sidings and upgrade of short-line tracks and bridges to maintain rail connections between major businesses and Class I railroads. Additional intermodal terminals or transload facilities (for bulk materials) could be established to serve markets where demand has not been sufficient to support private-sector investment.

- **Diesel Fuel Pricing –** Increasing the price differential between truck and rail service by increasing the cost of onroad diesel fuel. For long-haul truckload carriers, the cost of fuel approaches (and sometimes exceeds) the cost of driver labor. When fuel costs rise, truckload carriers, shippers, and third-party logistics providers (who act as agents for shippers) will move longer-haul shipments from truck to rail.

- **Shipper Incentives –** Providing subsidies or incentives (such as new-user discounts) for shippers to use rail in markets that are marginally competitive with trucking. This particular strategy is little used in today's economically deregulated freight markets, although the Port Authority of New York and New Jersey recently announced that it will reduce fees from $52 to $27 per container shipped by ExpressRail to any ocean carrier that increases the number of containers it transports over its 2008 levels (Journal of Commerce On-Line, 2009).

- **Logistics Parks –** Facilitating development of logistics parks. Logistics parks, sometimes dubbed "freight villages," cluster distribution and assembly facilities around a rail terminal to minimize the amount of time and truck travel needed to collate goods arriving from global and national suppliers and by train and dispatching loads tailored to the needs a specific store by truck. There are a number of examples of logistics parks in Europe, and CSX is pursuing this strategy in the Southeastern U.S.

- **Container Standardization –** Establishing greater standardization of intermodal boxes and trailers. While standard box sizes are common for ship and rail modes, trucking has used a variety of trailer payload configurations; these reduce the multibox capacity of intermodal transportation by rail and ship. Standardization has been proposed by the European Commission and holds some promise for long-term competitiveness improvements for rail and marine shipping.

Other actions that have been proposed but received little study include local zoning policies or "land banks" to preserve land around rail sidings for the exclusive use of rail-using businesses; and working with Class I railroads to provide trackage rights for short-line railroad operators to expand the reach of their service and reduce the number of separate movements involved in a particular shipment.

Rail System Chokepoints

Chokepoints can either cause delay to trains or limit a train's carrying capacity or productivity. Delay chokepoints are located at terminals (intermodal facilities, terminals, ports, and gateways, carload terminals, fueling stations, and maintenance facilities), bridges (such as those over the Mississippi or Ohio Rivers), tunnels (such as the Baltimore tunnels or the Virginia Avenue tunnels in Washington, D.C.), at grade crossings, single track segments, and tracks with low capacity signal systems. Productivity chokepoints include low overhead bridges that prevent passage of intermodal trains with doublestacked containers and track that cannot carry today's standard 286,000 pound railcar. These capacity constraints can cause a significant delay on rail trips and can reduce the total carrying capacity between important shipping markets.

Reducing delays at chokepoints can provide GHG reduction benefits by encouraging mode shifts from truck to rail. Chokepoints also increase rail GHG emissions by lowering traveling speeds, increasing yard idle delay, and increasing passing siding idle delay, and they increase auto and truck GHG emissions by increasing at-grade crossing idle delay. Productivity chokepoints increase GHG emissions by reducing train carrying capacity (i.e., requiring more trains to carry the same amount of freight).

Similar to highway bottleneck improvements, alleviating chokepoints on the rail network can be accomplished with infrastructure investment, operations strategies, or demand side improvements. For the rail system, infrastructure investments include installing additional track, adding capacity to significant bridges or tunnels, constructing additional crossovers, removing double stack operating restrictions by improving clearances throughout the network, and removing at-grade crossings. Operations strategies include improving signal systems, central traffic control, and real-time optimization software that identifies the most efficient routes. Demand side improvements include increasing productivity by increasing the number of trains on a segment, hauling more cars per train, and loading railcars more efficiently.

It is unclear how many chokepoints exist on today's rail network. In 2005, about 1,570 miles (about four percent) of the Class I railroad primary mainline track was operating at or above capacity, suggesting that there are mainline chokepoints for which signal and track improvements are appropriate fixes (AAR 2007). There are, however, many chokepoints not captured in a mainline analysis including significant bridges, terminals, tunnels, grade crossings, and clearance chokepoints. Due to the unique nature of individual rail projects and their potential savings, there are no sources that chronicle rail chokepoints or the potential benefits of relieving these chokepoints at a national scale.

Improvements to rail infrastructure are usually funded by the railroad owner. The railroads will pay for expansion so long as they receive a return on their investment. Examples of ongoing initiatives include Norfolk Southern's Crescent Corridor and CSXT's National Gateway projects. However, there is increasing interest in public-sector support for rail infrastructure improvements, as evidenced by the several State funding programs (e.g., Virginia's Department of Rail and Public Transportation's Rail Enhancement Fund and Pennsylvania DOT's Freight Rail Grants programs) and other national programs such as FHWA's Projects of National and Regional Significance. These programs are intended to bring about further improvements that would not occur through private initiative alone. In a few places, public or quasi-public agencies have taken over railroad ownership, maintenance, and operations responsibilities. For example, the Vermont Rail System operates 230 miles of track in the State of Vermont.

Magnitude and Timing of Greenhouse Gas Reductions

Shifting freight from truck to rail or marine is likely to have GHG reduction benefits, although the magnitude of these benefits will vary depending upon factors such as the length of the haul and the type of cargo. A review of recent estimates from the U.S. EPA SmartWay program, U.S. Maritime Administration, North American Commission for Environmental Cooperation, and Australian Network Access suggests that reductions on the order of 60 percent per ton-mile are feasible for shifts from trucking (trailers or containers) to long-haul intermodal rail, with reductions decreasing with shorter distances. An international study estimated the efficiency of rail freight to be 14 grams per ton-kilometer (g/ton-km) for the entire U.S. railroad system; however, this includes the more efficient bulk cargo transport trains. The efficiency for intermodal (container) trains, which would carry most of the freight shifted from truck to rail, is in the range of 35 to 50 g/ton-km. These figures compare with an average truck efficiency in the United States of about 150 g/ton-km (Buhaug et al., 2008).

Significant caveats must be considered when comparing nominal GHG reductions per ton-mile, however. One factor that must be considered is the distance of the movement. The greatest reductions per ton-mile occur for the longest-distance moves. For a given door-to-door movement, the truck haul is much more likely to use one vehicle in a direct route. For rail, the cargo must be moved by a drayage truck from the shipper to the railhead. Terminal equipment, including yard trucks, straddle carriers and other lifting devices, then transfer the container or truck trailer to flat cars. Smaller locomotives, know as switching engines, move the cars to configure the train. The very efficient rail line haul (the long-distance portion) must then be followed by the terminal and drayage activity on the destination end. Because the rail network is less dense than the highway network, the rail route may be less direct than the highway route. Because of the drayage moves in particular, which may range from 50 to over 200 miles, most of the GHG emissions advantage of rail disappears at distances less than 400-500 miles, and the maximum benefits are only gained at over 1,000 miles.

A second factor to be considered is the potential for shifting particular commodities. Only a limited number of commodities are amenable to shipment by both truck and rail. Heavy, lower-value commodities such as coal, grain, and iron ore will travel by truck only for short distances because of the higher labor and fuel cost of trucks and restrictions on weight-carrying capacity of bridges and highway pavements. Most heavy commodities move by rail, which is engineered to carry larger, heavier loads and realize economies of scale. The costs savings of moving by rail generally offset the slower and sometimes less reliable transit times of rail. Lighter, higher-value commodities are generally dependent upon trucks' generally higher speed and reliability (except perhaps for transcontinental movements). Thus, only commodities with more moderate weights and values may be considered for shipment by both modes.

In addition to the type of commodity, the volume of the commodity being moved must be considered. An individual rail car carries the equivalent of many truck loads. If the total volume of a commodity moving between a pair of cities is low, or the shipments are infrequent, it may not be economical for the shipper or the railroad to switch from truck to rail. The final factor is the network. The U.S. rail network has about half the mileage today that it had in early 1900s. Many rail lines have been abandoned as uneconomical because population and industry have shifted location, and trucking's more direct and timely service has become increasingly important with the rise of "just in time" supply chains to avoid warehousing. Reinvestment in abandoned lines would be needed to once again expand the reach of the rail system.

The portion of freight that might be divertible from one mode to a more GHG-efficient one will depend on many factors, including network infrastructure, supply chain logistics, goods bundling, and technology investment. One aspirational study estimated that if 10 percent of long-haul, dry-van truck freight (that is, boxed freight, grains, and other bulk materials moving over 500 miles) were diverted to intermodal rail, GHG emissions could be reduced by 185,000 metric tonnes CO_2e annually (U.S. EPA, 1999). The *Moving Cooler* study estimated that an aggressive program of rail capacity improvements (reducing chokepoints by 20 to 60 percent based on 2025 needs) could reduce emissions by 1.6 to 4.7 mmt CO_2e in 2030 (Cambridge Systematics, 2009). This range of results also reflects aspirational goals; the study assumes that 10 percent of rail traffic will be diverted to truck in the absence of chokepoint improvements and that between 20 and 60 percent of that traffic will be diverted back to rail with chokepoint improvements.[28]

Actions that do not require major capital investments can achieve GHG reductions quickly. These include price effects, operational improvements, incremental additions to existing terminals, and new services can produce benefits within months. Infrastructure investments require extended time to implement and are dependent on the availability of capital funding. The most significant benefits from infrastructure investments typically commence within five to 10 years of project inception. At some point, rail capacity limits will require additional investment for benefits to continue to grow.

Cost-Effectiveness

The cost-effectiveness of rail modal shifts is likely to vary widely because of the wide range of costs involved, different implementation mechanisms, and because of the variability and limitations of information on how much modal diversion might occur for a given improvement. Cost-effectiveness is highly dependent on the costs for infrastructure investment to facilitate intermodal rail service, which in turn varies widely. Capacity expansion projects can be capital intensive, and investments for mode-shift may require larger projects than incremental expansion of highway networks. Between 2005 and 2007, the railroads spent an average of $1.5 billion on capacity expansion per year. The average bridge, tunnel, or clearance project costs $200-$300 million per structure, the average signalization upgrade costs about $600,000 per mile, and the average mainline track upgrade costs about $4.4 million per mile (AAR, 2007).

Costs for an intermodal rail terminal can range from $10 million for a smaller, peri-urban top-lift/trailer ramp facility, to an estimated $612 million for the pending Detroit Intermodal Freight Terminal project. In the current supply chain paradigm that favors goods packaged for retail delivery with minimal warehousing, shippers may incur added logistics and handling costs associated with intermodal movements; these costs may offset the cost savings associated with greater fuel and labor productivity. Achieving system efficiencies based on low GHG targets would require that shippers realize a net cost

[28]Some consider this to be a conservative estimate of the amount of freight that could be diverted to rail.

savings, perhaps with economic instruments or public subsidies that motivate additional mode shifts.

Because of the variety of implementation mechanisms and the uncertainty over mode shift impacts there are no fully reliable estimates of cost-effectiveness. However, some rough estimates have been developed. Estimates based on implementation costs alone developed in the *Moving Cooler* study range from $370 to $450 per metric tonne of CO_2e reduced, with a net cost of -$50 to +$70 per tonne once operating cost savings are included. Other studies that incorporated operating cost savings have developed estimates ranging from $80 to $104 per metric tonne CO_2 (EPA 1999, Arkansas GCCW 2008), to $35 per metric tonne for the Michigan Climate Action Council's analyses (MCAC, 2009), which incorporated fuel savings directly. The analysis time horizon affects the cost-effectiveness estimates since costs are incurred up-front, but benefits are anticipated to grow over time; using a 20- or 30-year timeframe rather than the approximate 2020 timeframe of the State climate action plans usually would increase the estimated cost-effectiveness.

Under current practices, the costs of rail and intermodal improvements are borne primarily by the private railroads and by port authorities (which are generally financed through user fees). To create modal shifts beyond those expected from current levels of private investment, public funding or tax or financial incentives would be required. It is possible that some of the public capital investment or incentives could be recouped over time through user fees, as shippers benefit from the improved conditions.

Cobenefits

Any shipper or business that voluntarily shifts modes is assumed to realize a net benefit from reduced shipping costs, which would more than offset the value of any fees paid for the service as well as any increases in other logistics costs. The magnitude of the cost savings would depend greatly upon the specific improvements made and characteristics of the modal alternatives available to a given shipper.

Rail infrastructure improvements are expected to provide air quality benefits. One study of truck, rail, and marine alternatives along the East Coast suggests that – for all pollutants – rail vehicles emit less pollution per 20-foot equivalent unit (TEU)-mile than trucks, with reductions of about 60 percent for VOC and NO_x and 40 percent for PM_{10}, as shown in Table 4.4.[29] However, these estimates do not consider the emissions from truck drayage at one or both ends of the journey. The health impacts of these emissions will depend upon their potential exposure to human populations.

Rail chokepoint relief projects that involve major construction (such as adding trackage or reconfiguring rail yards) could result in re-accessing inactive easements, new property

[29] A TEU, or twenty-foot equivalent unit, is a common defined container unit for shipping cargo. At its standard, it is 20-feet long, 8'6"-feet high and 8-feet wide.

takings, or other community and environmental impacts. Closing at-grade crossings may hurt local mobility (unless overpasses are provided) but will improve safety by reducing exposure at train crossings.

Table 4.4 Emission Factors (grams per TEU-mile), Modeled East Coast Shipping Alternatives

Mode	VOC	CO	NO_x	PM_{10}	SO_x
Truck	0.34	1.64	6.86	0.12	0.22
Rail	0.14	0.39	2.81	0.07	0.03
Ship	0.30	1.37	7.93	0.23	3.91

Source: Corbett et al. 2007.

Feasibility

To date most of the easier rail capacity improvement projects have been built, leaving primarily the more difficult and expensive projects. In addition to being expensive, many of the remaining critical needs are set in urban environments where there are substantial constraints on right-of-way as well as added costs for mitigation of impacts. The railroads spent, on average, $1.5 billion annually for capacity expansion between 2005 and 2007. Assuming that today's freight mode shares continue in the future, the Class I railroads will need to fund about $4.8 billion in improvements per year just to implement capacity improvements and chokepoint relief and keep up with growing freight demand. Productivity improvements and increased revenue from higher traffic volumes will generate $3.4 billion per year for infrastructure improvement leaving the balance, an additional $1.4 billion, to be funded from public or other sources (AAR, 2007).

There are several State and Federal programs that will fund rail improvement to help bridge the gap between investment needs and the availability of private capital. The Federal-aid highway funding program also allows some flexibility in using funds for nonhighway freight transportation projects. However, neither the railroads nor the States will fund chokepoint improvement projects unless there is sufficient evidence that there will be an appropriate return on the investment. For example, Virginia will generally not fund rail projects unless they can measure an appropriately high (public) benefit/cost ratio. Resistance to the use of public funds may be overcome, as in Chicago's CREATE project, with extensive analysis showing the public benefits of responsible public investment.

Marine Modal Diversion

Description

Marine Modal Diversion

Benefits: **Low**: 0.2-0.4 mmt CO_2e in 2030

Direct Costs: **High**: $730 to $1,500 per tonne

Net Included Costs: **High:** $550 to $1,300 per tonne

- Cost estimates for inland waterway system only – short-sea shipping not estimated

Confidence in Estimates: **Moderate**

- Precise estimate uncertain, but magnitude is bounded by size of system

Key Co-Benefits and Impacts: **Mixed**

- Benefits from reduced truck traffic on roadways; may be positive or negative local air quality impacts

Feasibility: **Low to Moderate**

- Short-sea shipping initiatives have met with limited success

Key Policy Options:

- Capital investment in inland waterway system
- Subsidies for short-sea shipping

Greenhouse gas emissions from freight transport also may be reduced by shifting freight traffic from trucks or trains to ships, in markets where water-borne transport alternatives exist. These include short-sea shipping along coastal routes, as well as barge moves along inland waterways, especially in the Mississippi River basin and Great Lakes.

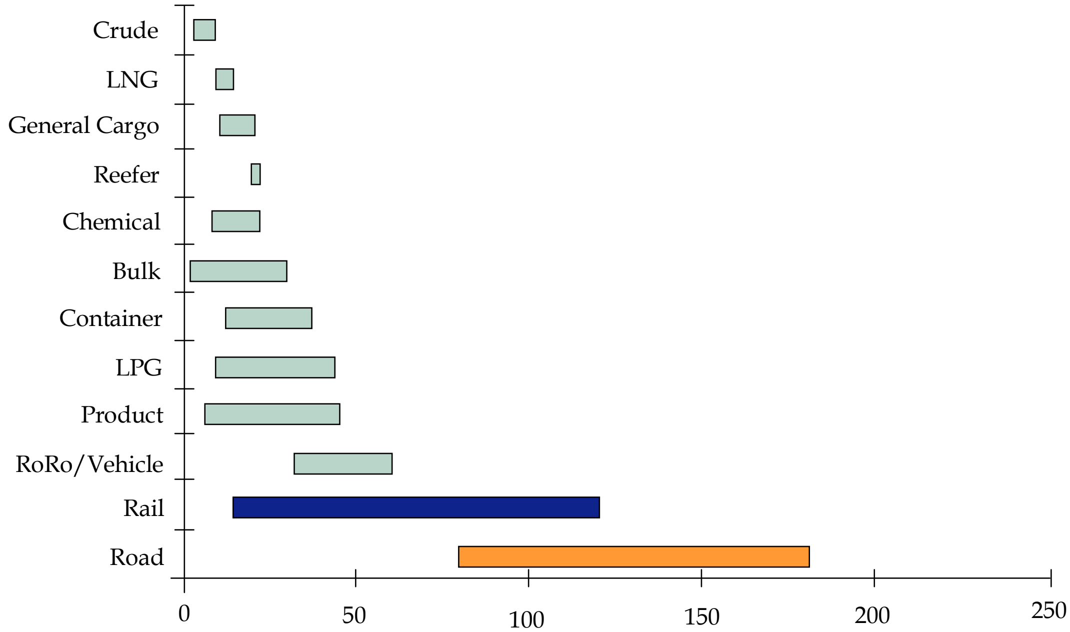
"Short-sea" shipping is defined as shipping on routes that do not cross the ocean. Several such services already in existence, including private services in niche markets on the West Coast (Cambridge Systematics, Inc. et al., 2007), and a privately run service along the Gulf Coast started in 2000 (GAO, 2005). The Port Authority of New York and New Jersey and the Port of Albany initiated a subsidized service in 2003, but this was discontinued when funding ran out (GAO, 2005). Expansion of short-sea shipping has been studied as a congestion reduction strategy.

"Marine highways," which encompass short-sea shipping routes, are coastal, intracoastal, and inland waterways, mostly in the Mississippi River basin, Great Lakes, and along the East Coast. The Marine Highway Program (run by the U.S. DOT's Maritime Administration, MARAD) was established in 2007 to designate marine highway corridors, make these corridors eligible for support for improvements, and provide assistance in coordinating with and obtaining funding from existing sources.

Magnitude and Timing of Greenhouse Gas Reductions

Shifting freight from truck or rail to marine vessels is likely to result in GHG reduction benefits under certain circumstances, although the magnitude of these benefits is debated. One study comparing inland waterway shipments with rail and truck estimated that inland towing can move 576 ton-miles per gallon, a 28 percent improvement over rail (413 tonne-miles/gallon) and a 73 percent improvement over truck (155 tonne-miles/gallon) (Kruse et al., 2007). An international study found that the efficiency of oceangoing and coastwise shipping, as measured in CO_2 per ton-km, is typically in the range of 10 to 35 g/tonne-km for general cargo and container ships, compared with 35 to 50 g/tonne-km for intermodal (container) trains and 150 g/tonne-km for road (Buhaug et al., 2008). Modal efficiencies vary substantially by the type of shipment (e.g., bulk versus container); ranges for a variety of types are shown in Figure 4.5.

Figure 4.5 Range of Typical CO2 Efficiencies for Various Cargo Carriers, g CO2/tonne-km



Source: Buhaug et al 2008.

As with rail shipping, GHG emissions resulting from drayage moves to the port, as well as terminal operations, must be accounted for. Inland marine routes are generally considerably more circuitous than highway or rail routes, and some routes are often further constrained by seasonal variation (e.g., inland water level, Great Lakes waterway freezing). Furthermore, marine access simply does not exist for some population centers far from coasts or rivers. Similar to rail, marine shipping is primarily suited to larger bundles of goods and heavier commodities; inland river service has been dominated historically by lower-value-per-ton commodities such as agricultural, mineral, and energy cargoes.

Comprehensive estimates of the amount of cargo that could shift from truck or rail to marine have not been developed. One study assumed that investment in the waterway system would allow water traffic to grow by 33 to 75 percent between 2006 and 2025, rather than the annual reduction of 0.42 percent that has been seen in recent years.[30,31] These assumptions resulted in a GHG emissions reduction of 0.2 to 0.4 mmt CO_2e in 2030 (Cambridge Systematics, 2009).[32]

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[30] A 50 percent increase was assumed in the *Waterborne Freight Transportation Bottom Line* prepared for AASHTO (Cambridge Systematics, Inc., 2006).

[31] Derived from U.S. Army Corps of Engineers (2006).

[32] Some consider this to be a conservative estimate of the amount of freight that could be diverted to marine.

Cost-Effectiveness

A private short-sea shipping service along the Gulf Coast has been successful in operating without public subsidies. However, for the New York service, the ports had to provide subsidies to set shipping rates 10 percent lower than truck rates, with the program funded at over $2 million in 2005 (GAO, 2005). A study of short-sea shipping between U.S. and Canadian ports in the Pacific Northwest concluded that service to the Ports of Vancouver and Seattle would yield only minimal shipping cost savings and therefore require a subsidy of at least $1.6 million per year to be viable. However, the study also found that service to the Port of Tacoma would generate a 9 percent cost savings and could be viable (Cambridge Systematics, Inc. et al., 2007). These cost differentials could change depending upon changes in fuel, labor, and other costs.

Overall, the cost-effectiveness of lakewise and inland waterway improvements when judged on GHG reduction appears to be poor, with one set of estimates ranging from $730 to $1,450 per tonne considering investment and operations costs only, or $550 to $1,270 per tonne considering shipper cost savings (Cambridge Systematics, 2009). This study assumed capital investment costs of $3 to $12 billion through 2025, based on the total construction backlog for Army Corps of Engineers navigation projects estimated to be $10 billion in 2003 (Vining, 2003), and annual maintenance costs of five percent of the capital costs.

Cobenefits

Any shipper or business that voluntarily shifts modes is assumed to realize a net benefit from reduced shipping costs, which would more than offset the value of any fees paid for the service as well as any increases in other logistics costs. The magnitude of the cost savings would depend greatly upon the specific improvements made and characteristics of the modal alternatives available to a given shipper.

Despite the higher energy efficiency of marine goods movement, emissions of air pollutants may not necessarily be reduced due to the less stringent air pollution controls on marine vessels. One study of truck, rail, and marine alternatives along the East Coast suggests that marine vessels emit slightly less VOC per ton equivalent unit (TEU)-mile than trucks, but slightly greater NO_x and PM and significantly greater levels of sulfur dioxide (Corbett et al., 2007). However, recent changes to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) may result in significant improvements for reducing marine emissions of NOx, SOx and PM and will likely reverse this situation. Marine vessels also have higher emissions than rail for all pollutants (Table 4.4). Another study comparing inland towing with truck and rail modes came to different conclusions, estimating that inland marine vessels emitted 13 percent less HC and about 35 percent less VOC and NO_x than trucks, and also less emissions than railroads (Kruse et al., 2007). None of these estimates include emissions from drayage activity. Furthermore, they do not consider future changes in emissions levels (such as will be achieved through greater regulation of marine vessel emissions), which could change the relative impact of each mode.

Even if emissions levels per tonne are higher from marine vessels, the net health impacts of these emissions will be lower if they are concentrated offshore, away from populated areas, as opposed to land-based truck and rail traffic concentrated near populated areas.

Feasibility

Public investment may be required in subsidizing services such as short-sea shipping, in order to establish services that may not be viable for the private sector. Substantial increases in fuel costs could potentially make short-sea shipping more competitive. Short-sea shipping has some unique additional constraints. As for truck-rail movements, costs are largely determined by the cost of handling shipments at the interchanges. The handling costs at ports are often high – the result of labor agreements as well as lower productivity rates in moving small volumes of container or trailers to and from barges compared to ocean-going containerships. An additional constraint on short-sea shipping is the Jones Act, which restricts water transport of cargo between U.S. ports to U.S.-flagged carriers. The provisions of the Jones Act protects U.S.-flagged carriers from competition by lower-cost foreign carriers (lower cost because the foreign carriers may be working under less rigorous labor, safety, and environmental regulations), but those provisions also make short-sea shipping more costly and less competitive than domestic trucking and rail-freight service.

Rail and Intermodal Terminal Operations

Description

Emissions may be reduced from locomotives through reduced idling or other operational efficiencies. Operating efficiency improvements may be realized by relieving chokepoints as discussed in the previous strategy, as well as by implementing revised operating procedures and idle reduction technologies in rail yards.

The most significant efficiency benefits may be from switcher locomotives, which spend virtually all of their time within a rail yard, assembling and disassembling trains. Switcher locomotives never reach high speeds and can spend up to 75 percent of their time idling, consuming 27 percent of their fuel while idling (Argonne, 2009). Idle

Rail and Intermodal Terminal Operations

Benefits: **Low**: 1-2 mmt CO_2e in 2030

- Includes only switchyard idle reduction and rail-highway grade crossing elimination

Direct Costs: **Unknown**

Net Included Costs: **Unknown**

- Net savings for locomotive idling reduction

Confidence in Estimates: **Low**

- Benefits of chokepoint relief, rail operations, and port/terminal equipment unknown

Key Co-Benefits and Impacts: **Positive**

- Air quality benefits from reduced idling and other emissions; cost savings to shippers

Feasibility: **Moderate**

- Some idle reduction initiatives undertaken at a State level

Key Policy Options:

- Investment in rail and intermodal infrastructure
- Regulations or voluntary partnerships with railroads to promote GHG assessment and reduction practices (e.g., idle reduction)

reduction technologies can be applied to locomotives, similar to trucks. Technologies that have been developed for locomotives include **automatic engine shut down/start up,** which controls the engine start and stop, based on a set time period or ambient temperature, and other parameters; a diesel driven heating system, designed to heat the coolant and oil to allow for main engine shutdown in cold temperatures; **auxiliary power units**; and **electrification** to provide the locomotive operator with climate control and other needs, eliminating the need to idle the main engine. These technologies are generally most effectively applied in combination. EPA's 2008 locomotive engine rule establishes new pollutant standards for locomotives, and requires the use of technologies that reduce the amount of time a locomotive spends idling (EPA, 2008).

Some efficiencies also may be achieved through truck operations serving intermodal terminals. For example, the Federal Motor Carrier Safety Administration's Cross-Town Improvement Project demonstrated the use of information technologies to facilitate the exchange of load data and availability information between railroads, terminal operators and trucking companies, and to provide a means for chassis owners and users to accurately account for asset use. These strategies can help maximizing the potential for linking moves, eliminating bobtail and empty moves, as well as maintaining a balance of truck chassis to support cross-town and other container deliveries (Cross-Town Improvement Project, 2009). Finally, cargo handling equipment using alternative propulsion systems (e.g., hydraulic hybrid vehicles or electric gantry cranes) also may be a strategy to reduce GHG emissions from intermodal terminal operations.

Magnitude and Timing of Greenhouse Gas Reductions

Comprehensive estimates of the potential GHG reductions from rail and intermodal terminal operating efficiency improvements have not been developed. While fuel savings and GHG reductions from reduced locomotive idling can be estimated, other changes to operating conditions (such as faster operating speeds) cannot be directly translated to increases or decreases in fuel consumption without the use of a detailed rail cost model. Estimates of the potential GHG emissions from low-emissions intermodal terminal equipment, or from truck operations serving these terminals, also have not been developed.

Locomotive engines can use 3 to 11 gallons of fuel per hour, depending upon outside temperature (EPA fact sheet EPA-901-F-001), so reductions in idling time will directly reduce GHG emissions. In a test in a Chicago rail yard, the installation and use of a combined "Diesel Driven Heating System" and a "SmartStart System" on a locomotive switchyard engine reduced overall idling times by 80 percent, which would save over 14,000 gallons of fuel annually for the average locomotive (EPA, 2004). Another case study in Vancouver, Washington found similar savings of 14,800 gallons over a year per locomotive (Southwest Clean Air Agency, 2005). If a similar reduction in idling and consequent fuel savings could be achieved on all switchyard locomotives, GHG emissions could potentially be reduced by up to 680,000 metric tonnes CO_2e annually.[33]

A study examining rail gateway chokepoint improvements in New Orleans estimated that the improvements would eliminate 91 hours per week of rail idling (Brown Cunningham Gannuch, 2007). This translates into a reduction of 215 metric tonnes of CO_2e per year. No data have been developed to extrapolate similar estimates to chokepoint improvements at a national level.

Rail-highway grade separation projects also should have a GHG benefit by reducing vehicle delay. A study in Riverside County, California estimate that 20 proposed grade separation projects in the county would eliminate 2,700 daily vehicle hours of delay in 2030, reducing annual GHG emissions by 544 tonnes (Riverside County Transportation Commission, 2008). Assuming that similar benefits per crossing could be achieved elsewhere, closing 10 percent of the 225,000 grade crossings in the U.S. would reduce GHG emissions by 611,000 tonnes annually.[34]

Efficiency improvements to rail operations such as switch yard idle reduction can be implemented relatively quickly—within a few years—compared to major capital investments such as chokepoint relief. Idle reduction technologies can be applied to existing locomotives.

The evolution of rail vehicle technology has the potential to affect the future benefits of operational strategies. In particular, the use of hybrid-electric locomotives would likely reduce the GHG emissions associated with idling and other inefficient movements, thereby also reducing the emissions benefits of strategies to reduce these movements. (Hybrid-electric locomotives are discussed in more detail in Section 3.0, Energy Efficiency.) However, locomotives tend to have a useful life of 40 years or more, so this effect will occur slowly as the fleet turns over.

Cost-Effectiveness

Comprehensive cost-effectiveness estimates for the operations benefits of rail improvements have not been developed. Idle reduction technologies for locomotives can cost as little as $4,000 to $7,000 for electrification or automatic engine shut-down/start-up, or up to $35,000 for a diesel-driven heating system; these costs can be offset through fuel savings. In a test in a Chicago rail yard, the combined savings from locomotive idle reduction technology was estimated to have a payback period of about 2.5 years at $1.00 per gallon of diesel fuel (EPA, 2004).

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[33] This calculation assumes total annual switchyard fuel consumption of 311 million gallons (DOT R-1 forms 2009), 27 percent consumed in idling (Argonne), an 80 percent reduction in idling, and 0.0101 metric tonnes CO_2 per gallon of diesel fuel. It does not account for the offsetting fuel use from the idle reduction technologies.

[34] Grade crossing data from FRA (2009).

Cobenefits

Most rail operations improvements would have air quality benefits. A test of idle reduction technology in a Chicago rail yard estimated that savings of 2.4 tons per year of NO_x and 0.07 tons per year of PM_{10} could be realized from an average switchyard locomotive. A study of the Alameda Corridor Project in Los Angeles, which consolidated and eliminated 200 grade-crossings on a rail line serving the Ports of Los Angeles and Long Beach, estimated reductions in rail locomotive emissions of 31 percent for ROG, 23 percent for NO_x, and 35 percent for PM_{10}, as a result of higher-speed and more efficient locomotive operations compared to the previous rail routes. Additional emissions benefits were obtained due to the reduction in vehicle delay at railroad grade crossings (Weston Solutions, 2005).

Greater use of hybrid-electric locomotives would likely reduce the air pollution emissions associated with idling and other inefficient movements, thereby also reducing the GHG emissions benefits of strategies to reduce these movements.

Feasibility

Implementation of rail operations efficiency improvements can be complex from an institutional perspective, because of the need to work with multiple interests within a private rail operator, and because of general resistance to changing established procedures or implementing new technologies. For example, the Vancouver switch yard idle reduction project required substantial relationship building with a very large rail company and the involvement of local rail yard managers, regional managers, safety managers, security managers, maintenance managers, and operations managers – many of whom resided in different locations. Unions in particular may be resistant to changes in procedures or activities falling outside of established job descriptions. There also are challenges with the technology of installations, which will frequently vary from locomotive to locomotive (Southwest Clean Air Agency, 2005).

The challenges faced with case-by-case implementation of such improvements suggest that a comprehensive Federal approach may be needed if locomotive idling reduction is to be implemented on a nationwide basis. In June 2005 the California Air Resources Board entered into a voluntary agreement with the State's two largest railroads, Union Pacific and BNSF Railway, to reduce pollution from California rail operations and to study and reduce the pollution from 17 identified California rail yards. As part of this agreement, the two railroads agreed to phase out all nonessential idling within six months and install idle reduction technologies on all California-based locomotives within three years (M.J. Bradley & Associates, 2009). This voluntary approach was taken to avoid the threat of litigation resulting from a mandatory requirement. To achieve similar actions nationwide, the Federal government could potentially either pass anti-idling legislation pertaining to rail yard operations, or enter into a similar voluntary agreement. EPA has issued State implementation plan (SIP) guidance to encourage States to incorporate locomotive idle reduction projects into their State air quality planning (EPA, 2004).

Ports and Marine Operations

Description

Numerous strategies have been proposed to increase the energy efficiency of operations at ports, thereby reducing GHG and criteria pollutant emissions. These include both land- and marine-side operations. Land-side strategies are focused on reducing truck idling, reducing truck VMT by eliminating empty hauls or shifting local movements from truck to rail, and introducing alternative propulsion systems for cargo handling equipment. Marine-side strategies are focused on reducing diesel generator use while at the dock, as well as reducing criteria pollutant emissions as ships enter or leave the terminal.

Ports and Marine Operations

Benefits: **Low**: 0.2-0.3 mmt CO_2e in 2030

- Reflects reduced truck operations at container ports only

Direct Costs: **Unknown**

- May vary widely depending upon technology or practice

Net Included Costs: **Unknown**

Confidence in Estimates: **Moderate**

- Some potential strategies not included in estimate

Key Co-Benefits and Impacts: **Positive**

- Significant local air quality benefits; some reductions in local truck traffic

Feasibility: **High**

- Initiatives in progress at some ports; number of major ports is small

Key Policy Options:

- Tools to assist in GHG assessment; regulations or voluntary partnerships to promote GHG reduction practices

Specific land-side strategies include:

- Reducing truck idling at terminal gates through the use of appointment systems;
- Charging peak-period fees in conjunction with extending gate hours to encourage truck trips during off-peak periods, reducing wait time as well as travel on congested roadways near the port (such as the PierPASS system established at the Ports of Los Angeles and Long Beach);
- Improving awareness of container location within the yard, via inventory tracking systems using Radio Frequency Identification (RFID) or global positioning systems (GPS) tags on containers;
- Establishing chassis pools to allow sharing of chassis among competing shipping lines, reducing empty backhauls;
- Implementing an Internet container matching service for empty containers known as a "Virtual Container Yard," to return empty containers to the port;
- Implementing cargo handling equipment using alternative propulsion systems (e.g., hydraulic hybrid vehicles or electric gantry cranes);

- Increase the use of on-dock and near-dock rail to reduce or eliminate trucking within the terminal or to nearby yards; and
- Implement short-haul rail service to inland ports.

Marine-side strategies include:

- Vessel speed reduction while approaching or leaving port, such as implemented at the Ports of Long Beach and Los Angeles to reduce emissions;
- Shore-side power ("cold-ironing") to obtain power at the dock from electricity rather than from diesel generators on board the ship; and
- Routing optimization techniques to take advantage of varying weather and ocean current conditions.

While all of these strategies are applicable to container ports, some—such as more efficient cargo handling equipment—also are applicable to ports handling bulk cargo for import or export. Marine routing optimization is primarily applicable to open-ocean shipping and therefore to international trade. By reducing delays at ports, improved cargo handling efficiency may have secondary supply-side and demand-side effects – such as allowing ships to operate at lower(more efficient) cruise speeds, and reducing diversion to less congested ports that may involve more circuitous routes (Hansen, Smirti, and Zou, 2008).

Magnitude and Timing of Greenhouse Gas Reductions

No national estimates have been developed of the potential GHG reduction of implemented these strategies at all major ports in the U.S., and only limited research has been conducted using examples at individual container ports. A nationwide estimate is complicated by the fact that many ports tend to have relatively unique operating environments, which means that some strategies appropriate for one port (such as on-dock or near-dock rail) may not be feasible at another, and activity patterns at each port (e.g., truck drayage) may differ widely. On the other hand, the number of major ports in the U.S. is relatively small, and evaluating a few of the largest ports would identify the majority of GHG emission reduction potential from this sector – the 10 largest container ports account for nearly 80 percent of the volume of container shipments at all U.S. ports (AAPA, 2007).

The Ports of Los Angeles and Long Beach alone handle 43 percent of container freight volume (expressed in ton-equivalent units) passing through major ports in the U.S. (AAPA, 2007). Operations at these ports have been extensively studied, primarily due to local air quality concerns and the desire to reduce air pollutant emissions. Estimates prepared for the U.S. EPA indicate that truck drayage activity in and near these ports consumes about 57 million gallons of diesel fuel annually, producing 643,000 tonnes of CO_2 (Tioga Group, 2008). This study estimated that initiatives already implemented, including automated gates, extended gate hours, and container information systems, reduced fuel use by 16.8 percent, which would correspond to a reduction of 108,000 tonnes of CO_2 annually. Another study conducted for the port operator estimated reductions in truck trips, VMT, and pollutant emissions resulting from the implementation of a virtual container yard, increased on-dock rail usage, a new near-dock rail yard, and local shuttle trains to a hypothetical inland port.[35] The strategies were estimated to reduce daily truck VMT by 291,000 in 2010 (Cambridge Systematics, Inc., 2005), which would correspond to an annual reduction of approximately 191,000 tonnes CO_2e.[36] The greatest reductions in truck VMT in this study were from shuttle trains to an inland port and increased on-dock rail use. However, there would be some offsetting emissions from rail operations, which were not calculated, so this estimate represents an upper bound of potential emission reductions. Extrapolating these reductions to all container ports, in proportion to the amount of container traffic carried, results in an estimate of less than 0.3 mmt CO_2e reduced.

Work for EPA also has examined drayage initiatives already implemented at the Port of Virginia in the Hampton Roads region, the Port of Houston, and the Ports of New York and New Jersey. In 2007, these initiatives were estimated to reduce CO_2 emissions at all three ports by just over 50,000 tonnes annually (Tioga Group, 2008). The potential for additional reductions beyond those already achieved was not estimated.

The impact of the marine-side speed reduction strategy has been estimated. In 2007, the 20-nautical mile Green Flag program at the Port of Long Beach eliminated an estimated 24,000 metric tonnes of CO_2e. If all vessels participate at the 40-mile range, the amount of emissions reduced is projected to more than double (Starcrest, 2008). The International Maritime Organization (IMO, 2000) estimated that the potential for reducing CO_2 emissions by effective weather routing is 2 to 4 percent, with additional benefits from routing to exploit ocean currents. (Since most of the benefits of ship routing optimization would occur in international operations, they are considered outside the scope of this study and are not further discussed.)

The potential GHG reduction benefits of other strategies, including alternative propulsion systems for cargo handling, shore-side power, and cargo handling at bulk cargo ports, has not been studied. The GHG benefits of shore-side power will vary by port depending upon the local electricity generation mix.

Many port operations strategies could be implemented relatively quickly, particularly those that do not involve major capital investments; in fact, a number of implementation examples already exist. The implementation timeframe, however, will be governed by potentially complex institutional issues. The primary motivations for these systems have

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[35] Emissions impacts from implementing extended gate hours were not calculated, because trips would not be eliminated or shortened from this strategy, only moved to a different time of day or to the weekend. The study also did not estimate emission reductions from reduced truck idling, or from reduced congestion on nearby freeways.

[36] CO_2 emissions were not calculated in the original study. This estimate assumes an average dray truck fuel efficiency of 4.66 miles per gallon, based on DrayFLEET model output for the Ports of Los Angeles and Long Beach (Tioga, 2008), and operations of 300 days per year.

been local congestion relief and air quality improvements, so the timing will depend on the perceived magnitude of these problems at individual ports and the political and community pressure to solve these problems. Capital-intensive solutions such as on-dock and near-dock rail yards and short-haul rail service to inland ports will take years to implement because of funding constraints, environmental approvals, design, and negotiations with railroads and shippers.

Cost-Effectiveness

The cost-effectiveness of port-focused strategies in terms of GHG reductions has not been estimated, but is likely to vary substantially for the different strategies. Port rail improvements appear to be costlier than truck efficiency improvements, at least in terms of initial investment, although they also achieve the largest GHG reduction benefits. Costs for a rail shuttle system could exceed $200 million, without consideration of mitigation costs, such as grade separations. Improved on-dock rail systems in the Ports of Los Angeles and Long Beach are estimated to cost nearly $1 billion and a new near-dock yard will cost about $200 million.

Less capital intensive strategies like appointment systems, extended gate hours, container tracking systems, a Virtual Container Yard, extended gates, and chassis pools may be feasible strategies in the short term. The Ports of Los Angeles and Long Beach invested $1.2 million in the Virtual Container Yard, but to date ocean carriers and truckers have not fully embraced the system. Thus, the cost effectiveness of this strategy has not yet been proven.

A 2004 report prepared for the Port of Long Beach concluded that cold ironing (shoreside power) is generally cost effective with vessels that spend a lot of time at the Port, and therefore have high annual power consumption (ENVIRON, 2004). It would not be particularly cost effective, however, to retrofit vessels that visit the port infrequently. The cost-effectiveness with respect to GHG reduction was not estimated.

Cobenefits

Significant cobenefits can be achieved from port and marine strategies. These cobenefits include reduced congestion on highways serving the ports, improved traffic safety, reduced highway traffic noise, and reduced fuel consumption and pollutant emissions. These cobenefits are generally in proportion to the reduction in truck traffic and idling from each strategy, although strategies that increase rail traffic will offset some of the emissions and fuel consumption benefits. Another potential cobenefit is greater reliability and speed of shipments, as well as lower shipping costs.

Improved on-dock rail service has a direct impact on the number of truck trips generated by the container terminals. In the case of new or improved near-dock rail yards, the benefit is in terms of shorter drays compared to service to the off-dock yards. These strategies also have safety advantages through the reduction of truck miles of travel on congested highways. Short-haul rail service to inland ports can reduce truck trips to local warehouses and distribution centers. For the Port of Los Angeles and Long Beach analysis, the combined scenarios were estimated to reduce weekday truck traffic on I-710, the primary access route, by 20 percent in 2010 and 27 percent in 2030 (Cambridge Systematics, Inc., 2005). The majority of this reduction is a result of extended gate hours, which would simply shift truck traffic to the weekend instead of reducing it overall, although congestion benefits would still result from the substantial weekday peak-period truck trip reductions. The same study estimated net reductions in criteria pollutant emissions (VOC, CO, NO_x, and PM) of 0.12 tons per day or 4.6 percent in 2010, compared to baseline emissions from the truck traffic generated by the port (this accounts for offsetting rail and weekend truck trip emissions). The extent to which the benefits of these strategies could be extrapolated to implementation at other ports is not clear.

Marine-side strategies also have resulted in reductions in pollutant emissions – the primary objective of these strategies. In 2007, the Green Flag program at the Port of Long Beach eliminated an estimated 678 tons of NO_x, 453 tons of SO_2, and 60 tons of diesel PM (Port of Long Beach, 2009). Depending on the size of the ship, shore-side power at Southern California ports is estimated to reduce NO_x by one ton and SO_x by more than half a ton each day the ship is at berth and plugged in, representing a 90 percent reduction in pollution (comparing the pollution from electricity generation versus on-board generators). This impact will vary at other ports, depending upon the local electricity generation mix (Starcrest, 2008).

Feasibility

The feasibility of appointment systems, extended gate hours, container tracking systems, and chassis pools has been demonstrated at ports, including Ports of Los Angeles and Long Beach, the Port of Virginia, and the Ports of New York and New Jersey. However, these may require complex multiparty agreements to implement. Thus, feasibility is most dependent on the willingness of the parties to change the status quo and to accept a different way of doing business. Some of the specific institutional barriers include:

- Many of these strategies involve new computer and Internet procedures that require retraining of personnel to effectively use these new tools. Implementation of Virtual Container Yards has been slow because of concerns over integration of shipping line computer systems with the VCY software, and because of equipment interchange and insurance issues.

- Extended gate hours require warehouses and distribution centers to be open at night to accept the containers. Larger importers usually can afford to keep warehouses open during off-peak hours, but smaller shippers without this ability often have no choice but to use the day gates and pay the extra fee.

- Shipping lines and container terminals control chassis pools at ports, and many shipping lines prefer to control their own chassis fleets.

- Longshore unions carefully watch the impact of new technology on labor requirements.

The capacity of on-dock yards and related trackage is one potential constraint to increasing on-dock rail usage; another is the fact that not all cargo can be handled on-dock. The feasibility of short-haul rail systems to inland ports is actively being investigated by various ports—often for economic development reasons—but is hampered by the fact that such systems currently are not cost-competitive with harbor truck drayage. Furthermore, the railroads have been slow to embrace short-haul service because the trains would take up valuable time slots on the rail corridors, thus adversely impacting their more lucrative long-haul services. There also are community concerns about grade crossing impacts along the routes to the proposed inland ports. The feasibility of these systems will depend on solving many problems at once, including identifying a viable market segment, resolving the differential cost structure of trucking versus rail, providing adequate track capacity, and mitigating impacts in communities.

■ 4.5 Aviation Operations

Description

Aviation operations strategies can conserve fuel and reduce CO_2 emissions from aviation by reducing delays and increasing efficiency in airport and airspace operational procedures. System and operational efficiency measures can be applied to each of three distinct elements of aviation operations: the airport infrastructure, carrier and airport operations, and the National Airspace System (NAS) operations. In addition, some measures affect both carrier/airport and NAS operations.

Aviation Operations

Benefits: **Low to Moderate**: 8.9 to 25.2 mmt CO_2e in 2035

Direct Costs: **Unknown**

Net Included Costs: **Unknown**

- Many strategies likely to achieve net cost savings

Confidence in Estimates: ***Moderate***

- Multiple sources in relatively close agreement
- Sources cite ranges due to uncertainty and interdependencies among NAS requirements and stakeholder objectives.

Key Co-Benefits and Impacts: **Positive**

- Reduced traveler delay; cost savings for airlines; reduced emissions at airports

Feasibility: **High**

- Initiatives in progress

Key Policy Options:

- Continued funding and institutional support for NextGen program and airport investment and modernization
- Requirements or incentives for airport GHG inventories and reduction practices

- **Airport infrastructure and equipment.** Examples of airport infrastructure improvements include new and extended runways to reduce delays at congested airports (though benefits may be offset by increased travel), improved taxiway design to facilitate better flow, and electrified gates to reduce aircraft engine use. Equipment includes more efficient or alternative-fuel airport ground support equipment (GSE) and ground access vehicles (GAV).
- **Carrier/airport operations.** During the ground operations, aircraft consume fuel while taxiing, maneuvering to and from gates, and idling while waiting to take off or for available gates. Airlines and airports can implement strategies to reduce fuel consumption and GHG emissions from these operations, including aircraft tugging to the runway and single-engine taxiing.
- **NAS operations.** The set of measures for controlling and managing airspace capacity are known as air traffic management (ATM) technologies. Ground, terminal and en route operations are carried out by pilots operating under the guidance and control of airlines and air traffic controllers. Operational efficiencies can be achieved during ground operations, vertical ascent and descent, and the horizontal en-route trajectory:
  - ATM efficiency measures during the **ground operations** include providing takeoff assignments to aircraft to limit the length of taxi queues and surface congestion.

- During the **vertical ascent and descent**, measures include implementing RNAV departures and using an Optimized Profile Descent (OPD) procedure (previously known as Continuous Descent Arrival) to optimize the vertical descent of an aircraft from high altitude to the airport at a near engine idle (as compared to the step-wise standard approach currently in place). Area Navigation (RNAV) and Required Navigation Performance (RNP) routes and procedures can allow for more efficient use of airspace through repeatable/predictable paths, improved climb and descent profiles, shorter ground tracks, and reduced delays.
- During the **horizontal en-route trajectory**, domestic reduced vertical separation minimum (DRVSM) is a recently implemented procedure that provides an increased probability that pilots will be cleared to their requested optimal cruise altitude that minimizes fuel use. Other systems such as Advanced Technologies & Oceanic Procedures (ATOP) and Wide Area Augmentation System (WAAS) should support more efficient operations by finding more efficient tracks or altitudes over long oceanic routes and providing precise horizontal and vertical navigation for landing approaches. ATOP is a satellite-based system that takes advantage of cockpit digital communications, rather than the voice communications used today. Satellite data link communication significantly reduces the manual workload for controllers, improving their ability to handle requests from airlines for more efficient routes over the ocean. Automatic Dependent Surveillance-Broadcast (ADS-B) uses global positioning system (GPS) and communications satellite signals to more accurately identify and broadcast the aircraft's location throughout the flight to safely reduce the separation standards between aircraft.

- **Carrier/airport and NAS operations.** Some ATM technologies address carrier/airport as well as NAS operations together. Several systems can improve coordination of arrival/departure routes to the airport. Departure flow management systems (DFM) coordinate and automate departure releases, and schedule depeaking can adjust demand so that the airport operates at or below capacity to reduce congestion. Integrated terminal weather systems (ITWS) provide better management of arrivals and departures under varying weather conditions, thus reducing delay.

DRVSM was implemented on a nationwide basis in 2005 (and prior to that, reduced vertical separation minimum was implemented in some oceanic, foreign and international airspace). Many of the other ATM measures listed here currently are being applied as part of the NextGen Implementation Plan (FAA, 2009).[37] Some airports have undertaken additional initiatives focused on infrastructure and operations, primarily for the purposes of congestion and delay reduction or air quality improvements. Recent and ongoing initiatives are described in more detail in the sidebar on page 4-68.

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[37]The AEO baseline GHG forecasts used in this report assume some improvements in aircraft efficiency, but it is not made explicit to what extent these result from aircraft improvements versus system operating improvements. Therefore, it cannot be determined to what extent initiatives in progress (such as NextGen) are already reflected in these forecasts.

For many of the ATM technologies in the testing phase, only a small scale trial has been implemented in several airports with the highest need (i.e., the most congested). Estimates of ATM efficiency will improve as these technologies are demonstrated on a larger scale. Although NextGen has a series of midterm goals to increase absorption of these technologies by 2018, an aggressive pursuit of these measures could be driven by policy mandates or initiatives towards technology adoption. Additional funding also would be required to roll out the package of ATM strategies nationwide.

Aviation System Efficiency Improvements in Progress

New and extended runways. New runways and runway extensions provide the most significant capacity increases, and also offer efficiency improvements. Since fiscal year 2000, 15 new runways and one runway extension have opened at the 35 Operational Evolution Partnership Plan airports, providing these airports with the potential to accommodate 1.9 million more annual operations (FAA, 2007).

Optimized Profile Descent procedures. OPDs have been implemented on all three standard, easterly arrival routes into Los Angeles International Airport using the Standard Terminal Arrival (STAR). Las Vegas and Phoenix have also designed and implemented STAR procedures with OPD, and six other airports now have STARs with OPD in various stages of development. OPD flight trials have also been conducted in Atlanta and Miami.

Area navigation and required navigation performance. In Atlanta, RNAV/RNP procedures have been implemented and have increased productivity by 20-30 percent, leading to as many as 10 additional departures per hour. Two RNAV STARs were implemented at Phoenix International Airport in October 2006.

Wide Area Augmentation System. As of March 2009, there are over 1500 WAAS-based LPV (Localizer Performance with Vertical Guidance) approaches at nearly 800 airports, and the FAA has a 2009 Flight Plan goal to publish at least 500 WAAS approaches.

Automatic dependent surveillance-broadcast. The FAA first rolled out ADS-B in Alaska. In the lower 48, United Parcel Service (UPS) voluntarily equipped 107 of its aircraft with ADS-B avionics in order to save time, fuel, and carbon emissions on flights to and from its Louisville hub (FAA 2009).

Advanced technologies and oceanic procedures. ATOP is now used at the three en route centers that handle oceanic traffic – New York, Oakland, and Anchorage.

Low emissions ground support equipment and access vehicles. A number of airports have implemented low-emissions GSE and GAV such as natural gas or electric vehicles, usually to reduce emissions of air pollutants in non-attainment areas. Examples include Boston Logan, San Francisco, Dallas-Ft. Worth, and Los Angeles international airports. The FAA's Inherently Low Emissions Airport Vehicle Pilot Program (ILEAV) provided grants to support testing and adoption of such equipment at six airports between 2000 and 2005 (FAA 2006).

Other airport emission reduction measures. The FAA's Voluntary Airport Low Emissions (VALE) program, created in 2004, is program that is designed to allow airports to improve or expand while still complying with Clean Air Act requirements; the program provides grants and credits for emissions reducing projects (alternative fuel vehicles, gate electrification, etc.), which also are likely to have GHG benefits. As of March 2009, the FAA has issued 22 VALE grants to 10 airports that have generated $30 million worth of investments in clean airport technology.

Source: Compiled from Federal Aviation Administration NextGen documents and personal communication with FAA staff, April 2009.

Magnitude and Timing of Greenhouse Gas Reductions

Aircraft Operations

Aircraft engine CO_2 emissions are, for the most part, directly related to fuel burn. Thus, operational efficiencies produce the dual benefits of decreasing fuel consumption and reducing GHG emissions.[38] According to a 1999 assessment by the Intergovernmental Panel on Climate Change, addressing inefficiencies in air traffic management (e.g., inefficient routings, suboptimal flight profiles, holding patterns) could reduce overall fuel burn by 6-12 percent, considering improvements that were expected to be implemented over the next 20-year period (IPCC, 1999). This represents a reduction of 15 to 31 mmt CO_2e if applied to 2030 baseline forecast U.S. emissions from aircraft. In 2009, FAA and EURCONTROL completed a joint benchmarking report that identified a fuel inefficiency benefit pool of 6-8%. The report emphasized these values represented an upper bound on the efficiencies examined as benefit was measured against idealized flight conditions. In 2008, CANSO surveyed ATM efficiency by world region and found similar benefit pools. The CANSO report also identified safety, capacity, weather and noise as factors that may prevent ATM from reaching the ideal condition. It concluded that less than half the theoretical pool may be recoverable. On a smaller scale a recent study from a United Kingdom source estimated that a 10 percent reduction is possible from improved air traffic management and operations by 2020 (Sustainable Aviation, 2008). This results in a similar reduction of 26 mmt CO_2e in 2030. This compares to the *potential* benefit pool for the more congested areas in the US. Regarding specific ATM technologies, "free flight" technologies for controlling and managing air space capacity are estimated to reduce fuel consumption by approximately 6 percent (FAA, 1998). Several studies have been conducted on the improvement of fuel burn due to implementing RVSM, with studies conducted in Europe and the U.S. finding a benefit ranging from 1.6 to 2.5 percent (Malwitz et al., 2009). The ASPIRE Flight Tests have identified gate-to-gate efficiency on the order of 4%, with some of benefit attributed to airline practice. This flight test has unique characteristics which make extrapolation to the US NAS problematic. However, it provides actual benefit by phase of flight that can be compared to the phase of flight benefit reported by EUROCONTROL/FAA.

Reducing delays in the air traffic system is an important contributor to reducing GHG emissions. Historically, system operational efficiency has been roughly constant – on the edge of exceeding capacity. When this is the case, any disturbance (such as inclement weather) can lead to a cascade of delay and fuel inefficiency effects. While the GHG reductions from aviation system efficiency improvements are typically modest under normal conditions, such improvements can be critical to avoiding larger impacts that

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[38]GHG emissions are not proportional to fuel consumption for all strategies. A study conducted at London's Heathrow Airport and Gatwick Airport showed that derated thrust can increase fuel use and CO_2 emissions during take-off and early climb-out by 12.3 percent, but reduce NO_x—another global warming contributor—by 14.5 percent (King and Waitz, 2005).

result from weather and other disruptive events. A report by the Joint Economic Committee of the U.S. Congress estimated that delayed flights consumed about 740 million additional gallons of jet fuel (JEC, 2008); this represents nearly 4 percent of all domestic aviation fuel use. This benchmark times used in this study represent an upper bound by using ideal flight times between source and destination. The delay benefit reported overlaps inefficiencies identified in the EUROCONTROL/FAA report. Participants in the second working group meeting of the Group on International Aviation and Climate Change held in February 2009 concluded that in the range of 0-10 percent relative gains in overall efficiency might be achieved from the construction of additional runways to increase capacity at congested airports, and 0-2 percent from more efficient use and planning of airport capacities (GIACC, 2009). In a study on CO_2 emissions reduction during the air and ground holding period for Osaka and Narita airports, the authors found that engine idling time could be reduced by 10 percent using improved airport operations techniques (Shioda and Hashimoto, 2006). Using a 4 percent reduction in fuel consumption from eliminating delay (from the JEC study) as an "upper bound" results in an estimated reduction of up to 10 mmt CO_2e annually.

None of these estimates account for potential offsetting growth in aircraft operations. There is considerable debate as to the magnitude of "unmet demand" for air travel and the extent to which operations increases would offset the benefits of operational improvements (Freire et al., 2000). At an airport level, increased system efficiency can lead to an increase in usable or effective capacity, sometimes resulting in "schedule backfill." This concept is related to induced demand effects, and because many studies assume that schedule backfill does not occur, they may overestimate GHG reduction strategies (Hansen, Smirti, and Zou, 2008; Williams and Noland, 2006). Regardless of how growth is characterized, there is anticipated aviation growth according to FAA forecasts.

These estimates also do not account for the contribution of aircraft to global warming through contrail formation at high altitudes. While contrails reflect sunlight that would otherwise warm the Earth's surface, they also absorb heat from the ground instead of allowing it to escape; evidence suggests a net warming effect from aviation contrails. More efficient routing patterns should reduce contrail formation by reducing flying time, but some routing changes that reduce contrail formation can increase fuel use.

Airport Operations

The potential GHG reductions from airport facilities, equipment, and operations have not been quantified on a nationwide basis but should be relatively small compared to the overall magnitude of GHG emissions from aviation operations. Participants in the GIACC working group meeting estimated that reductions in the range of 0-2 percent each could be obtained from enhanced terminal support services and from conversion of ground support equipment to alternative fuels (GIACC, 2009). Table 4.5, taken from the recent Aircraft Cooperative Research Program Report 11 on the preparation of airport GHG inventories, places these emissions in perspective with other aviation emission sources. The inventories indicate that aircraft are responsible for at least 95 percent of total emissions, while ground support equipment and on-site ground access vehicles account for less than 1 percent each of total emissions (if passenger access to and from the airport is not included). Airport facilities make up between about 1 and 5 percent of total emissions. Aircraft ground operations are not identified separately but should be a small fraction of landing and take-off operations, which are about 10 percent of total aircraft emissions. If total aviation emissions could be reduced by around 1 percent through airport equipment and operations strategies, the savings would be about 2 to 3 mmt CO_2 annually.

Table 4.5 Airport Greenhouse Gas Emissions Inventories

	City and County of Denver (2005)		Port of Seattle Aviation (2006)		Zurich Airport (2006)	
Contributor	**Metric Tonnes CO_2e**	**Percent**	**Tonnes CO_2**	**Percent**	**Metric Tonnes CO_2**	**Percent**
Aircraft	4,569,696	94.9%	4,220,098	98.0%	2,816,907	97.3%
Landing and Take-Off			348,195	8.1%	255,322	8.8%
Cruise			3,871,903	89.9%	2,561,585	88.5%
GSE	14,051	0.3%	45,438	1.1%	27,229	0.9%
GAV	21,968	0.5%	[a]		13,021	0.4%
Facilities	211,000	4.4%	40,636	0.9%	37,586	1.3%
Total	**4,816,715**	**100%**	**5,093,988**	**100%**	**2,894,743**	**100%**

Source: Kim et al. (2008).

[a] GAV emissions at the Seattle airport included passenger access by all modes, which totaled 788,000 tonnes or 15.5 percent of all emissions. These were removed to be comparable to the Denver and Zurich estimates, which only included on-site ground access vehicles and not all passenger access travel.

Efficiency savings through the aviation operations strategies discussed above could be largely if not fully realized within 10 to 15 years. Many of the ATM/free flight technologies already are partially in place or have been tested in operations, and roll-out can continue as funding is available. Some of the more advanced RNAV technologies for in-flight routing are still in development but deployment could commence before 2020 (PARTNER, 2009). Eleven ADS-B ground stations have been installed in Florida and a majority of the nationwide system is planned to be fully installed by 2013. Currently, complete aircraft equipage is likely to be required only by 2020 in order to make the costs to operators more affordable. Programs and incentives to accelerate equipage plans could help realize the efficiency benefits sooner.

Table 4.6 summarizes available evidence on the fuel savings and GHG reduction benefits across all aviation operations strategies, along with the extent of current implementation and the potential timeframe for future implementation.

Table 4.6 Aviation Operations Efficiency Improvements

Technology	Percent Reduction in Fuel Use and Combustion GHG[a]	Current Implementation	Potential Timeframe of Future Implementation
New/extended runways	0-4%[b]	Ongoing – 15 new runways since 2000	Multiyear planning and implementation horizon
Other airport infrastructure and aircraft operations – gate pushback, single-engine taxi, GPU/APU use, etc.	Unknown; probably < 1%[c]	Unknown	Short- to medium-term (0-15 years)
Low-emissions GSE and GAV	< 1%[d]	A number of major U.S. airports, mostly in nonattainment areas	Near-term – depending upon fleet turnover or accelerated replacement
Combined NAS strategies	2.5-6% of all aircraft combustion GHG*	To date, FAA has authorized more than 265 RNAV procedures at 90 airports and more than 145 RNP procedures at 45 airports	Increasing over 2012-2018 period; potentially widespread by 2019-2025 (see "timing")

a Does not account for contrail impacts or demand-side effects.

b Assumes 4 percent JEC estimate of total fuel consumed due to delay as upper bound.

c Less than 1 percent would be less than 10 percent of all landing and takeoff operations emissions (which include operations below 3,000 feet).

d Total contribution of these factors appears to be about 1.5 percent.

* the upper bound is consistent with FAA (1998), CANSO (2008) & EUROCONTROL/FAA (2009). The lower bound reflects observations on interdependencies that may prevent full realization of benefit. The range is supported by gate-to-gate efficiency observed in the ASPIRE flight test.

Costs

The net cost-effectiveness of aviation measures in terms of GHG reductions has not been estimated. However, certain air traffic management strategies have been estimated to produce net benefits because of the resulting fuel savings. RNAV procedures have been estimated to produce $8 million in fuel savings annually on the West Coast high-altitude

Q route, due to a savings of 20 miles per flight compared to conventional routes. RNAV Standard Instrument Departure (SID) procedures implemented in Atlanta and Dallas-Fort Worth are estimated to have saved Delta and American Airlines $15-30 million each annually per airport (JITI, 2007).

The DRVSM implemented in January 2005 is expected to provide $5.0-$8.8 billion worth of fuel savings through 2016, a 6:1 benefit cost ratio (JITI, 2007; FAA, 2009). The total operator cost to upgrade to DRVSM on a nationwide basis was approximately $800 million (FAA, 2004). Estimates for DRVSM compliance for operators on an aircraft-by-aircraft basis was $175,000 to $300,000 per airplane, in addition to a month of downtime to install new flight instruments and sensors (Pope, 2002).

Costs of implementing these strategies may be borne by various entities. Airport authorities will bear the costs of airport infrastructure and equipment. Aircraft operators will incur costs such as navigational system upgrades and training to comply with revised procedures. The FAA will incur the costs of NAS system improvements. Airlines will yield the direct benefits of the strategies, including reduced fuel costs and time delays, but may pass along some or all of these cost savings to consumers.

Cobenefits

In addition to GHG benefits, most strategies that provide for systemwide and operational efficiencies in aviation also decrease fuel consumption and pollutant emissions, especially NO_x. The previously cited studies of RSVM found NO_x reductions in the range of 0.7-1.0 percent (Jelinek et al., 2002; CDM, 2005; Malwitz, 2009). For the thrust derated take-offs, there is increased CO_2 due to increased fuel burn, but decreased NO_x, HC, and CO that can improve air quality (King and Waitz, 2005). A London study found that derated thrust can reduce NO_x by 14.5 percent during take-off and climb-out, more than offsetting the GHG effect from increased CO_2 emissions (King and Waitz, 2005).

Implementing OPD procedures not only reduce average fuel consumption, but also translate into lower noise impacts, with quieter flight operations due to reduced number of throttle transients and constant altitude flight segments near the ground (Russell, 2009). Changing of flight patterns may affect noise levels in different ways in individual neighborhoods, but RNAV/RNP approaches can be designed to minimize noise impacts on residential areas surrounding airports.

Many of these aviation measures decrease travel times, benefiting consumers while reducing airlines' labor, asset, and maintenance costs. ATM technologies can increase capacity, allowing more flights to arrive and depart the airport. To the extent that air traffic management can better coordinate arrival and departure schedules, there also will be fewer delays at both the ground and air levels. This reduced delay and increased reliability has substantial benefits to both consumers and the airlines. According to testimony by Senator Charles Schumer, in 2007 alone, the cost of delay to passengers, airlines and the U.S. economy amounted to $41 billion (JEC, 2008). The JEC report estimates that passengers were delayed by a total of 320 million hours, when accounting for padding in airline schedules – almost 20 percent of total domestic flight time in 2007. Of these flight delays 94 percent were caused by other flights arriving late, national system delays, or air carrier delays (less than 6 percent were due to security or extreme weather). Preliminary benefits analyses indicate that NextGen capacity increases could yield economic growth of as much as $175 billion through 2025 (FAA, 2007).

Feasibility

Air transport features a challenging mixture of local, regional, national, and international operations, management, and policy. Private operators (airlines) operate in publicly managed airspace. Locally controlled airports may seek to reduce emissions in the immediate area, but are constrained by competitive pressures and limited jurisdiction. National governments also are constrained by concerns about placing their own carriers at a competitive disadvantage, suggesting the need for an international framework for addressing emissions from air transport (Hansen, Smirti, and Zou, 2008).

Despite these complexities, examples of many operational procedures already have proven effective in the U.S. and other countries (see previous sidebar for examples of U.S. implementation). For OPDs, the technology has ready been implemented at multiple sites, but there is still concern over its impact and potential limitations on airspace capacity at certain locations. To move towards more "free flight" technologies, pilots would also have to be given training to decide on the most suitable and efficient routes and altitudes during their flights. Furthermore, the cost of systems and operations improvements will involve significant investment in air traffic management systems, both on the ground and for avionics on aircraft. Progress on FAA's NextGen initiative has been challenged by factors, including its complexity, costs to FAA and airlines, technology development, and interdependent government/industry implementation issues.(ATW, 2009).

Airport capacity expansion (runway extension, new runways, or even new airports) continues to take place, but is often contentious as a result of local concerns regarding aircraft noise, as well as other potential environmental impacts of expanding the airport's physical capacity. Airport design standards will likely change as part of NextGen, and operations on closely spaced parallel runways may be permitted at separations much closer than current standards. This would allow greater design flexibility, opening the potential for new runways to be added within existing footprints of airport property and allowing better use of existing runway layouts.

Other airport-specific operational practices, such as alternative-fuel GSE and GAV, gate power, and single-engine taxiing, have been implemented at some airports with the primary goal of reducing air pollutant emissions. Single-engine taxi can create some engine operation and maintenance issues, and aircraft tugging may create safety concerns, so care must be taken to determine when these procedures are appropriate to implement.

4.6 Infrastructure Construction and Maintenance

The energy used in the construction and maintenance of highway infrastructure, and the corresponding GHG emissions, are significant. One recent study estimated that infrastructure contributes up to 17 percent of total life-cycle transportation GHG emissions, with about two-thirds of these related to road construction (Chester, 2008). However, most of these emissions are attributed to other sectors, especially the industrial sector (construction and materials production), and therefore are not part of the transportation emissions inventory referenced in Section 2.0 of this report. A recent EPA study estimated that the highway, street, and bridge construction subsector is responsible for 17.6 mmt CO_2e annually, representing 13.2 percent of all construction sector emissions. Materials production and transport, as well as transportation agency facilities and operations, contribute additional GHG emissions.

Techniques are available to reduce the amount of energy consumed and GHG emitted in the construction, maintenance, and operations of transportation infrastructure. Some of these involve production techniques for materials (such as asphalt and concrete) that are most extensively used in highways, but also are used for other modes. Others involve reductions in energy use and GHG emissions associated with the construction and operating practices of transportation agencies, including highway departments, transit agencies, railroads, and port and airport authorities.

Construction Materials

Definition

Greenhouse gas emissions from infrastructure construction and maintenance activities can be reduced through the use of less energy-intensive construction materials by State and local highway departments and other transportation agencies. Most roadways, as well as airport runways, are built out of either concrete (made from Portland cement) or asphalt (blacktop). Greenhouse gas reduction strategies are available for both of these major materials:

Construction Materials

Benefits: **Low**: 18 mmt CO_2e in 2030

Direct Costs: **Unknown**; probably low for fly-ash concrete

Net Included Costs: **Unknown**

Confidence in Estimates: **High**

Key Co-Benefits and Impacts: **Positive**

- Recycling of material; reduced exposure to air pollutants

Feasibility: **High**

- Initiatives in progress

Key Policy Options:

- Continued research and development on warm-mix asphalt
- Construction material requirements/ standards

- The Portland cement production process produces a large amount of GHGs due to the large amount of fuel needed to heat calcium carbonate from limestone to chemically convert it to calcium oxide used in Portland cement. Recycled **fly ash**, which is a by-product from coal-burning power plants, can be used in the place of some of the cement used to form concrete. For example, the California Department of Transportation currently uses a 25 percent fly ash mixture, which has reduced GHG emissions from cement production by 25 percent, and it has a future goal of using a 50 percent fly ash mixture. This level is the maximum allowed by most State DOTs to ensure that structural integrity is maintained. **Blended cements** also can be made from other cementitious materials such as slag, although this is not a broad practice due to several factors, including availability of slag or fly ash to many cement plants.

- Aggregate, such as crushed rock or gravel, is another ingredient in concrete, and also can contribute to GHG emissions through the mining and transportation of these materials. **Recycling the aggregate** from existing roadways that are being rehabilitated and reusing it again in the same location also can reduce GHGs.

- Asphalt is produced by combining an asphalt binder (black gooey material made from crude oil) with an aggregate (crushed rock or gravel). Hot-mix asphalt is the traditional process used that heats the asphalt binder to high temperatures to lower its viscosity for proper mixing and paving. A new material, **warm-mix asphalt**, uses chemical additives to lower the temperature needed to achieve the proper viscosity. This in turn reduces the amount of fuel used and therefore GHG emissions. Lowering the temperature of the asphalt itself also lowers direct GHG emissions from the oxidation of the asphalt material. A number of demonstration projects using warm-mix asphalt have occurred in States around the country; however, this technology does not yet have widespread use.

For other materials used in construction, such as steel and wood products, the use of materials with a greater recycled material content, or the use of alternative materials with lower life-cycle GHG emissions, may provide GHG benefits. Little information is available on specific applications for the transportation sector. EPA's ReCon tool, designed to compare the GHG impacts of material purchasing and manufacturing, offers an option to evaluate the benefits of using common materials with various recycled contents (EPA, 2005).

Magnitude and Timing of GHG Reduction

Presently, fly ash is substituted for cement in concrete at a rate of 9.8 percent, which produces annual savings from the U.S. transportation sector of 3.3 mmt CO_2. If the substitution rate is increased to 50 percent, it would produce a savings of 18.4 mmt CO_2 annually, or 15.1 mmt beyond current levels (NCHRP 25-25 Task 45, draft work in progress). Benefits from fly ash usage in concrete can be realized in the very near term in the next few years due to the maturity of this technology and implementation practices.

Warm-mix asphalt has only been used to-date in demonstration projects in the U.S. This technology has the potential to reduce CO_2 emissions from asphalt production by 30-40 percent compared to hot-mix asphalt. In the future, if warm-mix asphalt technology develops to the point that it can be used in place of hot-mix asphalt on all roadways nationwide, the estimated GHG reductions would be 2.9 mmt CO_2 annually (NCHRP 25-25 Task 45, draft work in progress). Benefits from warm-mix asphalt will take longer to realize since the warm mix asphalt industry is in its infancy in the U.S. with only a few demonstration projects per year.

Costs

It is difficult to quantify costs of fly ash usage, but in general concrete made by replacing some Portland cement with fly ash will cost less than concrete made with all Portland cement due to the higher cost of Portland cement versus fly ash. However, as the percentage of Portland cement substituted with fly ash rises the need for some chemical additives offsets these cost savings.

The cost of warm-mix asphalt is somewhat uncertain due to its current small-scale usage. However, a recent research project (Anderson et al., 2008) has produced some estimates based on fuel savings as well as the increased costs due to the capital costs of additional equipment and material costs of chemical additives. Considering the range of costs given for each of these, the costs and cost savings are estimated at best cancel each other out to keep the cost of warm-mix asphalt the same as hot-mix asphalt. At worst, overall costs could increase by around $3-4 per ton of asphalt plus around $100,000 of capital costs per asphalt production company.

Cobenefits

Alternative material production techniques have some cobenefits, in addition to reductions in air pollution and fuel consumption associated with less energy-intensive technologies. For example, recycling fly ash and aggregate for use in concrete creates a use for these materials previously viewed as waste and keeps them out of landfills. Warm-mix asphalt can reduce plant emissions by 30–40 percent for SO_2, 50 percent for VOC, 60-70 percent for NO_x, and 20–25 percent for particulates. It also provides some benefits for paving (such as the ability to pave in cooler temperatures) and also reduces worker exposure to aerosols and hydrocarbons (FHWA, 2008).

Feasibility

Fly ash has been used in concrete since the early 1950s and does not require additional research on its performance. However, the use of fly ash in concrete requires careful attention to differing characteristics of the concrete and evaluation to ensure that the fly ash concrete meets the engineering requirements of individual projects. The availability of fly ash or other cementitious materials for concrete blending also may be limited in some areas, since these are by-products of other industrial activities.

Additional research and development is needed on warm-mix asphalt to evaluate field performance and adapt it to U.S. materials and production practices. However, a recent international scan tour to evaluate European practice concluded that with additional research and trials, there are no long-term barriers to the use of warm-mix asphalt in the U.S. (FHWA, 2008).

Other Transportation Agency Activities

Definition

Transportation agencies can introduce other practices to reduce GHG emissions associated with their activities. Examples include:

> **Other Transportation Agency Activities**
>
> *Benefits:* **Low**: 2.2 mmt CO_2e in 2030
>
> *Costs:* **Unknown**
>
> *Net Included Costs:* **Unknown**
>
> - Likely to vary widely by strategy
>
> *Confidence in Estimates:* **Moderate**
>
> - Poor inventory data, but estimates bounded by size of sector
>
> *Key Co-Benefits and Impacts:* **Positive**
>
> - Most activities will result in reduced criteria pollutant emissions; some will result in net cost savings
>
> *Feasibility:* **High**
>
> - Public and private sector initiatives in progress
>
> *Key Policy Options:*
>
> - Model practices and assessment tools; regulations to reduce GHG in construction; and/or funding incentives for GHG reduction activities

- **Construction Activities –** The U.S. EPA identifies a number of construction practices that can reduce GHG emissions, including increased vehicle fuel efficiency, reduced idling, better equipment maintenance, driver training, properly sized equipment, replaced or repowered equipment, biofuels for trucks and nonroad equipment, and alternatives to diesel generators. Since construction activities are generally contracted out by transportation agencies, the equipment and practices are not within their direct control, although the agency may set contract terms such as idle reduction practices or use of biofuels (U.S. EPA, 2009).

- **Fleet Vehicles –** Transportation agencies maintain a fleet of several types of vehicles and equipment for constructing, maintaining, and operating transportation facilities, as well as supporting other agency functions such as planning and design. These include on-road vehicles used by transportation agency employees for traveling between worksites and offices, and off-road vehicles such as maintenance equipment. A number of measures could be taken to reduce GHG emissions from these fleets of vehicles and equipment, such as:

  – Purchasing vehicles that are more fuel-efficient or that use alternative fuels can reduce the GHG emissions from gasoline or diesel combustion;

  – Implementing usage policies for these vehicles, such as anti-idling, and properly maintaining them; and

  – Implementing other measures to reduce vehicle use, such as planting ground cover that requires less mowing, and carpooling when using fleet vehicles to transport employees.

- **Buildings** – All transportation agencies have buildings for housing office staff and keeping equipment and supplies in a sheltered environment. A number of strategies can be implemented to increase the energy efficiency of these buildings, such as pursuing LEED certification or the EPA ENERGY STAR label for a building certification, or implementing energy efficiency measures separately such as energy efficient heating and air conditioning, fluorescent lighting, and energy efficient appliances.

- **Traffic Impacts of Work Zones** – When work zones are created to perform maintenance activities on roadways or to rebuild them a common side-effect is the creation of traffic congestion due to lane closures and speed reductions. This traffic congestion lowers the fuel efficiency of vehicles and often requires vehicles to idle, both of which increase GHG emissions. Strategies to prevent traffic congestion in work zones include scheduling activities at night or on weekends, scheduling simultaneous activities along a roadway where a bottleneck already is created, traveler information, variable speed limits, temporary contraflow lanes, and dynamic lane merging. Many of these strategies also are discussed earlier in this section as general traffic management and traveler information strategies.

Magnitude and Timing of GHG Reduction

Very limited data is available on the potential nationwide GHG benefits of transportation agency practices. A recent EPA report examined the potential for GHG reduction practices in the construction sector as a whole. The study noted a general lack of data on both total activity and the potential for emission reductions in this sector, but did provide some aspirational estimates for three practices: reduced idling, maintenance and driver training practices to increase fuel economy of heavy-duty equipment, and replacement of diesel with a 20 percent biodiesel blend (B20). The combined estimate was a reduction of 2.4 mmt CO_2e annually in the entire construction sector (U.S. EPA 2009), which, if allocated 16 percent to the transportation subsector (in proportion to transportation subsector's contribution to construction emissions), would imply a potential reduction of 0.37 mmt CO_2e annually from transportation construction activities.[39]

A recent NCHRP study examined the contribution of State DOTs to reducing GHG emissions (Cambridge Systematics, 2009b). This study estimated that about 19 percent of State DOTs' current vehicle fleet is powered by alternative fuels, saving 0.03 mmt CO_2 annually. If 100 percent of State DOT vehicles were alternative fuel vehicles using these

[39]The EPA study assumed a 10 percent reduction in idling from all off-road diesel equipment, a 3 percent increase in fuel economy due to improved maintenance and driver training, and a 10 percent replacement of diesel with biodiesel.

same fuel technologies, 0.17 mmt CO_2 could be saved annually.[40] Future reductions could be greater with the use of less carbon-intensive alternative fuels.

The potential for GHG reduction from transportation agency buildings is not well understood due to a lack of data on energy efficiency implementation in buildings. It is estimated, however, that if 100 percent of State DOT buildings implemented energy efficiency measures contributing to the LEED Silver rating, resulting in a 33 percent energy savings in buildings, GHG could be reduced by 1.7 mmt CO_2 annually (Cambridge Systematics, 2009b).[41] The rate at which these benefits could be achieved will depend upon the renewal of building stock as well as measures to retrofit existing buildings.

The combined GHG reduction estimates from the construction, fleet vehicle, and energy efficient building practices described above are about 2.2 mmt CO_2e annually in 2030. The GHG reduction from work zone management is extremely difficult to quantify because of the large variation in the amount of traffic created in work zones and the effectiveness of work zone management techniques on this traffic. Comprehensive national estimates have not been produced.

Cost-Effectiveness

The cost-effectiveness of alternative fuels is discussed in detail in Section 5.0. According to a 2009 McKinsey and Company report the cost-effectiveness of a "new building efficiency package" for commercial buildings is about $13 savings per metric tonne CO_2e reduced. The McKinsey report also examines retrofitting existing buildings with new HVAC, water heaters, lighting, appliances, and building envelopes. The cost-effectiveness of these retrofitting measures range from +$60 to -$120 per metric tonne CO_2e reduced (McKinsey and Company, 2009).

The cost-effectiveness of construction emission reduction practices has not been estimated. The cost-effectiveness of work zone management is difficult to quantify due to varying benefits depending on the severity of the traffic congestion created by the work zone, and no comprehensive estimates have been developed.

Cobenefits

Construction emission reduction practices have primary been implemented in order to reduce emissions of criteria pollutants and improve air quality in the vicinity of

[40] The estimate assumes continuation of the existing mix of alternative fuel vehicles, which includes about 70 percent ethanol (E85) vehicles with most of the remainder compressed or liquefied natural gas.

[41] The LEED standard does not specifically require energy efficiency measures, although most buildings subject to certification include such measures. Data from Turner and Frankel (2008) suggest that LEED certified buildings have about 33 percent lower energy use than uncertified buildings.

construction sites. Practices that reduce GHG emissions are likely to result in corresponding reductions in criteria pollutant emissions. The cobenefits of alternative fuels are discussed in detail in Section 5.0.

Feasibility

Fuel-efficient and alternative fuel vehicles, energy efficient buildings, and traffic management in work zones have all been demonstrated to be feasible by transportation agencies around the country. Transportation agencies can require emission reduction practices to be implemented by construction contractors, and in a few cases (such as the Massachusetts Central Artery/Tunnel project and the Virginia Byways project in North Carolina) have done so with the objective of reducing criteria pollutants.

One primary barrier to vehicle and buildings strategies is up-front capital costs, which may in many cases be recouped over time through energy and fuel savings. The adoption of alternative fuel vehicles also may be inhibited by the need for refueling infrastructure. The feasibility of using some alternative fuels (such as biodiesel) in certain types of equipment or under particular operating conditions (e.g., cold weather) has not been fully demonstrated.

Policy actions by the Federal government to promote GHG reduction practices by transportation agencies could potentially include technical assistance (e.g., development of GHG inventory and assessment tools, cost-savings information, model contract language to require GHG reducing practices by contractors); regulations requiring transportation agencies to inventory the GHG emissions from their activities and implement GHG reduction practices; and/or funding targeted at specific activities. A pending NCHRP project (Project 25-25, Task 58) is developing a tool to estimate life-cycle GHG emissions from transportation agency construction, maintenance, and operations activities. This tool should provide much better information to assist agencies in identifying the most significant sources of GHG emissions and implementing GHG reduction practices.

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5.0 Strategies to Reduce Carbon Intensive Travel Activity

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5.1 Summary

Strategies to reduce carbon-intensive travel activity seek to reduce greenhouse gas emissions by influencing travelers' activity patterns in order to shift travel to more efficient modes, reduce the need for travel, or otherwise take actions that reduce energy use and GHG emissions associated with personal travel.[1] These strategies may include changes to transportation infrastructure, services, and land use patterns that facilitate or encourage less carbon-intensive activity patterns, as well as policy and programmatic actions such as financial incentives and disincentives, information, and education. Travel activity strategies discussed in this report include:

- **Pricing strategies** that increase the cost per mile of driving. Pricing strategies will result in a variety of effects including fewer trips, shorter trips, greater use of alternative modes, and a shift in travel to periods of lower congestion (Section 5.2);
- **Improvements to transit, nonmotorized, and intermodal travel**, including urban transit, intercity bus and rail, nonmotorized infrastructure, and intermodal facilities and information, to encourage mode-shifting and increase the energy efficiency of travel per person-mile traveled (Section 5.3);
- **Land use and parking management strategies** to create more compact development patterns that reduce trip lengths and support the use of alternative travel modes through walkable and transit-oriented communities (Section 5.4);
- **Commuter/worksite trip reduction programs**, to encourage alternatives to single-occupancy vehicle work trips through ridesharing, vanpooling, transit, nonmotorized travel, alternative work schedules, and telework (Section 5.5); and
- **Other public information programs** to educate people about the choices available to them regarding travel options, vehicle purchase, driving habits, and other issues, and the effects of these choices on costs, environmental impacts, and other factors (Section 5.6).

These strategies are described in greater detail in the sidebar on page 5-2.

[1] Strategies to shift freight to more efficient modes are discussed in Section 4.0, System Efficiency.

Strategies to Reduce Carbon-Intensive Travel Activity

Pricing

- **VMT Fees –** Charging drivers per mile of travel.
- **Intercity Tolls –** Applying tolls to rural InterState and other limited-access highways.
- **Pay-as-You-Drive Insurance –** Converting a significant portion of the essentially fixed cost of insurance to a marginal cost based on mileage.
- **Congestion Pricing –** Pricing roadway facilities when they are congested in order to reduce traffic on those facilities to an improved level of service.
- **Cordon/Area Pricing –** Applying a fee for vehicles to enter or operate within a selected area, such as a central business district.

Transit, Nonmotorized, and Intermodal Travel

- **Transit Expansion, Promotion, Service Improvements –** Investing in new fixed-guideway urban transit, expanding coverage of bus systems, increasing the frequency and/or time coverage of service on existing routes, or making other improvements to the quality of service on urban transit systems.
- **Intercity Bus and Rail –** Bus and rail passenger services (improvements to existing Amtrak services, or investment in new high-speed rail corridors) in corridors up to 500 miles between major city pairs.
- **Nonmotorized Transport –** Capital investments in nonmotorized infrastructure (e.g., bicycle facilities, sidewalks), or supporting activities such as design standards, bicycle parking at destinations, or education programs, to encourage bicycling, walking, and other forms of nonmotorized transport.
- **Passenger Intermodal Improvements –** Coordinating infrastructure and services to facilitate transfers between modes in order to maximize the efficiency of travel and minimize passengers' time and costs.

Land Use and Parking

- **Land Use –** Coordinated regional transportation and land use planning to develop and implement growth policies (e.g., zoning for compact, walkable communities), in conjunction with supportive infrastructure investment, to reduce vehicle-travel.
- **Parking Management –** Changes to parking supply, pricing, or other management techniques to create disincentives to driving.

Commute Travel Reduction

- **Worksite Trip Reduction Programs –** Requirements for employers to reduce single-occupancy vehicle trips by their employees, or outreach, assistance, and incentive programs to encourage them to do so.
- **Telework –** The practice of working from a location other than the regular workplace and using modern telecommunications and computer technology to bridge the resulting distance.
- **Compressed Work Week –** A scheduling system whereby a regularly scheduled number of hours are worked in a shortened span of time.
- **Flexible Work Schedules –** Employer-facilitated alternatives to a standard 9:00 a.m. to 5:00 p.m. work schedule for commuting employees.
- **Ridematching, Carpooling, and Vanpooling –** Programs such as ridematching databases, vanpooling programs, and other supportive actions to increase vehicle occupancies for work trips.

Public Information Campaigns

- **Information on Travel Choices –** Mass marketing and individualized marketing campaigns to provide people with information on the full range of travel options and impacts of their choices.
- **Information on Vehicle Purchase –** Information directed at influencing consumers' purchasing decisions by providing complete information on the environmental, cost, and other impacts of their purchases.
- **Driver Education/Eco-Driving –** Education programs directed at increasing vehicle fuel efficiency by affecting both driver behavior and vehicle maintenance.

Summary of Impacts

Pricing strategies are among the travel activity strategies evaluated in this report with the greatest potential to reduce GHG emissions. Economists argue that pricing strategies can internalize the costs of the externalities associated with travel,[2] discourage low-value trips, and encourage more efficient use of the transportation network. Comprehensive pricing strategies that affect all travel—including VMT fees and pay-as-you-drive insurance—could potentially each reduce GHG emissions in the short term[3] by up to 3 percent of all transportation emissions at typical levels of implementation, or about 75 million metric tons carbon dioxide-equivalent (mmt CO_2e) emissions. If applied together, impacts would be greater. Strategies focused on specific markets, such as intercity tolls or cordon pricing, will have much smaller benefits consistent with the size of the market affected, and may also have some offsetting negative impacts by shifting vehicle-travel to unpriced locations rather than reducing it outright. Congestion pricing—in which higher prices are charged for traveling in periods of high demand—will not only reduce VMT, but also result in more efficient traffic operations. Benefits from comprehensive congestion pricing on all roadways could be as high as 1.4 percent of transportation GHG emissions or 35 mmt CO_2e, but this figure is subject to substantial uncertainty.

Despite its effectiveness, increasing the price of travel has so far proven unpopular with the general public. In general, in order for pricing to yield net benefits to the traveling public and not produce unacceptable equity impacts, a large fraction of the revenues must be reinvested in transportation services that benefit travelers (such as transit) and/or returned to the public (for example, through tax rebates). Potential Federal policies to encourage more widespread pricing include: implementing a national VMT fee system to replace or supplement the gas tax; easing or eliminating restrictions on congestion pricing programs and tolling on Interstate highways; providing funding for congestion pricing programs or making Federal funding contingent upon adoption of pricing strategies by States or metropolitan agencies; and establishing requirements to ensure that pricing revenue is used in a way that addresses equity concerns.

Investments in **transit** also have the potential to generate modest to moderate reductions in GHG emissions. Expansion of and improvements to **urban transit** have the potential to reduce transportation GHG by 0.2 to 0.9 percent by 2030, or 5 to 19 mmt CO_2e.[4] Benefits

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[2] Externalities can be defined as environmental, congestion, and other impacts that the traveler imposes on others but does not directly incur, and therefore does not generally factor into his or her decision-making.

[3] In this report, "short-term" refers to benefits realized within five years or less (2015); "mid-term" refers to benefits realized in about 20 years (2030); and "long-term" refers to benefits realized in 30 to 40 years (2050).

[4] Some of the benefit estimates for a number of travel activity strategies, including transit, nonmotorized improvements, land use, and commuter strategies, incorporate "induced demand" effects. As some travelers shift to other modes or reduce their travel, roadway congestion will be

(Footnote continued on next page...)

will increase over time as transit systems expand, up to as much as 32 mmt CO_2e in 2050. The benefits of transit investment will vary greatly, however, depending upon ridership productivity (passengers carried per vehicle), and service expansions that do not carry sufficient new ridership could actually result in a net increase in GHG emissions. Ridership productivity will depend heavily upon transit-supportive land use patterns and pricing policies that support the use of transit. **Intercity bus and rail**, including Amtrak improvements, high-speed rail, and expanded intercity bus service, has modest potential for GHG reduction (up to 0.2 percent of transportation emissions, or 6 mmt CO_2e in 2030), due to the limited travel markets in which use of these modes is likely to be significant. Again, benefits will depend upon the level of ridership productivity achieved. By themselves, both urban and intercity transit have low cost-effectiveness as GHG reduction strategies, with implementation costs of $400 to $3,000 per metric ton (tonne) for urban transit and intercity rail. In many cases, however, transit expansion may be justified on the basis of other benefits, especially mobility improvements for low-income and other limited-mobility travelers. Also, in some cases, personal vehicle operating cost savings can exceed the public-sector cost of transit investment. Furthermore, certain types of improvements (such as transit priority at traffic signals) could have greater cost-effectiveness by improving the quality of service without increasing the amount of service provided. The primary Federal need to support transit expansion is additional funding, both for capital investment and operations.

Nonmotorized improvements, including pedestrian and bicycle infrastructure, have modest potential for GHG reductions (0.2 to 0.6 percent of transportation emissions, or 4 to 12 mmt CO_2e by 2030), but are also relatively inexpensive compared to highway or transit investment and therefore have moderate cost-effectiveness based on implementation costs ($70 to $180 per tonne). Personal vehicle operating cost savings can outweigh public-sector investment costs for these strategies. Some improvements are low-cost, such as incorporating bicycle lanes and enhanced pedestrian crossings into new or reconstructed roadways; others, such as shared-use paths or retrofitting suburban areas with sidewalks, are more costly. Nonmotorized improvements complement transit improvements—they support transit use and, as with transit, are much more effective in densely developed areas where destinations are close together. Federal initiatives could include additional funding targeted for nonmotorized infrastructure and policy directives such as requiring the adoption of "complete streets" policies or other supportive policies by State and local transportation agencies.

Land use and parking management has moderate to high potential for GHG reductions over the mid- to long-term by reducing trip lengths and supporting travel by transit, walking, and bicycling. Reductions from aggressive strategies to create more compact, walkable communities could range as high as 3.9 percent of transportation emissions or 84 mmt CO_2e by 2030, and potentially double this level by 2050. Land use patterns change slowly over time; nevertheless, it is estimated that by 2050 two-thirds of all development

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reduced, thereby potentially allowing or encouraging other people to drive more. This effect has been estimated to reduce GHG benefits of these strategies by a modest amount (about 14 percent) as discussed in Appendix A.

on the ground will be new or rebuilt, compared with today's building stock. The direct cost of implementing land use strategies (including planning and administration) is minimal (less than $10/tonne) and these strategies will result in significant vehicle operating cost savings. They also have a variety of other implications related to environmental impacts, livability, and housing affordability, which may vary depending upon the specific land use policies implemented. Land use represents a particularly challenging issue from a Federal policy perspective, due to the traditional sovereignty of local governments on this issue and the strong influence of the private sector. Building on State and regional agency models, however, the Federal government could potentially play a more significant role in encouraging more efficient land use patterns, by providing funding incentives and disincentives as well as technical assistance.

Commuter/worksite trip reduction programs appear to have modest potential for GHG reductions (0.1 to 0.6 percent of transportation emissions, or 2 to 14 mmt CO_2e in 2030). Telework and other alternative work schedules can further reduce GHG from work travel by up to 0.7 percent (17 mmt CO_2e), although telework is likely to spread largely through private initiative and the role of the public sector in encouraging adoption of alternative work schedules appears limited. Trip reduction programs can generally be implemented at modest cost compared to investment in infrastructure or services, with implementation costs from $30 to $180 per tonne. Net savings may result from reduced vehicle operating costs. The Federal government could play a greater role in commute strategies by providing funding for employer outreach programs and other regionally provided TDM services, providing tax incentives for businesses offering commute alternatives, and potentially by establishing trip reduction requirements.

Public information campaigns to encourage travelers to change behavior exhibit modest GHG reduction potential—in the range of 0.3 to 0.4 percent of transportation GHG emissions (6 to 8 mmt CO_2e). Campaigns based on mass marketing have demonstrated little ability to influence travel behavior. Individualized marketing, in which people are provided with customized information on travel alternatives, shows somewhat greater promise in areas where good alternative services are available, but has not been proven in areas with limited alternatives. The impacts of educational efforts to encourage eco-driving and proper vehicle maintenance are potentially much more significant – between 0.8 and 4.3 percent of transportation emissions or 18 to 94 mmt CO_2e. Achieving these benefits, however, is dependent upon comprehensive and sustained efforts, including requiring instruction as part of driver education and requiring automakers to provide in-vehicle feedback technology. Furthermore, the only empirical research on eco-driving benefits has been conducted outside the United States, primarily in Europe, and it is not clear that findings can be translated to United States conditions.

The 2030 emissions benefits (expressed in mmt CO_2e) cited for these strategies will be lower in absolute terms if vehicle efficiency improves and/or the carbon content of fuel is reduced beyond baseline levels assumed in this report. For example, if vehicle efficiency is increased by 20 percent compared to baseline projections, the absolute CO_2e reduction benefits will be 20 percent lower. Similarly, if total travel activity is more or less than baseline projections, the absolute GHG reduction benefits will increase or decrease proportionately.

Cumulative Benefits

While the effects of the individual strategies presented in this report cannot simply be added together to provide a cumulative savings, it is still desirable to make a rough estimate of cumulative benefits from travel activity strategies, in order to compare with other types of strategies. To do so, the following strategy benefits were added together, considering both the low and high range of benefits cited from the literature:

- Pay-as-you-drive insurance;
- Congestion pricing;
- Urban and intercity transit;
- Non-motorized travel;
- Land use;
- Parking management;
- Commuter/worksite trip reduction;
- Telework and compressed work week;
- Individualized marketing; and
- Eco-driving.

Pay-as-you-drive insurance and congestion pricing are considered as a representative subset of pricing measures; it is unlikely that all pricing measures would be implemented at once, but a VMT fee instead of PAYD would have similar effects. Ridematching and mass marketing were deemed to be largely redundant with commuter/worksite trip reduction and were therefore excluded. The benefits of these strategies would not necessarily be purely additive; a multiplicative approach would give slightly lower combined benefits, but also would not account for any potential synergies among strategies.[5]

Combined benefits are estimated to range from 5 to 17 percent of total transportation emissions in 2030, or 6 to 21 percent in 2050, as shown in Table 5.1.

[5] A multiplicative approach would, for example, first reduce GHG by *x* percent from one strategy, then *y* percent from the second strategy applied to the new baseline, etc. For example, two strategies with benefits of 10 percent each would have a combined benefit of (1 – (0.9 * 0.9)) = 19 percent.

Table 5.1 Combined Benefits of Strategies to Reduce Carbon-Intensive Travel Activity

Year	GHG Reduction from Baseline, mmt CO_2e Low	High	Percent of All Transportation Emissions Low	High
2030 Combined Benefits	107	366	4.9%	16.9%
2050 Combined Benefits	138	463	6.4%	21.3%

Summary Evaluation

Table 5.2 summarizes the strategies discussed in this section and presents an assessment of each strategy's effectiveness, cost-effectiveness, and cobenefits, as well as a summary of key Federal policy initiatives that would be needed to implement the strategy beyond current levels. The factors presented in the table are rated according to the following metrics:

- **Effectiveness**: Low = < 0.5 percent of transportation GHG emissions in 2030 (12 mmt CO_2e; Moderate = 0.5-2.5 percent (12-60 mmt CO_2e); High = > 2.5 percent (60 mmt CO_2e);

- **Costs**: Cost is measured as "net included cost" per metric ton (tonne) of CO_2e reduced. A positive number represents increased costs, while a negative number represents a net savings. High Cost = > $200 per tonne CO_2e reduced; Moderate Cost = $20-$200 CO_2e reduced; Low Cost = < $20/tonne CO_2e reduced; Net Savings = < $0/tonne CO_2e reduced. Costs for travel activity strategies are presented in two ways:

  – Direct costs (implementation costs only) per tonne of CO_2e reduced; and

  – "Net included costs" (which includes both direct costs and any reported cost savings, usually vehicle operating costs). A discussion of how costs are calculated and presented in this report is presented in Appendix A.

- **Cobenefits**: Plus (+) = significant positive cobenefits; minus (–) = significant negative cobenefits; plus/minus (+/-) = both significant positive and negative cobenefits; zero (0) = modest or negligible cobenefits.

Table 5.2 Overview of Strategies to Reduce Carbon-Intensive Activities

Strategy	GHG Reduction (2030)	Direct Cost per Tonne	Net Included Cost per Tonne	Cobenefits	Key Federal Policy Options
5.1 Pricing					
5.1.1 VMT Fees	Moderate 0.8-2.3%	Moderate	Net Savings	–	Establishment of national VMT fee, or requirements or incentives for State-level implementation R&D to address privacy as well as technical issues with monitoring
5.1.2 Intercity Tolls	Low <0.1%	High	Net Savings - Moderate	–	See VMT fees; plus removal of restrictions on tolling Interstate highways
5.1.3 Pay-as-You-Drive Insurance	Moderate-High 1.1-3.5%	Low-Moderate	Net Savings	+/-	Federal requirement that States 1) allow or 2) require insurers to offer mileage-based insurance Demonstration projects (?)
5.1.4 Congestion Pricing	Low-Moderate 0.4-1.6%	High	Net Savings	+/-	Requirements or incentives for metro-level implementation R&D to address privacy as well as technical issues with monitoring (same issues as VMT fee)
5.1.5 Cordon/ Area Pricing	0.1%	High	Net Savings	+/-	Requirements or incentives for city or metro-level implementation
5.3 Transit, Nonmotorized, and Intermodal Travel					
5.3.1 Transit Expansion, Promotion, Service Improvements	Low-Moderate 0.2-0.9% (2030) 0.4-1.5% (2050)	High	Net Savings – High	+	Funding for transit investment and services
5.3.2 Intercity Passenger	Low 0.3%	High	Net Savings – High	+	Funding for intercity and high-speed rail expansion, intercity bus route expansion National rail plan and policy framework to reconcile passenger and freight rail needs
5.3.3 Nonmotorized Transport	Low-Moderate 0.2-0.6%	Moderate – High	Net Savings	+	Funding for bike/pedestrian projects Requirement for States to adopt complete streets/design policies for alternative mode accommodation

Table 5.2 Overview of Strategies to Reduce Carbon-Intensive Activities (continued)

Strategy	GHG Reduction (2030)	Direct Cost per Tonne	Net Included Cost per Tonne	Cobenefits	Key Federal Policy Options
5.4 Land Use and Parking					
5.4.1 Land Use	Moderate-High 1.2-3.9% (2030) 2.5-7.7% (2050)	Low	Net Savings	+	Transportation funding incentives to support regional and local planning for efficient land use Federal inter-agency policy coordination to support efficient development patterns and practices
5.4.2 Parking Management	Low 0.2%	Unknown	Unknown	+/-	
5.5 Commute Travel Reduction					
5.5.1 Worksite Trip Reduction Programs	Low-Moderate 0.1-0.6%	Low-Moderate	Net Savings	+	Funding for regional employer outreach and commuter support programs
5.5.2 Telework	Low 0.4%	High	Moderate	+	Expanded tax incentives for alternative commute measures (telework, transit subsidies, etc.) (Federal requirement for States to implement employer trip reduction ordinances)
5.5.3 Compressed Work Week	Low 0.1-0.3%	Low	Unknown	+	
5.5.4 Flexible Work Schedules	N/A	Low	Unknown	+	
5.5.5 Ridematching, Carpool, Vanpool	Low 0.0-0.2%	Moderate	Unknown	+	
5.6 Public Information Campaigns					
5.6.1 Information on Travel Choices	Low 0.3-0.4%	Moderate-High	Unknown	+	Funding for individualized marketing programs—additional pilots, broader-scale implementation
5.6.2 Vehicle Purchasing	Low 0.1-0.2%	Unknown	Unknown	+	Continuation/expansion of outreach programs
5.6.3 Eco-Driving	Moderate-High 0.8-4.3%	Unknown	Net Savings	+	Requirements for auto manufacturers to incorporate in-vehicle fuel efficiency feedback Requirements for States to teach eco-driving practices in driver training and drivers' manuals Funding for eco-driving education
Combined Benefits	4.9-17% (2030) 6.4-21% (2050)				

Cobenefits and Implications for Other Key Transportation Goals and Objectives

Strategies to reduce carbon-intensive travel activity have a number of common cobenefits, implications for DOT goals and objectives, and implications for infrastructure finance, as described below. Some strategies also have unique cobenefits and impacts which are described in their respective subsections. They can be evaluated against the five strategic goals of the U.S. DOT (identified in the U.S. DOT's Strategic Plan), as well as other key objectives established for transportation by the Obama Administration:

- **Safety –** Most travel activity strategies reduce VMT. By doing so, they should reduce the number of crashes and associated costs and human impacts. Alternative modes typically carry much smaller crash risks per passenger-mile or vehicle-mile than highway travel.

- **Reduced Congestion/Increased Mobility –** Strategies that improve the availability and quality or reduce the cost of travel options, as well as those that provide information about options, can provide increased mobility to travelers. In particular, these strategies include improved urban and intercity transit services, nonmotorized improvements, commute-focused travel options programs, and traveler information. Mobility benefits are particularly acute for low-income people for whom an automobile may be a financial hardship, as well as for children, seniors, and those with disabilities that make driving impossible. Strategies that are implemented through requirements or disincentives (such as price increases) represent a constraint on mobility and will make some people worse off. Any strategy that reduces VMT during peak periods should also reduce congestion; however, this does not necessarily imply an increase in mobility, as some people may have been discouraged from traveling due to a higher cost or other disincentive.

- **Global Connectivity –** Strategies implemented in a way that improves passenger movement to and through airports, border crossings, and intermodal terminals (or infrastructure in the vicinity of these facilities) should improve global connectivity by enhancing connections between modes and across national borders.

- **Environmental Stewardship –** All of the travel activity strategies reduce GHG emissions by reducing vehicle travel and its associated energy consumption, without changing the mix or source of fuels used. As a result of burning less fuel and reducing VMT, most of these strategies should also result in reductions in other air pollutants, including ozone precursors (volatile organic compounds and oxides of nitrogen), carbon monoxide, particulates, and air toxics. A reasonably close correspondence is expected between reductions in air pollutant emissions, VMT, and GHG emissions. Strategies that affect congestion and travel speeds, such as those that reduce peak-period travel, may provide additional benefits by reducing emissions associated with congestion. Strategies that involve shifting travel to other modes will have more complicated effects because the emissions characteristics of each mode will differ. For example, the diesel engines commonly used in buses and rail locomotives may in some cases increase NO_x and PM emissions relative to passenger car travel, although they will generally reduce VOC and CO emissions. Greater reliance on electricity (e.g., for urban or intercity transit) will shift the location of pollutants from urban areas to often-rural power plants, resulting in net health benefits; the magnitude of pollution reductions, however, will depend upon the fuel and technology characteristics of the affected powerplants.

- **Security –** Travel activity strategies may benefit national security by reducing dependence upon foreign oil. The reduction in oil use will be in direct proportion to GHG reductions for each strategy. Strategies that reduce roadway congestion should have security benefits from improved emergency services (police, fire, and medical) response time.

- **Livability –** Land use and nonmotorized strategies will provide more options for physical activity through walking and bicycling, not only for transportation but also for recreation. These strategies may also improve livability by reducing vehicle travel speeds – thus making neighborhood streets safer and reducing traffic noise. Other livability effects may be more complex and be viewed as either positive or negative by different people. For example, some people may positively value the feel of an urban community and its greater opportunities for casual social interaction, while others will prefer the privacy and space afforded by low-density development.

- **Economic Vitality –** To the extent that travel activities strategies reduce congestion, they will generally support economic vitality by reducing business and consumer costs and increasing business productivity. Congestion and cordon pricing are the two travel activity strategies most directly targeted at congestion reductions; others will have more indirect effects through reduced VMT during both peak and off-peak periods. However, businesses will also incur increased costs from pricing strategies; whether these costs outweigh the benefits of reduced congestion will depend upon how each strategy is applied. Transit investment may have localized economic benefits by encouraging development in communities with transit stations.

Effects on Infrastructure Funding

All of the strategies in this section will result in varying demands on infrastructure funding sources depending upon their costs. Some strategies have relatively low public-sector costs, such as those that involve marketing and outreach to promote the use of alternative modes, and planning for land use changes. Others will have higher costs in proportion to the amount of infrastructure investment and services provided by the public sector.

Reductions in vehicle travel will lead to proportionate reductions in motor fuel sales and therefore reduced revenue for transportation programs, under the current finance structure. The Federal Highway Trust Fund was established in 1957 as a dedicated, user-funded source of revenue for the United States highway system and is the source of revenue for the Federal-aid Highway Program. Net receipts in FY 2007 were $34.3 million to the Highway Account and $5.0 million to the Mass Transit Account (FHWA, 2008).

The strategies analyzed in this report for reducing carbon-intensive travel activity will reduce total Federal Highway Trust Fund revenues in rough proportion to fuel savings and GHG reductions. Under the 2030 combined scenario described above, the net impact on revenues could range from about $2.2 to $7.3 billion annually.[6] Funding shortfalls could be mitigated or avoided in the future through shifts in tax structures or through alternative infrastructure funding mechanisms. In particular, the pricing strategies evaluated in this section (including a VMT fee, intercity tolls, or congestion or cordon pricing) would provide a supplemental funding source to support other infrastructure investments and services.

[6] Based on a total fuel savings of 11.8 to 39.8 million gallons and a tax rate of 18.4 cents per gallon.

■ 5.2 Pricing

Pricing strategies are designed to increase the cost of driving in order to internalize the external costs associated with travel (environmental and congestion), discourage low-value trips, and encourage more efficient use of the transportation network. Pricing strategies will result in a variety of effects including fewer trips, shorter trips, greater use of alternative modes, and shifting travel to times when congestion is less. Five pricing strategies are discussed in this section:

- VMT fees, which charge a fixed cost per mile driven;
- Intercity tolls, applied specifically to rural InterState and other limited-access highways;
- Pay-as-you-drive insurance, which converts the variable costs associated with insurance (i.e., costs such as crash risk that are proportional to distance driven) into a per-mile cost paid by the vehicle owner;
- Congestion pricing, in which highway travel under conditions of high demand is priced higher to keep travel and therefore congestion at levels of optimum economic efficiency; and
- Cordon pricing, which is essentially congestion pricing applied to a particular area (usually the region's central business district) to discourage enough travel to keep traffic in the area moving efficiently.

Economy-wide market measures, including a cap-and-trade system or carbon tax (see Volume 1, Section 4.0), will also increase the cost of driving, and therefore bear similarities to a VMT fee. Unlike a VMT fee, however, the carbon-based costs will also affect drivers' vehicle purchasing habits since the carbon price rewards lower fuel consumption, not just fewer miles driven. Increased motor fuel taxes, which are not discussed separately in this report, will have the same effects as a carbon tax of equivalent magnitude. The advantages and disadvantages of various pricing mechanisms are discussed in Volume 1, Section 3.0.

Some of the other strategies discussed in this report also encompass pricing measures. For example, Parking Management (Section 5.4.2) can include pricing as a management strategy. Worksite Trip Reduction Programs (Section 5.5.1) strategies often include financial incentives for the use of transit, nonmotorized travel, or ridesharing, or parking pricing to discourage driving.

The five transportation-specific pricing measures that follow can be analyzed using broadly similar methods. Estimates of VMT reductions generally rely on common assumptions regarding elasticities (how much VMT changes with respect to a given change in travel cost) and baseline vehicle operating costs. The cost and elasticity assumptions used to develop the estimates presented in this report are described in detail in Appendix A. In addition, while congestion pricing and cordon pricing will affect total VMT, their primary goal is to affect the efficiency of travel by reducing travel in congested locations and time periods. These strategies can provide GHG reductions greater than their VMT reduction impacts by also decreasing fuel wasted because of congestion.

VMT Fees

Description

VMT fees have been proposed both as an alternative or supplemental revenue source to the gas tax, and to reduce VMT by making travel more expensive. Fees on vehicle miles of travel have been suggested by the National Surface Transportation Policy and Revenue Study Commission and the National Surface Transportation Infrastructure Financing Commission, and by reports from the National Chamber of Commerce, the Transportation Research Board, and the National Cooperative Highway Research Program. VMT fees would most likely vary by type of vehicle, to reflect principles of highway cost allocation, or perhaps to reflect also the different emissions characteristics of vehicles.

VMT Fees

Benefits: **Moderate**: 17-50 mmt CO_2e in 2030

- Based on fee of 2 to 5 cents per mile

Direct Costs: **Moderate**: $60 to $150 per tonne

Net Included Costs: **Net Savings**: -$600 to -$800 per tonne

Confidence in Estimates: **High**

- Price elasticities well-documented
- Primary variable is magnitude of fee

Key Cobenefits and Impacts: **Mixed/Negative**

- Mobility decreases for most travelers
- Potential equity concerns, depending upon how revenues are used
- Transportation revenue source provides opportunities for reinvestment

Feasibility: **Low**

- Fees significant enough to measurably affect behavior unlikely to be popular in the current political climate

Key Policy Options:

- Adoption of a national VMT fee-based highway revenue collection system

Two basic approaches are available for monitoring VMT as a basis for assessing charges:

1. **Administrative Reporting –** Motor vehicle mileage would be reported through the motor vehicle registration and inspection process or on-board odometer readings. This approach uses existing technology and could be implemented quickly. While simplest from a reporting perspective, enforcement would be required to ensure proper reporting and to control odometer tampering.

2. **Wireless Reporting –** Motor vehicles would link to a receiver located at gas stations, where a radio frequency receiver would pick up a transmission from an on-board unit that would provide the odometer reading since the last gas station visit. This strategy would require additional technology deployment but would reduce or eliminate the capability for fraud and also reduce manual labor associated with reporting. Electronic fee collection has the additional advantage that it could potentially be used to implement congestion pricing as well, if used in conjunction with a global positioning system (GPS) unit to assess variable fees based on the time and location of travel.

Magnitude and Timing of GHG Reductions

VMT fees could be applied to all VMT on all systems (2.9 trillion VMT in 2006). Assuming price elasticities and vehicle operating costs as documented in Appendix A, a toll of 2 cents per mile (roughly equivalent to current motor fuel taxes) is estimated to reduce VMT by about 1 percent, with a corresponding reduction in GHG emissions from motor vehicle travel.[7] A higher toll of 5 cents per mile would reduce VMT by about 2.5 percent. The VMT impacts of a 2- to 5-cent fee equate to a reduction of about 30 to 75 billion VMT, or 17 to 50 mmt CO_2e in 2030. These estimates could potentially be lower or higher by at least a factor of two, reflecting the range of uncertainty in the literature regarding travelers' response to price changes.

Very limited empirical evidence is available from a mileage-based fee experiment. A study conducted on 130 households in the Minneapolis–St. Paul metropolitan area concluded that per-mile pricing would result in a VMT reduction of 4.4 percent for all daily travel, or somewhat higher reductions (6.6 percent) during weekday peak periods (Cambridge Systematics, 2006). This study was based on a relatively high fee rate—between 5 and 25 cents per mile, varying for different participants—based on converting automobile fixed to variable costs. The study concluded that some households were willing to change their behavior even at relatively low fee levels; but that increasing fees toward the higher end of the range had little additional impact on travel, since other households were unwilling or unable to change their behavior. If the daily reduction were applied to all light-duty VMT nationwide (impacts on truck travel were not evaluated in this experiment), GHG emissions would be reduced by 51 mmt CO_2e in 2030. This finding corroborates the elasticity-based estimates provided above.

VMT fees can be implemented in a very short timeframe using mechanical hubodometers; implementation of electronic systems would take somewhat longer but still could be done within a few years. Some impacts would be realized immediately after implementation. The effects will increase somewhat over the first few years of implementation, as travelers can make more structural adjustments (such as changing residential or activity locations) in response to price signals.

Cost-Effectiveness

Using cost factors from two recent studies (Howard, no date; Kitchen, 2008), the national full application of VMT fees is estimated to cost $131 billion through 2050 if based on mechanical hubodometers, with a net present value of $61 billion. More effective electronic systems are estimated to cost $230 billion through 2050, with a net present value of $166 billion. The cost-effectiveness of a VMT tax has been estimated to be

[7] Two cents per mile would equal about $0.50 for the average round-trip work trip of 25 miles, or about $500 per year per person given the average of about 10,000 VMT per capita. To have a net impact on GHG emissions, of course, the VMT fee would either need to supplement the gas tax or be significantly greater than the gas tax it replaces.

approximately $100 per ton for a fee of $0.03 per mile, including only direct implementation costs (Cambridge Systematics, 2009); for a range of fees from $0.02 to $0.05 per mile this would correspond to a cost-effectiveness in the range of $60 to $150 per tonne (assuming the same implementation costs regardless of fee level). Higher fees should be more cost-effective than lower fees because they will have a greater impact on VMT with little or no additional administrative cost. These cost estimates do not include vehicle operating cost savings to travelers, welfare losses from decreased mobility, or the fees themselves; including vehicle operating costs would yield a net savings of $650 per tonne for a one-cent fee or $840 per tonne for a three-cent fee, according to analysis conducted for the *Moving Cooler* study (Cambridge Systematics, 2009).[8] The fees are considered to be transfers (from individuals to the transportation operator, and which may be returned to individuals through transportation investments or tax rebates), and would not represent a net social cost.

Cobenefits

Reductions in air pollutant emissions and crashes should be roughly proportional to the reduction in VMT as a result of the fee. Consumers will experience some welfare losses as a result of decreased mobility. To the extent that congestion is reduced, however, some peak-period travelers with high values of time (or those riding transit and not paying fees) will benefit.

A VMT fee of 1 cent (averaged across vehicle classes) would generate annual gross revenues ranging from $30 billion currently to between $46 and $57 billion per year in the future, depending on the level of future VMT growth. Even with reduced travel due to higher prices, a 5-cent-per-mile VMT fee would generate over $150 billion per year, growing annually. Some of these costs would be needed to cover administration of the fee; the remainder could be reinvested in infrastructure or returned to taxpayers. The additional revenue generated does not represent a net benefit to society; instead, it is a transfer that offsets the losses to travelers who are paying higher fees.

Feasibility

VMT fees have not yet been implemented in the U.S. A weight distance tax is administered by Oregon for heavy vehicles, and Oregon is also one of the leading States in considering the application of VMT fees to all vehicles. A shift to mileage-based pricing must overcome considerable political and institutional resistance due in particular to concerns over privacy issues, the logistics of implementation, and the appearance of implementing a new tax. Monitoring through mechanical hubodometers requires a relatively frequent (annual or biennial) inspection which is not currently conducted in all

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[8] The *Moving Cooler* study (Cambridge Systematics, 2009) examined the GHG impacts and cost-effectiveness of a wide range of strategies directed at reducing VMT and improving transportation system efficiency. More information on this study, which is referenced for a number of strategies presented in this section, is included in Appendix A.

parts of the country. For a shift to electronic monitoring, some technical issues, as well as the establishment of technologies and procedures to protect the privacy of travelers, still are being resolved. Fees have been proposed both at the State and national level. The Federal government could either directly implement a VMT fee system, or encourage States to do so through transportation funding incentives or other means.

Intercity Tolls

Benefits: **Low**: 1-3 mmt CO_2e in 2030

- Based on fee of 2 to 5 cents per mile applied to rural Interstates

Direct Costs: **High**: \$500 to \$800 per tonne

Net Included Costs: **Net Savings - Moderate**: -\$500 to +\$200 per tonne

Confidence in Estimates: **Medium-High**

- Price elasticities well documented; primary variable is magnitude of fee
- Key uncertainty is potential diversion to non-Interstate routes

Key Cobenefits and Impacts: **Mixed/Negative**

- Mobility decreases for most travelers
- Potential equity concerns, depending upon how revenues are used
- Transportation revenue source provides opportunities for reinvestment

Feasibility: **Low**

- Fees significant enough to measurably affect behavior unlikely to be popular in the current political climate

Key Policy Options:

- Adoption of national tolls on rural Interstate highways

Intercity Tolls

Definition

Intercity tolls could be expanded from the current toll roads present in some States to all or most of the intercity highway system. Tolls could be collected on rural Interstate segments and other limited-access rural highways either using toll barriers and cash payments, through the use of electronic toll collection (where all vehicles would be required to have transponders), or through mixed systems which combine physical toll barriers and electronic toll collections. Most existing toll facilities in the eastern U.S. now have combined systems. As with existing toll facilities, it is anticipated that different tolls would be set for different vehicle classes. Several intercity toll roads (including in New Jersey, Maine, and Oklahoma) have different time-of-day/ day-of-week prices. Rates could be varied for light-duty versus heavy-duty vehicles based on highway cost allocation studies, relative emissions rates, and/or other factors.

Magnitude and Timing of GHG Reductions

Approximately 260 billion VMT occurred on all rural Interstates in 2006, which is 8.6 percent of total VMT. Intercity tolls would have a similar VMT reduction effect as VMT pricing, but only on this much smaller market segment. Using the same response assumptions as described under VMT Fees, a toll of 2 to 5 cents per mile is estimated to reduce rural Interstate VMT by about 1 percent to 2.5 percent. This equates to a reduction of about 2.6 to 6.5 billion VMT, or 1.2 to 3.0 mmt CO_2e in 2030. Higher tolls would have greater impacts on VMT and GHG emissions. The effects of differentiated tolls by vehicle type or other factors were not evaluated.

This estimate, however, does not account for any likely diversion effects which could offset or even increase GHG emissions. For example, the leading firms in the trucking industry maintain sophisticated cost models which they utilize to determine when and when not to use toll roads. Assuming that tolls are applied only to the Interstate highway system, truckers and other travelers could divert to local roads in order to save money, although potentially incurring a longer trip.

Tolls could be collected on Interstate highways within a few years. The primary time requirement would be to establish toll collection infrastructure and systems.

Cost-Effectiveness

Existing State toll road authorities collect about $4.3 billion in tolls per year (FHWA, 2006), and additional tolls are collected for State toll bridges and tunnels and local toll roads, bridges and tunnels. State toll road operations expenses totaled $604 million and administrative and miscellaneous expenses $681 million, according to Highway Statistics. Although operations expenses included snow removal and other costs besides toll collections, the administrative expenses are also partially attributable to collection costs. Thus it is not unreasonable to estimate that existing toll collection costs absorb over 10 percent of toll revenues. The *Moving Cooler* study estimated the cost-effectiveness of intercity tolls to be in the range of $500 to $800 per ton CO_2e considering only direct implementation costs, with the lower estimate reflecting a higher toll rate. Considering vehicle operating cost savings, cost-effectiveness ranges from -$500 to +$200 per tonne.

Cobenefits

Cobenefits would be similar to those realized through a VMT fee, although on a smaller scale, in proportion to the amount of traffic affected. This does not account for any potential diversion effects to nontolled roadways.

Feasibility

New highways are increasingly being constructed as tolled facilities. However, conversion of existing nontolled facilities to tolling has, to date, been rare in the U.S. It is likely that conversion of currently free highways to toll highways would face substantial opposition. Federal policy would also need to be changed, as current Federal legislation allows only limited conversions of existing free Interstates to toll applications, with Federal approval.

Pay-as-You-Drive Insurance

Description

Pay-as-you-drive insurance (PAYD) is the conversion of a significant portion of the essentially fixed cost of insurance to a marginal cost based on mileage. The logic behind PAYD is that crash risk—which represents a significant portion of insurance costs—is directly related to distance driven, and therefore, people who drive less should have lower premiums. Some insurance cost elements, such as theft and other risk of damage when stationary, would still remain fixed. Per-mile charges would still be related to crash risk, meaning that low-risk drivers or those living in low-risk areas would pay less per mile. Mileage could be tracked either through manual reporting of hubodometer readings or through electronic monitoring, as previously discussed for VMT Fees.

Pay-as-You-Drive Insurance

Benefits: **Moderate-High**: 23-75 mmt CO_2e in 2030

Direct Costs: **Low-Moderate**: $30-$90 per tonne

Net Included Costs: **Net Savings**: -$900 per tonne

Confidence in Estimates: **Medium- High**

- Price elasticities well documented
- Primary variable is adoption of PAYD if offered voluntarily

Key Cobenefits and Impacts: **Mixed/Mostly Positive**

- Lower average insurance premiums
- Mixed equity- many lower-income drivers likely to benefit, but some (long-distance drivers) will see negative impact

Feasibility: **Medium-High**

- Some pilot-tests conducted

Key Policy Options:

- Federal legislation requiring States to allow or require PAYD insurance premiums

Pilot studies of PAYD and mileage-based user fees (which have very similar behavioral impacts) have been conducted in Georgia, Minnesota, Oregon, Texas, and Washington State. Progressive Insurance and GMAC Insurance both currently offer PAYD insurance options in selected States. However, pay-as-you-drive would need to be encouraged or mandated in order to achieve broad or universal application.

Magnitude and Timing of GHG Reductions

Anticipated cost-shifting for the measure should result in an average additional marginal cost of 4 to 6 cents per mile, which is roughly equivalent to a $1.00 per gallon increase in the price of fuel. Such an increase could result in light-duty VMT reductions of about 3.8 percent, using the same elasticity assumptions as applied to other pricing measures, and again acknowledging the uncertainty in these assumptions. One recent study estimated that a moderate implementation of PAYD (requiring all States to permit the offering of per-mile insurance rates) could reduce GHG emissions by 23 mmt in 2030, while an aggressive implementation (requiring that all auto insurance policies have at least 75 percent of premiums paid for on a mileage basis) could reduce GHG emissions by 75 mmt (Cambridge Systematics, 2009).

The assumption that simply switching from a fixed to a variable price will have a strong impact on drivers' behavior is uncertain, and is based primarily on responses measured among those who might be more interested in achieving insurance cost savings. A Minnesota study estimated that only 11 percent of households would participate in a voluntary program (Cambridge Systematics, 2006); therefore the overall VMT reductions for a voluntary program would be much less.

PAYD systems can be implemented within a few years, as administrative and mileage tracking systems are established. Once implemented, they can have immediate impacts on VMT and GHG emissions. The effects will increase somewhat over the first few years of implementation, as travelers can make more structural adjustments (such as changing residential or activity locations) in response to price signals.

Cost-Effectiveness

Implementation costs for full nationwide applications of PAYD insurance are estimated to be of the same magnitude as implementation costs for VMT fees, since the same mileage information would need to be collected. Based on the similar VMT fee cost estimates, PAYD would cost $131 billion through 2050 if based on mechanical hubodometers, with a net present value of $61 billion. Over 40 years, this cost is $3.3 billion per year. More effective electronic systems are estimated to cost $230 billion through 2050, with a net present value of $166 billion. Over 40 years, this cost is $5.7 billion per year. These costs could potentially be borne by private insurance companies and/or vehicle owners, and would be offset by reduced aggregate premiums (see "cobenefits").

The cost-effectiveness of PAYD on a nationwide basis, considering only direct implementation costs, has been estimated to range from a high of $90 to a low of $30 per ton GHG reduced, with the lower value corresponding to a more aggressive level of implementation as previously described. Considering vehicle operating cost savings, net cost-effectiveness is in the range of -$900 per tonne, a net savings (Cambridge Systematics, 2009).

Cobenefits

By shifting more of the insurance costs onto high-mileage drivers, PAYD may benefit lower-income drivers (who tend to be lower-mileage drivers). Interestingly, since a minority of high-mileage drivers is responsible for the majority of driving within each risk class, Bordoff and Noel (2008) estimate that auto insurance premiums would *decrease* for two-thirds of households under a PAYD system (while increasing for the remaining one-third). PAYD insurance is also expected to result in a reduction in crashes and related insurance claims that are disproportionate (1.34 times) to the mileage reduction (FHWA, 2009). There is also an equity benefit to having those that drive more and therefore are likelier to have more crashes pay a higher share of insurance costs.

Feasibility

At least two private insurers currently offer PAYD insurance options in selected States. Current insurance regulations in many States, however, preclude private companies from offering mileage-based insurance.[9] The insurance industry has generally opposed PAYD pricing because it requires changes in their practices and may reduce long-term profits by reducing total premiums (VTPI, 2008c). While some States have taken actions to enable PAYD, questions remain about the adoption of necessary enabling legislation across States, as well as penetration rates and timing. Consumer acceptance of much more effective mandatory programs, as opposed to the current voluntary programs, also has not been tested.

Potential government initiatives to support PAYD insurance include:

- Providing a tax credit for each new mileage-based policy that an insurance company writes, at least for the initial stages of the program, to offset the cost of technological devices that would measure and transmit mileage data;

- Requiring States to rewrite regulations to permit or encourage private insurers to offer per-mile insurance rates; and/or

- Requiring States to require that a certain percentage of premiums in each State (for example, 50 or 75 percent) are mileage-based.

[9] Since regulations were always written with yearly premiums in mind, per-mile premiums are sometimes technically illegal even if that was never the intention of the regulators (Bordoff & Noel, 2008).

Congestion Pricing

Description

Congestion pricing is the application of pricing to congested facilities in order to reduce traffic on those facilities to achieve an improved level of service.[10] Congestion pricing will have somewhat lower overall VMT impacts than universal pricing measures such as VMT fees or pay-as-you-drive, because it will be applied only to congested facilities. However, this measure will decrease congestion and thus will improve fuel economy. In the rudimentary form of either simple off-peak discounts or more involved pricing structures, congestion pricing has been implemented on a number of tolled facilities in the U.S., such as the Dulles Greenway in Northern Virginia; New Jersey Turnpike; Midpoint and Cape Coral toll bridges in Lee County, Florida; and State Road 91 from Riverside to Los Angeles. However, it has not been implemented on an areawide basis to-date.

Congestion Pricing

Benefits: **Low-Moderate**: 9-35 mmt CO_2e in 2030

Direct Costs: **High**: $300 to $500 per tonne

Net Included Costs: **Net Savings**: -$500 per tonne

Confidence in Estimates: **Low**

- Benefits will be strongly dependent upon operation of pricing system, geographic scale applied, baseline congestion levels

Key Cobenefits and Impacts: **Mixed**

- Mobility decreases for some travelers, increases for others
- Equity impacts will depend upon how revenues are used
- Transportation revenue source provides opportunities for reinvestment

Feasibility: **Low-Moderate**

- Limited applications (e.g., HOT lanes) proven feasible
- Areawide fees significant enough to measurably affect behavior unlikely to be popular in the current political climate

Key Policy Options:

- Requirements or incentives for States or metropolitan areas to implement congestion pricing systems

While its most immediate application is on roads and bridges that already are tolled, congestion pricing also could be implemented on other limited-access facilities by adding toll collection. To date it has been studied on at least six other major facilities in the U.S. as well as for the Puget Sound region's highway network. The broader-scale application of this strategy beyond existing or proposed toll highway facilities is likely to require the universal deployment of electronic toll collection technologies. This will require coordination by a State or regional transportation agency (e.g., State DOT or MPO). The U.S. DOT is encouraging greater experimentation in this area. In 2007, the Department awarded $853 million in funding to five metro areas for Urban Partnership Agreements to reduce congestion, which include a significant focus on tolling/pricing strategies.

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[10]The term "congestion pricing" in this report is used to mean pricing of specific transportation facilities or of all facilities within a region. "Cordon" or "area" pricing, discussed as a separate strategy, can also be considered a form of congestion pricing, as it applies specifically to a congested area (and potentially only to more congested times of day).

Magnitude and Timing of GHG Reductions

The VMT reduction effects of congestion pricing can be calculated using the same elasticity assumptions as for other pricing measures addressed in this study. Further assuming that a congestion fee is applied to all freeways and arterials operating at level of service E or worse, the proportion of VMT subject to congestion pricing is estimated to be 29 percent in urban areas and 7 percent in rural areas across all functional classes of roads.[11] Applying an average fee of 65 cents per mile, which is the price estimated to be necessary to improve level of service to D on these roads, the result is approximately a 20 percent reduction in peak period traffic levels or an overall VMT reduction of 3.1 percent. Accounting for fuel savings from reduced delay as well, this results in a GHG reduction of 35 mmt CO_2e in 2030. Lesser reductions would be achieved at lower fee levels, or if congestion pricing applications are not universal.

It should be noted that this is a very rough approximation. It does not account for any increases in off-peak travel if people simply shift the time of their trip rather than forgoing it or choosing an alternative mode. Sophisticated regional models are needed to analyze more sensitively the necessary congestion fees and their impacts, which would vary substantially by facility and by time of day.

Regional simulations using travel demand models have been conducted in a few metropolitan areas. A study in the Washington, D.C., region concluded that a comprehensive distance-based toll, with tolls varying by time of day, would result in an average cost of 3.3 cents per mile and an overall VMT reduction of 7.1 percent. Just applying the variable toll to freeways would reduce VMT by 2.1 percent (Harrington, Houde, and Safirova, 2007). Another study for the U.S. Department of Energy used travel demand models in Minneapolis–St. Paul and Seattle, in conjunction with speed-fuel efficiency relationships, to evaluate the combined benefits of travel reductions and operating efficiencies from areawide systems of managed lanes.[12] The results from different scenarios ranged from an 0.1 percent impact on fuel consumption and GHG emissions to 2.5 percent depending upon the scenario. Extrapolating these results to a national level based on projected 2030 congestion levels in different urbanized areas led to an overall estimated reduction in national fuel consumption ranging from 0.5 to 1.1 percent (EEA, 2008), which would correspond to a reduction of 9 to 21 mmt CO_2e in 2030.

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[11] "Level of service" is a measure of roadway performance that ranges from A (best) to F (worst). It is based on traffic volumes for freeways, and on intersection delay for arterial streets. The estimate of future mileage operating at level of service E or worse is based on forecasts of congestion by FHWA under various scenarios (U.S. DOT, 2006).

[12] These systems included high-occupancy/toll (HOT) lanes on freeways, in which drivers of single-occupancy vehicles can use the lane if they pay a fee which depends upon the congestion on the nontolled travel lanes. Depending upon the scenario, either existing/planned high-occupancy vehicle (HOV) lanes were converted to HOT lanes, or a new HOT lane was constructed alongside an existing/planned HOV lane to form two HOT lanes.

A common problem in the literature, as well as in some applications proposed to date, is to assume that congestion pricing could or would be applied only to limited-access facilities. Applying congestion pricing only to limited-access facilities could have the impact of shifting travel to arterials, where fuel efficiency may be lower, and potentially causing travelers to make more circuitous trips. Since properly applied congestion pricing would apply higher prices to arterials (because the impacts of each added vehicle on arterials is worse than on limited-access facilities), comprehensive congestion pricing applications would reduce travel more efficiently than facility-specific applications.

Congestion pricing can be implemented in a relatively short timeframe, perhaps a few years to develop the appropriate infrastructure and administrative structure for a regionwide application. Benefits will occur as soon as implemented.

Cost-Effectiveness

The costs of implementing systemwide congestion pricing are potentially significant, due primarily to the costs of equipping all vehicles with the necessary monitoring equipment. Using the same cost factors as cited in Section 5.2.1, VMT Fees, the cost of applying congestion pricing to all urban areas is estimated to range up to $1.05 trillion through 2050, with a net present value of $445 billion. Because costs are dependent primarily on the population affected (since all vehicles will need to be outfitted with monitoring equipment) but revenues are highly proportional to the levels of congestion and percentage of travel on congested facilities, cost-effectiveness will be higher in more highly congested areas. Congestion pricing revenues have been estimated at $10.3 trillion through 2050 for aggressive nationwide implementation, and thus costs would represent about 10 percent of fees. The cost-effectiveness of congestion pricing applied nationwide has been estimated to be in the range of $300 to $500 per tonne GHG reduced, considering only direct implementation costs. Including vehicle operating costs, a net savings in the range of -$500 per tonne is estimated (Cambridge Systematics, 2009).

With respect to the incidence of costs, public agencies (in particular, the transportation system operators) will experience a net benefit as revenue collection far outweighs administrative costs. Travelers in congested periods will experience additional costs, which may be inequitably distributed as described below. Revenue from congestion pricing could be used in any number of ways, including reinvestment in the highway system or investment in transit and other travel alternatives, or could be returned to consumers through tax rebates.

Cobenefits

Congestion pricing will provide significant cobenefits to many travelers in the form of travel time savings. The Puget Sound congestion pricing study predicted that regionwide value pricing would reduce delay by 55 percent compared to baseline forecast levels (Kitchen, 2008). If dedicated to transportation investments, congestion fees could have additional cobenefits in terms of improved roadway levels of service and/or mobility by alternative modes.

Other travelers will experience disbenefits from congestion pricing. The *Traffic Choices Study* for the Puget Sound Regional Council (Kitchen, 2008) provided estimates of the incidence of pricing's impacts. Pricing will benefit higher-income travelers, who are likely to place a greater monetary value on saving a given amount of time because of their greater ability to pay. It will also benefit those for whom exact arrival time is important (e.g., parents picking up kids at day care), as they will benefit from improved reliability resulting from less congestion. Other travelers, who may be priced off the roads or for whom the time savings do not outweigh the value of the fee paid, will experience welfare losses (as measured by the economic concept of consumer surplus). The losses in consumer surplus of $97.1 billion are the largest impact of congestion pricing, far outweighing the $36.6 billion consumers save in travel times (Table 5.3).

Table 5.3 Benefits and Costs of Network Road Tolling in Puget Sound Region

Benefits	Dollars in Billions	Costs	Dollars in Billions
Time Savings	$36.6	OBU Units	$1.5
Reliability Benefits	$4.5	Enforcement	$0.1
Operating Costs	$2.5	System, Data	$3.8
Consumer Surplus	$-97.1	Other	$0.1
Operator Tolls	$87.0		
Totals	**$33.6**	**Totals**	**$5.5**
Present Value – Benefits Minus Costs	**$28.2**		

Source: Kitchen (2008). Values are net present value in billions of 2008 dollars.

Thus, until the tolls themselves are counted as a benefit, the net impacts are negative. Therefore to achieve net benefits to the traveling public, the tolls must be reinvested or redistributed in a manner which results in net benefits. The study also estimated the impacts by user income group. For user groups, the transit users are the only net beneficiaries before reinvestment of the revenues, due to their time savings not being offset by any cost increases. For those who continue to travel via auto, or for those tolled off, total impacts are negative unless the revenues are reinvested in a manner which generates more offsetting benefits.

Congestion pricing should also have environmental benefits. The increased cost of travel will result in some reduction in VMT, thereby reducing fuel consumption and air pollutant emissions; fuel use and emissions should be further reduced due to improved operating conditions (higher speeds and smoother traffic flow). While comprehensive estimates of air quality benefits have not been developed, one study that examined a comprehensive time-of-day toll in the Washington, D.C., region estimated that pollutant emissions would be reduced by 5 to 8 percent regionwide depending upon the pollutant (Harrington, Houde, and Safirova, 2007).

Feasibility

From a technical standpoint, congestion pricing is relatively easy to implement on facilities that already are tolled. However, there is likely to be general public opposition to paying for something that was previously free, as well as opposition specifically regarding equity concerns. Implementing pricing on currently nontolled facilities will face numerous additional hurdles, including the need for broader-scale deployment of toll collection technology; privacy concerns related to data collection and monitoring; and reluctance to cede control of transportation infrastructure to private entities (for privately operated facilities) or the need to involve existing operators of private toll facilities. If congestion pricing is implemented only on a limited basis (e.g., only freeways), diversion of traffic to other nontolled facilities is likely to be a significant concern because of the impacts on neighborhood and local traffic.

Cordon/Area Pricing

Description

Cordon or area pricing would apply a fee for vehicles to enter or drive within a selected area, such as a central business district (CBD).[13] The funds could be used for mobility improvements or for other purposes. Cordon or area pricing have been implemented in a few European and Asian cities including London, Stockholm, and Singapore. While no U.S. cities have implemented cordon or area pricing, cordon pricing has been considered in New York City (Manhattan) and San Francisco.

Thus far, implementations of cordon and area pricing abroad have reinvested funds into transit—thereby achieving additional mode shifts and VMT reductions beyond what would be

Cordon/Area Pricing

Benefits: **Low**: 2-3 mmt CO_2e in 2030

Direct Costs: **High**: \$500-\$700 per tonne

Net Included Costs: **Net Savings**: -\$600 per tonne

Confidence in Estimates: **Low**

- Benefits will be strongly dependent upon operation of pricing system, geographic scale applied, baseline congestion levels

Key Cobenefits and Impacts: **Mixed**

- Mobility decreases for some travelers, increases for others
- Equity impacts will depend upon how revenues are used
- Transportation revenue source provides opportunities for reinvestment

Feasibility: **Low-Moderate**

- A few international examples
- Unlikely to be accepted in most U.S. cities

Key Policy Options:

- Requirements or incentives for major cities to implement cordon/area pricing systems

[13] "Cordon pricing" would involve charging a fee to vehicles entering an area, while "area pricing" would involve charging a fee to any vehicle operating within the area, whether or not it crosses the boundary of the area.

achieved through the pricing alone (although there will be some offsetting increases in GHG emissions from the additional transit service). The reduced congestion as a result of cordon pricing should also improve fuel economy, achieving further greenhouse gas reductions. On the other hand, it may result in more traffic and congestion outside of the congestion pricing zone, leading to GHG increases in these areas.

Magnitude and Timing of GHG Reductions

Cordon or area pricing has been found to result in a significant reduction in VMT and congestion in the few central city areas to which it has been applied. In London, 21 percent less traffic entered the central zone in 2006 than in 2002 before the application of cordon pricing. This resulted in an estimated reduction in CO_2 emissions of 16 percent in the pricing zone, of which about half was due to changes in traffic volume and half due to changes in speeds (Transport for London, 2007). Stockholm's pricing scheme was estimated to reduce CO_2 emissions by 10 to 14 percent in the inner city, or 2 to 3 percent on a countywide basis (KT Analytics 2008). A modeling study estimated that an $8 fee applied to all traffic entering the Manhattan central business district could reduce traffic in this area by 7 percent (NYCEDC and NYCDOT, 2007).

Cordon/area pricing has limited overall effectiveness, however, because it only applies to a small amount of total travel. The application of cordon pricing to all CBDs nationwide is estimated to affect only 3 percent of urban VMT,[14] reducing GHG emissions by 1.6 to 3.2 mmt CO_2e in 2030 (Cambridge Systematics, 2009). This estimate considers only VMT reduction effects and not the GHG benefits of congestion reduction.

Furthermore, cordon/area pricing could have the negative impact of shifting travel to routes which bypass the selected cordons, thus increasing some trip lengths and travel times and reducing any GHG benefits from reduced travel into the CBD. In the long term, applying pricing only to CBDs could also impact development patterns. A recent study of the Washington, D.C. metropolitan area used an integrated transportation and land use model to evaluate the effects of both downtown and beltway cordon pricing, including land use as well as travel changes. The study found an overall regional VMT reduction in the range of 0.8 to 1.3 percent (Safirova, Houde, and Harrington, 2007). GHG reductions (which were not analyzed) are likely to be greater because of the benefits of reduced congestion.

Cordon/area pricing can be implemented in the short term (less than five years), with immediate impacts. Tolls may need to be continually adjusted after the project is implemented, in order to keep congestion to economically efficient levels.

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[14] The three percent estimate is based on an estimate of urban VMT in the greater London region affected by London's cordon pricing system (Transport for London, 2007).

Cost-Effectiveness

Because cordon or area pricing will affect only one tenth as much urban VMT as congestion pricing (3 percent versus up to 29 percent), but many vehicles will still need to be outfitted with collection technology, cost-effectiveness will be lower than for system-wide congestion pricing. Cordon pricing systems implemented in London and Stockholm required an initial investment of $400 to $500 million, or about $35 to $50 million per square mile covered. Annual operations and maintenance expenses of the London system are about $170 million or roughly 40 percent of annual revenues. For the New York City congestion pricing proposal, the "Mayor's Plan" was projected to incur $224 million in capital costs and $229 million in annual operating costs, representing about 35 percent of gross operating revenues. Other plans were proposed with lower ratios of costs to revenues (Cambridge Systematics, 2008).

The cost-effectiveness of cordon pricing if implemented on a nationwide basis (all metropolitan CBDs and major employment and retail centers) is estimated to be in the range of $500 to $700 per tonne GHG reduced, including direct implementation costs only. Considering vehicle operating costs, a net savings on the order of -$600 per tonne is estimated. (Cambridge Systematics, 2009).

Cobenefits

Cordon/area pricing has strong but very localized cobenefits in terms of improved levels of service and improved conditions of transportation facilities and vehicles. The transportation cobenefits are greater if revenues are dedicated to transportation investments such as transit service, to improve mobility options for those who are priced off the roadway. Cordon/area pricing has the potential to provide a net benefit to the traveling public and to the regional economy, by reducing the costs to businesses and individuals associated with congestion. An evaluation of London's congestion pricing scheme found that with the £5 charge the scheme generated £90 million in net welfare benefits for a year's operation (Transport for London, 2007). However, the level of benefit that is achieved will depend upon the amount of congestion in the city, as well as whether the tolls are optimized to achieve an economically efficient level of congestion. One evaluation of Stockholm's congestion pricing system concluded that the net social benefits were negative (Prud'homme and Kopp, 2006) because of lower congestion levels than London and non-optimized tolls, although another came to the opposite conclusion that Stockholm's system produced significant positive benefits (Eliasson, 2007). Potential savings to businesses from reduced congestion are offset to some amount by the fees assessed on service vehicles and goods-moving trucks serving businesses within the cordon.

Like other pricing measures, cordon/area pricing will have mixed equity impacts. Some travelers will be better off because travel time benefits outweigh the additional costs of travel, or because alternative modes have been improved. Others will be worse off, if the travel benefits do not outweigh the additional costs of travel. Unlike congestion pricing, cordon pricing is likely to be applied primarily to an area with high-quality transit service, and is therefore likely to have fewer negative equity impacts. The perception that cordon pricing is "unfair" to low-income drivers has not been a major concern in Singapore, London, and Stockholm after implementation; in fact, in both London and Stockholm it has been argued that the equity impacts have been positive due to the significant improvements in public transportation (K.T. Analytics, 2008).

Cordon/area pricing should also result in improved air quality as a result of reduced VMT and congestion, as well as reduced crashes due to lower exposure rates. Evaluation of the London system found reductions in NO_x emissions of 8 percent and PM_{10} emissions of 6 percent in 2003 within the charging zone, as a result of changes in traffic volumes and speeds after pricing was implemented in 2002. However, there was a slight increase in PM_{10} emissions on the inner ring road just outside the zone, as a result of increased traffic volumes (Transport for London, 2007). Stockholm's system was estimated to reduce NO_x emissions by 7 percent and particulate emissions by 9 percent in the inner city (K.T. Analytics, 2008).

Feasibility

In the U.S., cordon pricing came close to being implemented in New York City, but ran into political barriers. In general, it will most likely be opposed by businesses in the cordoned area, who fear that customer traffic will decline or employees' commutes may be negatively impacted; as well as by commuters or other visitors to the cordoned area from other locations. However, opposition to schemes implemented in London and Stockholm has waned as clear benefits have been achieved in terms of reduced traffic congestion, and transportation alternatives have improved. A five-year evaluation of the London pricing scheme found that retail sales in central London have continued to experience strong growth, and other sectors have shown no evidence of reduced economic performance compared to comparison areas (Transport for London, 2007). A 2006 referendum in Stockholm found majority support for the trial pricing scheme among City of Stockholm residents (52 percent in favor versus 46 percent opposed); the scheme was then made permanent despite opposition from some of the surrounding municipalities (K.T. Analytics, 2008).

■ 5.3 Transit, Nonmotorized, and Intermodal Travel

Improvements to transit and nonmotorized modes, including urban transit, intercity bus and rail, nonmotorized infrastructure, and intermodal facilities and information, can increase the energy efficiency of travel per person-mile traveled. Urban transit improvements may include investing in new fixed-guideway transit, expanding coverage of bus systems, increasing the frequency and/or time coverage of service on existing routes, or making other improvements to the quality of service. Intercity bus and rail improvements may take the form of expanded or enhanced service on existing bus or rail routes, new intercity bus or rail routes, and high-speed rail. Nonmotorized improvements may take the form of capital investments in nonmotorized infrastructure (e.g., bicycle facilities, sidewalks), or supporting activities such as pedestrian-friendly design standards, bicycle parking at destinations, or education programs. Use of nonhighway modes can also be increased by making highway modes less attractive, e.g., through pricing, or less direct routing compared with transit or nonmotorized routes.

A related strategy not discussed in more detail in this section is passenger intermodal system efficiencies. Improvements to intermodal facilities and information help minimize travelers' time, costs, and inconvenience and make it easier to for people to utilize the most efficient mode for each segment of a trip. By enabling passengers to switch easily between modes, each mode can do what it does best: private vehicles for point to point flexible routing, bus and rail for longer-haul service in high-density travel corridors, foot or bicycle for short access trips, etc. Examples of specific intermodal improvements might include: intermodal transportation centers that provide a central exchange point for different modes; integrated fare payment systems; multimodal traveler information systems (also discussed in Section 6.0); "first and last mile" programs that focus on ways to get people from their origin or destination to line-haul transit stations (e.g., bikes on transit, station cars, local flex-route transit); and programs that support alternative mode by providing backup travel options when necessary, such as guaranteed ride home programs or occasional-use parking passes for employees receiving transit benefits (also discussed in Section 5.5, Worksite Trip Reduction). There is little information available on the GHG benefits of these strategies. Nevertheless, they play an important complement to the strategies discussed elsewhere in this section and report, especially transit improvements and worksite trip reduction.

Transit Expansion, Promotion, Service Improvements

Description

In 2007, Americans took nearly 10 billion trips using public transportation, or approximately 33 million trips each weekday (FTA, 2008). Since 1998, public transportation ridership in the U.S. grew by 21 percent, faster than highway travel at 15.3 percent (according to FHWA's *Highway Statistics* series) or the U.S. population at 11.5 percent (U.S. Census). Without transit service, many cities and regions would suffer from even more severe traffic congestion and degraded air quality.

Transit Expansion, Promotion, Service Improvements

Benefits: **Moderate**: 6-18 mmt CO_2e in 2030

- Assumes broad expansion of transit service at current or greater productivity levels (average ridership)
- Growing over time: 9-32 mmt in 2050

Direct Costs: **High**: $1,200 to $3,000 per tonne

Net Included Costs: **Net Savings to High**: -$900 to +$1,000 per tonne

Confidence in Estimates: **Moderate**

- Impacts may vary greatly depending upon nature and context of transit improvements – high productivity needed to realize benefits

Key Cobenefits and Impacts: **Positive**

- Mobility benefits for travelers, especially low-income

Feasibility: **High**

- Primary barrier is funding

Key Policy Options:

- Targeted funding

According to data from the 2007 National Transit Database (FTA, 2008), public transportation services are available in 456 urbanized areas. In every State, some level of public transportation is available to support rural residents, elderly individuals, and/or physically challenged individuals. While these services are critical mobility providers for these populations, the primary role of transit in reducing GHG emissions is tied to influencing behavior of choice riders.

In 2007, the sum of Federal, State, local and other funds for capital and annual operating expenses for transit totaled $47.3 billion. Unlike highways where the bulk of funding comes from Federal and State sources, most transit funding is local. Federal transit funding accounted for 17 percent of the total transit funding in 2007, State sources 20 percent, and local funds including funds from dedicated taxes 36 percent. Other funds, which include fare revenues, subsidy from other sectors of operations, and revenues accrued due to purchased transportation, represent 27 percent of the total (Commission 2007a).

The use of transit could be expanded through the following means:

- Construction of new fixed-guideway transit, including rail transit and busways;
- Expansion of transit service to new areas (i.e., new bus routes); and
- Improvements in service frequencies, reliability, and attractiveness on existing transit routes, as well as expanded marketing and promotion of transit services, including customization to specific market segments.

Some of these strategies involve adding additional transit services. Others (such as service customization and improved schedule reliability) represent enhancements to existing services that may be able to attract more riders without increasing fuel consumed. Some strategies may even reduce fuel consumption and GHG emissions from transit—such as signal preemption, queue-jumper lanes, or other roadway operational improvements to reduce run times; or limited-stop services. However, to attract and maintain systemwide ridership, improvements may also be needed that nominally increasing GHG per passenger-mile on some segments, such as reducing passenger densities on the most crowded services in order to maintain operational performance and customer satisfaction; and maintaining minimum service levels even during low-utilization periods.

The effectiveness of transit as a GHG reduction strategy may be increased by planning transit services in coordination with supportive land use patterns. Dense, mixed-use, and pedestrian-friendly development supports transit ridership by allowing more travelers directly and conveniently access transit, and by reducing the relative attractiveness of automobile versus transit travel. The greatest benefits will be realized through transit-supportive land use patterns at both the origin and destination end of the trip.

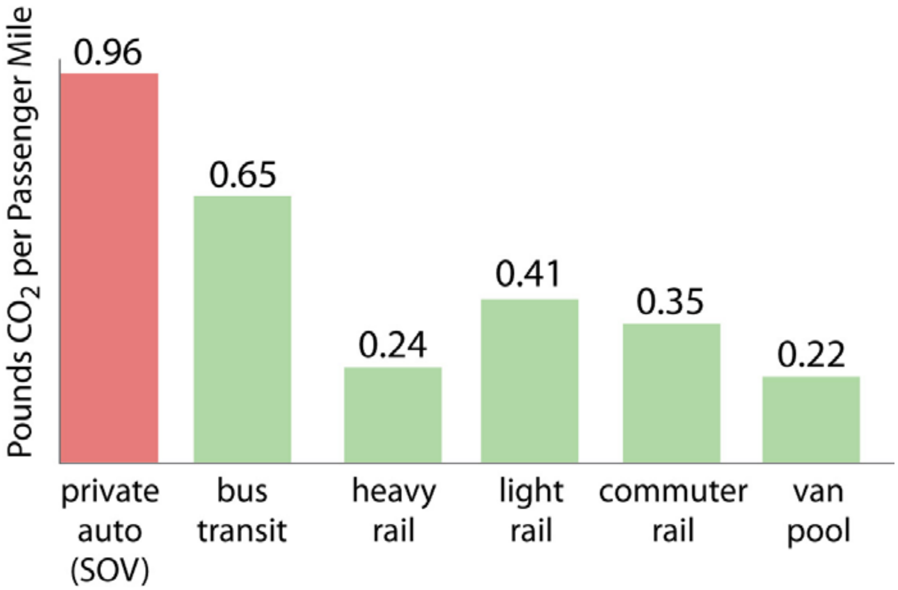
Magnitude and Timing of Greenhouse Gas Reductions

Urbanized area transit systems have the potential to reduce fuel consumption and greenhouse gas emissions related to surface transportation. The reductions occur through both direct emission benefits per passenger-mile of transit versus automobiles, and the additional indirect effect on emissions that transit provides through its impact on land use patterns.

Emission reductions are a result of the lower than average emissions per passenger-mile for transit versus private vehicles. In 2006, based on fuel consumption data from the National Transit Database, the average greenhouse gas emissions rate for urbanized area transit systems (excluding demand response services) is 0.48 pounds CO_2e per passenger-mile.[15] With an average on-road fuel economy of 20.3 mpg, a single-occupant vehicle releases 0.96 pounds CO_2e per passenger-mile; at the average occupancy for all trips of 1.63 passengers per vehicle (based on the 2001 NHTS), personal vehicle travel releases 0.62 pounds CO_2e per passenger-mile. Transit emissions vary by mode, however, with rail emissions lower than bus emissions on the average. As shown in Figure 5.1, FTA calculates that bus transit averaged 0.65 pounds CO_2e per passenger-mile, compared to 0.41 for light rail, 0.35 for commuter rail, and 0.24 for heavy rail, calculated at average occupancy levels across all systems in the United States (FTA, 2009). These figures reflect differences in loading for different systems as well as inherent differences in vehicle efficiency and emissions characteristics for electric versus diesel vehicles.

[15] Based on emission factors of 10.15 kilograms CO_2 per gallon for diesel fuel and 1.185 pounds CO_2 per kilowatt-hour for electricity (EPA 2006).

Figure 5.1 Average CO2 Emission Rates by Mode



Source: FTA (2009).

The data on average GHG emissions by mode were used in the *Moving Cooler* study to estimate the GHG reductions that are achieved through the transit services in place today. Based on data from the National Transit Database, total GHG emissions from public transit vehicle operations in 2007 are estimated to be 11.8 mmt CO_2e. It is further estimated that urbanized transit systems in 2007 removed 32.0 billion VMT from the nation's roadways, representing 1.6 percent of urban area VMT. The net effect is a reduction of 14 million metric tons of GHG emissions.[16]

Transit also has been credited with achieving indirect effects on emissions as a result of its ability to facilitate denser, more mixed land use patterns. Such patterns result in fewer and shorter auto trips compared to development patterns without transit and thus reduced emissions. A recent study for the American Public Transportation Association (APTA) estimated the average reduction of VMT per household by level of transit availability, based on household trip data from the 2001 NHTS. This reduction was estimated to be 2.2 VMT per household per day with access to transit (Bailey et al, 2008). The combined GHG reduction of direct and indirect effects, accounting for emissions from public transit, in 2007 results in a total emissions reduction of 39 mmt CO_2e.

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[16]This figure represents the effect of the substitution of public transit passenger miles with private automobile travel. The calculation assumes the following, based on data from the 2001 NHTS: 1) An average auto occupancy of diverted trips of 1.43, which is lower than the 1.63 average for all trips. The 1.43 value assumes that 60 percent of transit trips are home based work with an average occupancy of 1.14 and the remaining nonwork trips have an average occupancy of 1.84. 2) The current auto based person miles of travel share for all trip types is 88.2 percent—i.e., 88.2 percent of transit passenger miles are saved VMT.

A different study for the U.S. Public Interest Research Group (USPIRG) concluded that transit reduced GHG emissions by nearly 26 mmt CO_2e in 2006. This study used slightly different assumptions than the APTA study, including accounting for lower fuel economy of automobile trips removed during congested periods, and additional fuel savings from reduced highway congestion. The study also accounted for "leveraged" benefits from more compact land use patterns (Baxandall, Dutzkik, and Hoen, 2008).

For any data using national average GHG emissions by mode or total GHG reductions, the caveat must be included that the results are heavily influenced by the most heavily used and productive services in a few major cities, such as Boston, Chicago, New York, Philadelphia, San Francisco, and Washington, D.C. For example, the USPIRG study found that nearly half of the GHG reductions from transit—11.8 mmt CO_2e—were from New York State alone, with another 10.4 mmt from six other States; and that 26 States saw reductions of less than 0.01 tonnes or even slight increases in GHG from their transit services. It is not clear whether future transit expansion will result in the same level of GHG reduction productivity.

The net GHG effect of future improvements to transit will depend on factors including the amount of new ridership attracted from automobiles, number of passengers per transit vehicle, relative efficiency of transit vehicles and automobiles, and carbon content of fuels. Transit ridership growth will also depend on a variety of factors that are difficult to predict, such as fuel prices, economic growth, socioeconomic and demographic trends, and land use patterns. One recent study developed three possible scenarios for future ridership growth: a continued 2.4 percent increase; a 3.52 percent increase, which represents a doubling of transit ridership in 20 years, and would require aggressive strategies to grow ridership; and a target growth rate of 4.63 percent (TCRP, 2008).[17]

Based on these three scenarios, the *Moving Cooler* study estimated future GHG reductions from additional transit investment. The study assumed that load factors would increase from 10.5 passengers per bus in 2006 to 12 passengers per bus in 2030. Savings were estimated separately for three different strategies: reduced fares; improvements to headways and level of service; and expanded fixed-guideway services.[18] The study also

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[17]The target growth rate assumes a variety of potential factors that could cause public transportation ridership to grow more rapidly, including higher energy prices, implementation of policies to promote development around public transportation services, increased concern for the impacts of climate change, and stronger emphasis on the relationships between land use and transportation.

[18]Fare reductions range from 25 to 50 percent. For LOS improvements, signal prioritization, limited-stop service, and other enhancements are implemented to improve travel speeds by 10 to 30 percent. Increased service levels and fixed guideway expansion occur at a rate of 2.4 to 4.67 percent annually, consistent with ridership forecast scenarios; investments are assumed to be targeted in areas with at least 4,000 persons per square mile or that otherwise facilitate high passenger loads per vehicle revenue-mile.

accounted for increasing efficiency of both automobiles and transit vehicles.[19] Table 5.4 shows the range of GHG reductions in 2030 and 2050 estimated for each strategy, with the range reflecting the least and most aggressive levels of implementation (Cambridge Systematics, 2009).

Table 5.4 Greenhouse Gas Benefits of Transit Service Improvements
Annual mmt CO_2e Reduced

Year	Fare Reductions	Improved Headways and LOS	Fixed Guideway Expansion	Combined Measures
2030	0.5-1.9	1.0-2.1	3.7-14.1	5.7-18.1
2050	0.5-1.8	2.0-3.7	6.5-26.1	9.0-31.6

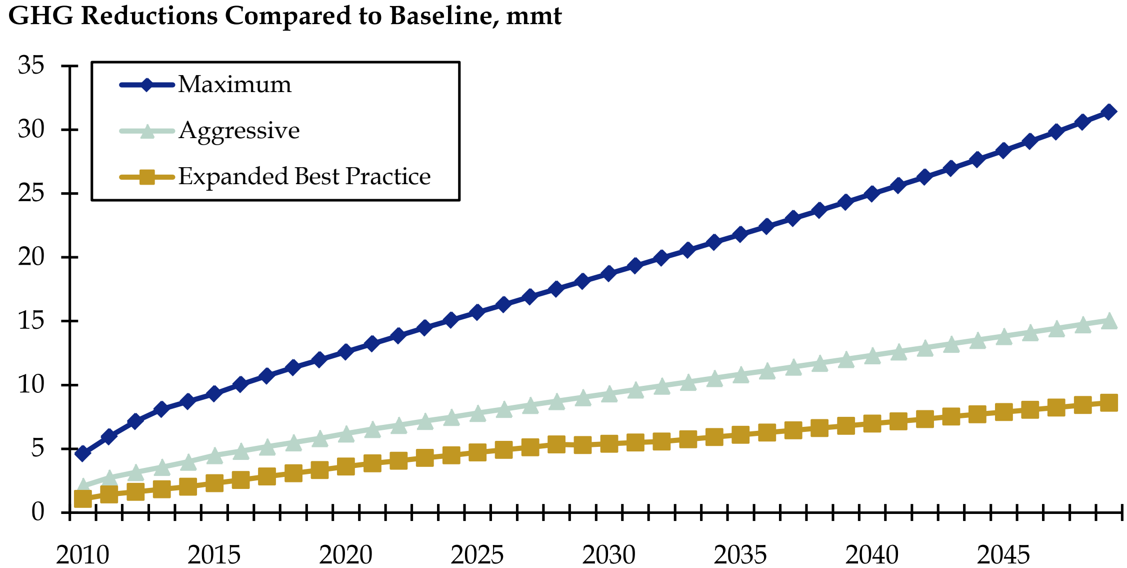
Source: Cambridge Systematics, 2009.

The annual savings in 2030 are estimated at 6 to 18 mmt CO_2e, respectively, for the three ridership growth scenarios described above. By 2050, benefits grow to 9 to 32 mmt CO_2e annually. Figure 5.2 illustrates the growth in benefits over time, reflecting the continued expansion of transit services.[20]

[19]For buses, GHG emission factors are assumed to decline from 0.71 pounds GHG per passenger mile in 2006 to 0.35 pounds GHG per passenger mile in 2050, assuming the increased penetration of hybrid-electric, alternative fuels, and other advanced technologies. Commuter rail factors are assumed to decline from 0.36 to 0.19 pounds per passenger mile. For electric rail vehicles, CO_2 emissions of per kilowatt-hour are estimated using EPA's eGrid database of 1.185 pounds CO_2/kwh in 2006, decreasing at 2.5 percent per year after 2015, which is based on an extrapolation of the rate of GHG reduction between 2010 and 2018 from targets set through the Regional Greenhouse Gas Initiative (RGGI) in 10 Northeast and Mid-Atlantic States. The net effect is that heavy rail emissions decline from 0.28 pounds per passenger-mile in 2006 to 0.10 in 2050, and light rail from 0.40 in 2006 to 0.18 in 2050. (These factors also reflect modest increases in load factors.) Automobile fuel efficiency is projected to improve at somewhat faster rates than in the AEO Reference forecast—1.91 versus 1.61 percent annually.

[20]The *Moving Cooler* results for transit strategies as well as for a number of other travel activity strategies (including land use, non-motorized travel, and employer trip reduction) consider induced demand effects, i.e., an offsetting increase in vehicle-travel as vehicles are removed from the roads and congestion is reduced. This effect reduces the estimated benefits of these strategies by about 14 percent, as discussed in Appendix A.

Figure 5.2 Annual GHG Emissions Reduction of Transit Expansion



Source: Data from Cambridge Systematics, 2009.

Cost-Effectiveness

Expansion of transit infrastructure and service will require significant additional investment. In a 2008 report to Congress, the National Surface Transportation Policy and Revenue Study Commission estimated baseline transit investment needs based on the "Improve Conditions and Performance" scenario (Commission, 2008). The analysis estimated total transit baseline needs to be $1.1 trillion through 2020, $2.4 trillion through 2035, and $4.4 trillion through 2055, based on an annual transit travel growth rate of 1.57 percent. The average annual investment required through 2055 is $89.8 billion, 90 percent more than total funding from all sources in 2006. While some transit expansion initiatives have been funded through local sources, in most areas, significant expansion beyond current levels could require significant additional Federal investment—whether for capital or operating expenses. The amount of additional local revenues leveraged by this additional Federal investment will depend upon Federal match requirements, as well as the ability of local sources to support the match requirements.

The AASHTO Bottom Line report (AASHTO, 2009) includes annual capital cost estimates to accommodate new riders for each ridership scenario across four investment strategies (Table 5.5). The investment strategy for maintaining physical conditions and improving system performance assumes that the public transportation fleet and other assets will continue to be replaced following current replacement cycles, and that additional improvements are made to reduce passenger densities on the most crowded systems and to improve overall speed of service.

Table 5.5 Average Annual Capital Requirement, 2006-2026
Billions of Dollars

	Maintain Physical Conditions, Improve Service Performance			
	Replacement/ Rehabilitation of Existing Assets	Total Including Expansion and Modernization of Assets to Accommodate Annual Ridership Growth at:		
Needs Component		**2.4%**	**3.5%**	**4.6%**
Urbanized Area Total	$13.9	$40.8	$53.9	$69.9
Rural/Small Urban	$0.8	$1.5	$1.5	$1.5
Total Needs	**$14.7**	**$42.4**	**$55.4**	**$71.4**

Source: AASHTO, 2009.

The *Moving Cooler* study used these estimates of capital investment needs, in conjunction with estimates of future annual operating costs, to estimate total cost-effectiveness in terms of GHG reduced for transit system expansion.[21] Considering direct implementation (capital and operating) costs only, cost-effectiveness to meet the three ridership growth rates is estimated to be about $1,800 to $2,000 per tonne for urban transit expansion and $1,200 to $3,000 per tonne for level of service increases. Including vehicle operating cost savings to private vehicle owners as a result of a reduction in VMT, cost-effectiveness ranges from $800 to $1,000 per tonne for system expansion and -$260 to +$130 per tonne for service improvements. Direct cost-effectiveness is not estimated for transit fare reductions, as the change in fare is simply a revenue transfer from the public sector to the transit rider; vehicle operating cost savings would provide a net savings of about -$900 per tonne (Cambridge Systematics, 2009).

Cobenefits

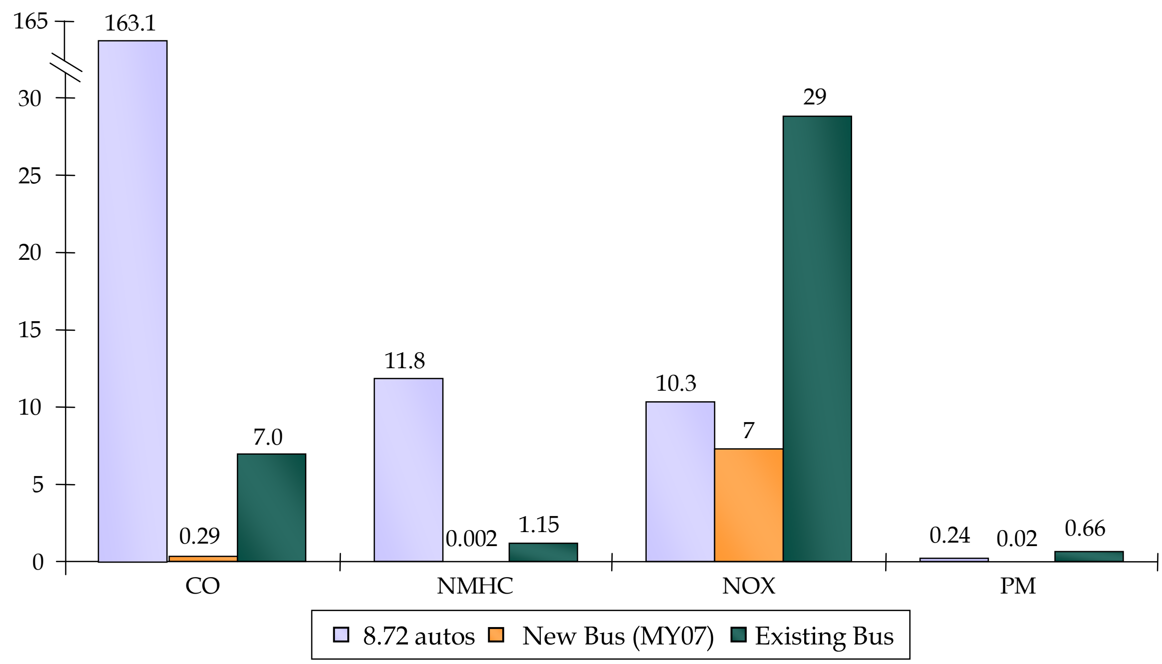
A significant co-benefit associated with transit is its ability to reduce the relative degree that those who choose not to drive, or who do not own vehicles, are disadvantaged compared with drivers (VTPI, 2008d). Transit increases accessibility to economic and social opportunities, and helps achieve equity objectives, such as helping physically and economically disadvantaged people access public services, education, and employment.

Transit will result in reductions of some criteria pollutant emissions, but may cause increases in others. The relative emissions impacts will depend upon the vehicle type (small bus, 40-foot bus, light rail, locomotive, etc.); fuel source (diesel, natural gas, electric); electricity generation source (for electric rail or trolley bus systems); vehicle emissions control technology; and operating characteristics of the vehicle (e.g., average speed, time

[21] Excluding paratransit services, the estimate for operating costs per unlinked transit trip in 2007 is $2.61 (FTA, 2008). The cost per unlinked trip is assumed to increase with inflation through 2050.

spent idling). Transit vehicles—especially diesel buses without advanced emission controls—may actually increase emissions of some air pollutants, such as NO_x and PM, compared to the offset vehicle traffic. Figure 5.3 shows emissions of various criteria pollutants for diesel buses with average passenger loads, including both an average bus (as of 2006) and a new (model year 2007) diesel bus, compared with the equivalent emissions from 8.72 displaced passenger cars. While an average bus will increase NO_x and PM emissions compared to an average passenger car, a new bus meeting EPA regulations for model years 2007-2009 will result in decreases of all pollutants.[22] This relationship may continue to change over time as both bus and automobile emissions standards and technology progress.

Figure 5.3 Comparison of Emissions (g/mi) from Buses versus Automobiles Displaced



Source: Ayres (2007).

Note: The "new bus" is a new 40-foot transit bus running on ultra-low-sulfur diesel that meets 2007-2009 EPA emissions standards. The "existing bus" is an average diesel bus in service as of 2006. "8.72 autos" is the average number of automobiles displaced by a bus, considering an average of 9.97 passengers per bus and 1.14 occupants per automobile. Average automobile emission rates are based on 2002 EPA emission inventory and FHWA highway statistics data.

Another co-benefit is the impact of fixed guideway transit infrastructure on future land development, particularly transit-oriented development. The synergy between transit and

[22] The automobile emission factors are based on 2002 data and would be lower if evaluated using more current data. The conclusion that CO, NMHC, and PM would be decreased with a new bus would still hold, given the very large difference in emissions, although NO_x levels would probably be comparable.

dense, mixed, transit accessible land uses result in a potential for significantly higher VMT reductions as well as reduced infrastructure expansion costs (water/sewer/new roads) and avoiding further greenfield development.

Feasibility

As of November 2008, Americans had cut their driving by more than 112 billion miles over the past 13 months, a likely result of the combination of a slowing economy and high fuel prices. Over the same period (comparing January through June 2008 with the same period in 2007), public transportation ridership rose by 3.75 percent (NTD Monthly Database, 2008). This short-term gain reflects an increased demand for public transportation services, largely as a result of economic factors including higher fuel prices and a weak economy. The longer-term growth in ridership over the past decade may also reflect the influence of other factors, including system expansion (particularly new rail investments in some cities) and increasing highway congestion.

Funding is a major barrier, but not the only barrier, to transit expansion. Implementing the scenarios discussed above would require a more than doubling of annual funding for capital investment and annual operations and maintenance for transit. These funds could potentially be raised through a variety of methods including increased transit fares, new local and State taxes, or additional Federal funding from gas taxes, VMT fees, carbon fees, or other sources.

Another significant barrier is the existing low-density nature of most U.S. urban areas. The auto-oriented residential and commercial development patterns prevalent in second half of the 20th century are generally unsupportive of transit services. Regions with minimal congestion challenges and low-cost parking also present challenges to achieving GHG reductions through transit services, since transit is simply not competitive with the automobile (as measured in travel time or cost) for most trips. This is reflected in the estimates of existing GHG benefits of transit, which, as discussed previously, are dominated by a few States with high-density, transit-oriented metropolitan areas.

Transit expansion – particularly via major capital investment projects such as new rail or busways—also may face political, environmental, or community hurdles. Project community and environmental impacts must be considered and addressed in the project planning and development process.

Intercity Bus and Rail

Description

Intercity bus and rail passenger services, including Amtrak and a variety of private bus operators, provide an alternative to travel between cities by automobile or air. Intercity corridor service can be defined as frequent service operated between major city pairs up to 500 miles apart, serving both business and leisure travel markets. (Intercity corridor service can be contrasted with "long-distance" service in corridors of over 500 miles, which is generally not time-competitive with flying and therefore serves primarily leisure and personal travel markets rather than business travel.) If efficiently connected to local transit systems at the trip origin and destination, intercity service can completely replace the need for an automobile trip. Intercity bus and rail services are most effective in high-density travel corridors. To date, in the U.S., they have been most successful in the Northeast Corridor between Washington, D.C., Philadelphia, New York, and Boston.

Intercity Bus and Rail

Benefits: **Low**: 1-6 mmt CO_2e in 2030

- Lower estimate is for intercity rail improvements only; higher includes HSR and intercity bus expansion

Direct Costs: **High**: $400 to $1,400 per tonne

Net Included Costs: **Net Savings to High**: -$600 to $1,000 per tonne

Confidence in Estimates: **Moderate-High**

- Achieving benefits depends upon services with high ridership productivity

Key Cobenefits and Impacts: **Positive**

- Mobility benefits for travelers, especially low-income
- May be environmental/community impacts associated with HSR construction

Feasibility: **High**

- Primary barrier is funding

Key Policy Options:

- Targeted funding

Amtrak (the National Railroad Passenger Corporation) is a government-owned corporation, established by the Federal government in 1971, that operates a national rail network of corridor and long-distance trains. Amtrak currently serves 504 stations in 46 States on more than 21,000 route miles. Amtrak's ridership and revenue has grown nearly 20 percent over the last five years, with Federal Fiscal Year (FFY) 2007 totals of 25.8 million riders and $1.52 billion in revenue (Commission, 2007). Among the factors contributing to growth are corridor service reliability and speed improvements, increased State support for enhanced and improved passenger rail corridor service, lack of capacity for parallel highway improvements, highway and aviation congestion, and higher fuel costs.

Amtrak relies on an annual Federal appropriation, which in FY 2007 totaled $1.294 billion. Fourteen States also provide financial support for intercity rail operations. State-supported services account for 35 percent of Amtrak's daily ridership and about half of all passenger trains in the system.

Restructuring of intercity bus services in the 1980s and 90s and reorganization of Greyhound in 2004 resulted in a shift of intercity bus services away from serving rural communities to services that primarily link major cities. Nationwide, intercity bus ridership peaked at about 130 million passengers in 1970 and is currently about 40 million annual passengers. Recent increases in scheduled intercity bus service, resulting from market demands due to higher fuel prices, led to a 9.8 percent growth in departures in 2008 (DePaul University, 2008). This marks two consecutive years of robust growth after more than four decades of persistent decline.

Intercity bus and rail passenger services could be expanded by:

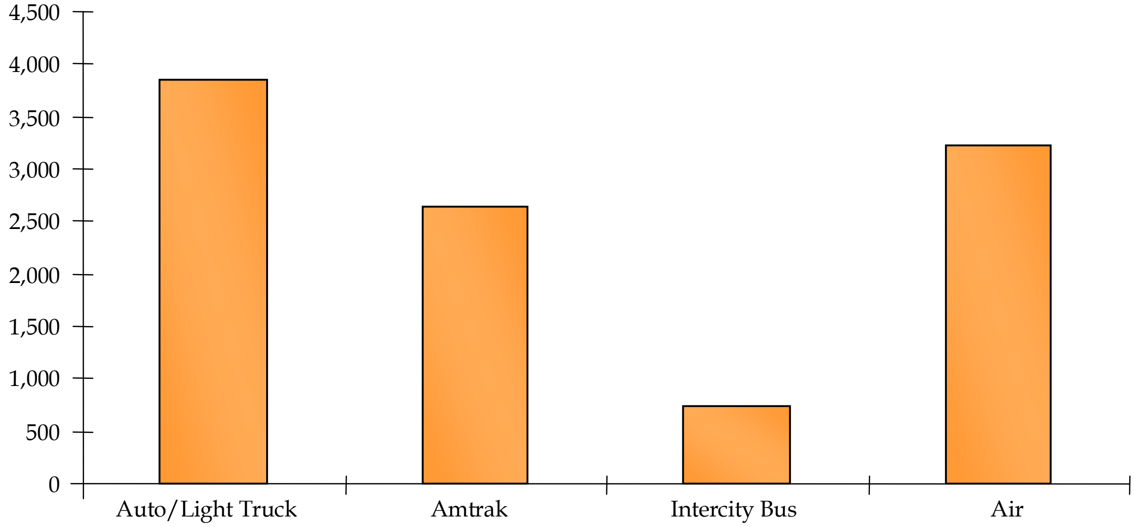
- Increasing investment in Amtrak's system, to create new intercity corridor service and to increase speeds, service frequencies, and/or reliability on existing routes;
- Investing in high-speed rail systems (whether operated by Amtrak or another carrier) that have been identified by the Federal Railroad Administration (FRA) in 12 intercity markets around the country; and
- Providing capital and/or operating subsidies to intercity bus service providers, to expand service and attract greater ridership.

Magnitude and Timing of Greenhouse Gas Reductions

Figure 5.4 shows average energy consumption for passenger-mile for intercity passenger rail, intercity buses, automobiles, and aircraft. The data show that intercity passenger rail (Amtrak) consumes 17 percent less energy per passenger-mile than air travel and 31 percent less energy per passenger-mile than the average private vehicle (automobile or light truck) (ORNL, 2007). Based on fuel consumption and operating data from Greyhound, intercity buses are approximately 81 percent more efficient than intercity rail as estimated by ORNL. This chart gives a general indication of the relative GHG impacts of these various modes.[23]

[23] Energy consumption will be roughly but not completely proportional to GHG emissions. GHG emissions from electrified intercity rail will depend upon the electricity generation mix, and aviation may have additional global warming impacts from contrail formation. There are also minor differences in the energy and carbon content of gasoline, diesel, and aviation fuel.

Figure 5.4 Energy Consumption per Passenger-Mile
Intercity Modes



Source: ORNL (2008); Greyhound (2009).

Note: Automobile and light truck efficiencies were combined based on weighted VMT, and assuming the same vehicle occupancy for light trucks as for automobiles (since energy consumption for light trucks is only reported per vehicle-mile, not per passenger-mile).

The *Moving Cooler* study estimated the net GHG benefits of increased intercity rail service as a result of shifting passengers from other modes, subtracting the added GHG from increased rail operations. Baseline projections suggest that Amtrak passenger-miles will continue to increase at the same rate as the increase between 1996 and 2007 (12 percent cumulatively over this period; BTS, 2009).[24] Increasing passenger miles at this same rate through 2050 would result in 6.78 billion miles in 2030 and 7.72 billion miles in 2050. An aggressive future scenario might assume a 20 percent increase in passenger miles over the baseline projection by 2025, as a result of additional investment to improve the quality of Amtrak's existing services. Compared to the baseline scenario, the aggressive scenario results in a reduction of about 1.2 mmt CO_2e in 2030 (Cambridge Systematics, 2009).[25] The modes new passenger miles shift from, and thus the potential for emission reductions, will

[24] This forecast is also the basis for the AEO baseline GHG forecasts presented in Section 2.0 of this report.

[25] This analysis assumes CO_2 emissions per kilowatt-hour estimated through EPA's eGrid database of 1.185 pounds CO_2/kwh in 2006, decreasing at 2.5 percent per year after 2015, which is based on an extrapolation of the rate of GHG reduction between 2010 and 2018 from targets set through the Regional Greenhouse Gas Initiative (RGGI) in 10 Northeast and Mid-Atlantic States. For diesel rail vehicles, AEO forecasts show rail emissions declining from 0.49 pounds GHG per passenger-mile in 2006 to 0.26 pounds per mile in 2050; a further 20 percent reduction is assumed to be phased in over the 2011-2030 period from the use of regenerative braking technology.

vary by corridor. This analysis assumes they are shifted proportionally from passenger vehicle, air, and intercity bus modes according to shares for long-distance travel from the 2001 National Household Travel Survey.[26]

The *Moving Cooler* study also estimated GHG benefits from the introduction of intercity high-speed passenger rail, based on a report published by the Center for Clean Air Policy and Center for Neighborhood Technology (2006). This report compiled data on the 11 Federally designated high-speed rail corridors (not including the existing Washington to New York to Boston corridor), including estimates of passenger-miles from the FRA. The Danish IC-3, a diesel powered train that has been demonstrated in the U.S., is identified as the primary high-speed rail technology. The IC-3 has lower emissions per train compared to other high-speed rail technologies, estimated at 0.26 pounds of CO_2 per passenger-mile at an assumed 70 percent occupancy (Center for Clean Air Policy and Center for Neighborhood Technology, 2006). In 2030, it is estimated that these 11 high-speed rail corridors could reduce GHG emissions by 4.0 mmt CO_2e.

In 2007, Greyhound—the largest intercity bus operator—operated nearly 5.8 billion passenger miles, achieving an estimated 184 passenger miles per gallon of fuel (Greyhound 2009). This results in total annual GHG emissions from the operation of Greyhound buses of 320,000 tons CO_2e. Comparatively, if these passenger miles were distributed proportionally to existing intercity shares of vehicle, air, and rail travel, total greenhouse gas emissions would be 872,000 tons CO_2e. This represents a greenhouse gas savings in 2007 by Greyhound alone of 0.55 mmt CO_2e. An assumption of an average annual 3 percent expansion in intercity bus service (approximately the growth expected this decade) would result in a total reduction of 1.2 mmt CO_2e in 2030. This assumes continued growth at the same level of ridership productivity as current services (which might occur, for example, as a result of rising fuel prices); if services were subsidized to expand into less productive markets, the GHG benefits would be somewhat lower as well.

The potential GHG reductions outlined above are for each system individually. The estimates suggest that a combination of interconnected intercity rail service with high-speed rail in select corridors and parallel and feeder intercity bus service would reduce GHG emissions by a total of about 6.4 mmt CO_2e in 2030. Again, this figure will depend heavily on factors including the ridership productivity of the expanded services, prior mode (if any) of riders, and relative advances in the energy efficiency of each mode.

Cost-Effectiveness

Intercity passenger rail is expensive to build and operate. According to Amtrak financial reporting for January to September 31, 2008, there were 6.16 billion passenger miles with total operating costs of $762 million (operations, fuel, utilities, and materials). Amtrak

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[26]This assumption may overstate the GHG benefits of these services, as it is likely that in the absence of such services, some intercity trips simply would not be taken. However, the added trips reflect a mobility benefit even if they do not provide a GHG reduction benefit.

recovers only a portion of its operating expenses through ticket revenue (48 percent in 2007).[27] The combined Federal and State subsidy needed to operate the entire system is very high: in 2001, Amtrak estimated that it would need about $16 billion (in 2000 dollars) in Federal capital support from 2001 to 2020 just to maintain current operating levels of service (GAO 2002).

Expanding intercity passenger services will require significant additional funding. The National Surface Transportation Policy and Revenue Study Commission intercity passenger rail vision includes a recommendation for the creation of an Intercity Passenger Rail Program. To implement the national and regional corridor vision, the Passenger Rail Working Group of the Commission recommends initial funding of $5 billion annually for intercity passenger rail, including Amtrak funding and grants to States. This recommendation is 3.9 times more than Federal funding support for Amtrak in 2007. The total capital cost estimate for maintaining and expanding the national intercity passenger rail network between 2008 and 2050 is $357.2 billion in 2007 dollars, an annualized cost of $8.1 billion (Commission 2007b). This results in an average capital cost through 2050 of $0.20 per passenger-mile.

The *Moving Cooler* study estimated the cost-effectiveness of expanding intercity rail, considering capital and operating costs only, to range from $420 per tonne CO_2e for the base investment scenario identified in the Commission report to $1,500 per tonne CO_2e for a passenger-mile growth scenario 20 percent beyond the baseline, considering total costs and GHG benefits over the 2010 to 2050 period. These costs, however, may be offset by reductions in personal vehicle operating costs; including these savings, cost-effectiveness ranges from -$600 per ton CO_2e for the base investment scenario identified in the Commission report to +$360 per ton CO_2e for the highest passenger-mile growth scenario. Additional costs to implement high-speed rail in 12 corridors result in high-speed rail cost-effectiveness of $1,000 to $1,400 per ton CO_2e considering capital and operating costs only; or $700 to $1,000 per ton CO_2e including personal vehicle operating cost savings (Cambridge Systematics, 2009).[28]

Cost-effectiveness estimates for intercity bus service are difficult to develop due to the lack of a formal process for reporting passenger-mile, cost, and revenue data by intercity bus operators. According to data from the Federal Motor Carrier Safety Administration (FMCSA, 2001), intercity bus services carried 32.2 million passengers in 2001 with total operating expenses of $1.04 billion, resulting in an operating cost of $32 per passenger.

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[27] This is based on ticket revenues of $1.52 billion versus total expenses of $3.18 billion (NRPC 2008).

[28] The high-speed rail costs are estimated based on an average capital cost of $4.08 per passenger mile, and annual operating costs at 2.5 percent of total capital costs. The $4.08 figure is the weighted average capital cost per passenger mile for three high speed rail corridors with environmental documentation and cost estimates: California (California High Speed Rail Authority, 2009), Midwest (Transportation Economics & Management Systems, Inc., 2004), and Southeast (Georgia Rail Consultants, 2004; Georgia Rail Passenger Authority, 2004). The California system would be on new right-of-way while the Midwest and Southeast systems would be upgrades to existing rights-of-way.

Assuming an annual 3 percent increase in ridership 2010 through 2050 at the same operating cost would result in a cumulative operations cost of $740 per ton CO_2e reduced. This cost-effectiveness calculation excludes bus replacement costs and vehicle operating cost savings.

Cobenefits

Cobenefits from intercity passenger service expansion include user benefits that accrue to passengers, such as shorter journey times and improved personal comfort while traveling. These services provide additional alternatives that some travelers may prefer, and can support mobility for low-income populations who may benefit from economical intercity bus travel. Intercity passenger service also has the potential to complement urbanized area public transportation as well as land use patterns that reduce car travel. Improved intercity passenger rail service could potentially benefit national security by increasing redundancy in the transportation system and facilitating mass evacuations, since a disruption that has major effects on one mode might still allow travel by other modes.

Feasibility

While costs represent a primary barrier to the expansion of intercity bus and rail services, interactions with existing freight railroads also represent a constraint on rail service expansion or reliability improvement. About 95 percent of Amtrak's 22,000 route miles of service are on track owned by the private freight railroads. The rail industry is already straining to meet the growing demand for rail freight transportation, and it must add capacity to handle a projected 60 percent more tonnage and 73 percent more ton-miles by 2035 (Cambridge Systematics 2007a). With capacity tightening on most freight rail lines, the freight railroads may be less willing or able to accommodate expansion of the intercity rail program.

High-speed rail lines may be built on new right-of-way in order to avoid conflicts with existing freight users as well as to provide grade-separated trackage that supports high operating speeds. However, construction of new rail lines may have potentially significant environmental and community impacts, and must proceed through the NEPA environmental review process like any major Federally project. Major upgrades to existing rail lines—for example, straightening curves, separating grade crossings, or electrifying track—may also encounter environmental or community constraints.

The American Recovery and Reinvestment Act (ARRA) allocates $9.3 billion for the development of intercity and high-speed passenger rail. ARRA provides a significant funding opportunity to potential intercity and high-speed rail project sponsors. Of the total identified, $1.3 billion is available for capital improvements and security upgrades for Amtrak. The remaining $8 billion is provided for the development of new intercity and high-speed rail passenger service.

Since intercity bus operators will be reluctant to operate services that are not profitable, the primary Federal policy lever for expanding intercity bus service would be subsidies to serve additional markets or improve the frequency or quality of service in existing markets. As previously noted, however, such service expansions would likely be less productive than current services in terms of reducing GHG emissions. Services targeted at premium or "choice" travel markets (such as business travelers who otherwise would have driven or flown) would have the greatest GHG benefits, although they may be less effective at achieving other objectives such as increasing mobility for low-income populations. Another potential Federal role in supporting intercity bus services is to support the construction and operation of intermodal transportation centers to provide convenient access for travelers between intercity bus, rail, urban transit, and automobile modes for local access. In the past, some intermodal facilities have been constructed using funds from existing FTA and FHWA programs.

Nonmotorized Transport

Definition

Nonmotorized transport strategies seek to make walking, bicycling, and other nonmotorized modes more attractive and competitive with automobile travel. Examples of nonmotorized strategies include: infrastructure improvements such as sidewalks, pedestrian crossings, traffic calming, on-street bicycle lanes, and off-street/shared-use paths; destination-based facilities including secure bicycle parking and lockers and showers for changing; land use policies to promote pedestrian-friendly site design; and information and education, such as wayfinding programs, bicyclist training programs, and other safety-focused programs.

Nonmotorized Transport

Benefits: **Low-Moderate**: 4-12 mmt CO_2e in 2030

Direct Costs: **Moderate-High**: $80 to $210 per tonne

Net Included Costs: **Net Savings**: -$600 to -$700 per tonne

Confidence in Estimates: **Low-Moderate**

- Uncertain analytical basis for benefits estimates
- Uncertain ability to achieve cultural acceptance required to realize bicycling benefits

Key Cobenefits and Impacts: **Positive**

- Mobility benefits to travelers, especially low-income
- Physical activity/health benefits

Feasibility: Moderate to High

- Primary barrier is funding
- Some bicycle improvements may require compromises with automobile mobility

Key Policy Options:

- Targeted funding

Pedestrian facilities are extensive in areas developed prior to the mid-20th century and are generally being included in most recent development (within the past decade), but are lacking in many areas developed in the second half of the 20th century. Many transportation agencies, including about three-fifths of State DOTs (Wilkinson and Chauney, 2003), are now working to include pedestrian accommodations in new or reconstructed roads; many are also making improvements in targeted areas (such as school zones, through U.S. DOT's Safe Routes to School program). Bicycle facilities are very limited in all but a few smaller U.S. cities with high college student populations. Dill and Carr (2003) found that a sample of 42 U.S. cities had an average of 0.66 miles of lanes or paths per square mile—meaning that the average bike route would be spaced three miles apart. However, in the past few years a number of major cities—including Chicago, Miami, New York, Philadelphia, Portland (Oregon), and

Washington, D.C.—have developed and have begun to implement aggressive plans to expand bicycling infrastructure as well as supportive programs. In addition, a growing number of State and local transportation agencies are adopting "complete streets" policies or revising design practices to ensure that all modes are accommodated in future street construction and reconstruction. According to FHWA, between Fiscal Years 1992 and 2005, the number of new Federally funded stand-alone pedestrian and bicycle projects grew significantly, from 50 in 1992 to over 1,000 in 2005, with total annual obligations for these projects of nearly $400 million (FHWA, 2005). This was a direct result of policy and funding changes under the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). In addition, the U.S. DOT's Safe Routes to School program has provided funding for pedestrian and bicycle safety improvements near schools, increasing from $54 million in FY 2005 to $183 million in FY 2009. Federal-aid obligations for pedestrian and bicycle projects were $1.2 billion in FY 2009. This figure does not include all FHWA or FTA spending on bicycle and pedestrian facilities. Bicycle and pedestrian projects are broadly eligible for almost all FHWA and FTA program funds. See http://www.fhwa.dot.gov/hep/bkepedtble.htm.

Magnitude and Timing of GHG Reductions

Pedestrian improvements are likely to have only minor impacts unless they are implemented in conjunction with land use strategies to promote compact, mixed-use development. This is because the primary factor in choosing to walk is the distance to the destination, and walk trips are short (0.7 miles on average, according to the 2001 National Household Travel Survey). Nevertheless, pedestrian improvements can help to reduce VMT and GHG especially in areas where destinations are relatively close together, but wide streets or a lack of sidewalks or safe crossings discourage pedestrian activity. Nearly 25 percent of all trips are less than one mile, yet approximately 75 percent of these trips are made by automobile; and less than 30 percent of trips to school (children ages 5 to 15) less than one mile are made by walking or bicycling (U.S. DOT, 1999).

Substantial investments in bicycle infrastructure have been demonstrated to lead to very high bicycle mode shares in college towns. For example, 14 percent of commuters bicycled to work in 2000 in Davis, California, which has a comprehensive network of off-street and on-street paths. Larger cities have recently begun to make significant bicycle improvements and are beginning to gather evidence on the impacts of these improvements. For example, in Portland, Oregon, 8 percent of city residents reported bicycling as their primary commute mode in 2008, up from 6 percent in 2007 (City of Portland, 2008), and compared with 2 percent in the 2000 Census. Additional evidence is available from Europe. Countries with little investment in bicycling infrastructure (including the U.K. and France) report bicycle mode shares of 2 to 3 percent; this share increases to 9 to 10 percent for Germany and Sweden, 18 percent for Denmark, and 27 percent for the Netherlands, which has a particularly extensive cycling infrastructure. Another comparison can be made by examining time-series data on bicycling in German cities, which found mode shares of 2 to 6 percent in the 1970s versus 6 to 20 percent in the 1990s and early 2000s, after major infrastructure improvements were made (Pucher, 2008). Bicycling is most competitive for shorter trips, and in areas where automobile travel is relatively slow (due to traffic congestion) and/or expensive (due to high fuel and/or parking prices). Therefore, it is likely that similar mode shifts might be seen in the U.S. only in the higher density portions of U.S. cities, and under conditions of high fuel prices.

The *Moving Cooler* study estimated the potential benefits of comprehensive programs of bicycle and pedestrian improvements implemented between 2010 and 2025 in all U.S. metropolitan areas. Pedestrian improvements focused in areas of higher population density, as well as around schools, business districts, and transit stations, were estimated to reduce GHG emissions by 2.2 to 6.6 mmt CO_2e in 2030, depending upon the extent of the improvements. Bicycle improvements, including comprehensive networks and supporting factors such as parking and cyclist training, were estimated to reduce emissions by about the same amount—2.0 to 6.1 mmt CO_2e in 2030—depending upon the density of the bicycle network and extent of on-street versus off-street or protected routes (Cambridge Systematics, 2009). Because of the limited evidence on pedestrian and bicyclist response to such improvements, however, there is considerably uncertainty in these estimates.

The GHG benefits of nonmotorized investment should increase over time, as facilities are deployed. Substantial progress on pedestrian improvements and limited bicycle improvements (such as on-street facilities) can be made over a 10- to 15-year timeframe, if resources are deployed aggressively. More significant transformations (such as the establishment of an extensive network of bicycle facilities separated from traffic) will likely require at least 20 to 25 years.

Cost-Effectiveness

For new development areas, pedestrian and bicycle enhancements can be implemented at relatively low-cost (and bicycle parking costs may be offset through reduced automobile parking). Retrofitting existing developments and roadways may in some cases incur higher costs because of right-of-way or other constraints. A review of the literature for *Moving Cooler* identified cost estimates for a variety of improvements. Bike lanes were found to cost as little as $5,000 per mile for signing and striping only, or up to $50,000 per mile for designing a roadway with additional width to accommodate a lane. Conversion of minor streets to "bicycle boulevards" was estimated to cost $250,000 to $500,000 per mile. Construction of an off-street shared-use path ranges from $500,000 to as high as $2 million per mile. These costs can be compared with typical local road construction costs of about $2 million per mile (Burchell et al., 2002).[29] Similarly, pedestrian improvements can be as little as $1,000 for a painted and signed crosswalk to in the range of $10,000 to $20,000 for a traffic calming device; while sidewalk construction may range from $200,000 to $800,000 per mile. The total costs of bicycle and pedestrian facilities are relatively small compared to the costs of roadway investment for motor vehicles. A review of comprehensive bicycle plans in five large U.S. and Canadian cities found total costs of implementing the plans to range from $70 to $240 million over a 10- to 20-year period, or

[29] Assumes a two-lane road in a developed area with moderate population densities.

an average cost of $211 per person. Pedestrian plans in four cities were on the same order of magnitude.

Moving Cooler developed three hypothetical scenarios of nationwide pedestrian improvements which were estimated to cost between $20 and $55 billion over a 15-year period, with three scenarios of bicycle improvements costing between $6 and $59 billion. The funding range amounts to an annual Federal investment in bicycle and pedestrian facilities of approximately $760 million to $3 billion.[30] The low end is actually lower than current Federal-aid obligations for pedestrian and bicycle projects of $1.2 billion in FY 2009. The $1.2 billion figure does not include all FHWA or FTA spending on bike/ped facilities. Bike/ped projects are broadly eligible for almost all FHWA and FTA program funds. See http://www.fhwa.dot.gov/hep/bkepedtble.htm. Additional maintenance costs are anticipated beyond this initial investment period. The resulting cost-effectiveness estimates range from $180 to $200 per ton CO_2e reduced for the pedestrian improvements, and $80 to $210 for the bicycle improvements, averaged over the 2010-2050 period. Considering vehicle operating cost savings, net cost-effectiveness is in the range of -$600 to -$700 per tonne (Cambridge Systematics, 2009).

The costs of bicycle and pedestrian improvements will largely be borne by the public sector, including municipalities as well as regional and State agencies. However, for new development, they often can be recouped from the private developer. For example, many cities require developers to include sidewalks and other pedestrian enhancements as part of their project. Local street and trail improvements in new developments may also be paid for through impact fees or other developer contributions.

Cobenefits

Nonmotorized improvements will provide increased opportunities for and encourage recreational activity as well as nonmotorized transportation, thereby increasing physical activity and improving public health. Estimates suggest that nearly 70 percent of American adults do not obtain recommended physical activity levels (U.S. Department of Health and Human Services, 1996). Similarly, sedentary lifestyles are associated with the rapid increase in the percentage of adults that are overweight and obese; 64 percent of

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[30] The $114 billion over 15 years ($55 billion + $59 billion) high end figure reflects all spending on bicycle and pedestrian improvements, from Federal, State, local, private developer, and other sources. $114/15 years is $7.6 billion per year. According to the U.S. DOT *Conditions and Performance Report*, 44% of capital funding for highways comes from Federal sources while 56% comes from State, local, and other sources. 44% of $7.6 billion would be $3 billion per year in Federal spending on bike/ped facilities. (Data is not immediately available on the percent of bike/ped funding from Federal versus other sources. However, it is likely lower than 44% as these facilities are often placed on local roads and private developers often bear the cost of providing sidewalks and other amenities as part of their development.) The $26 billion low end figure over 15 years amounts to $1.7 billion annually. A 44% Federal share would be $760 million annually.

American adults are now overweight and nearly one in three is obese (Flegal et al., 2002). Many researchers believe that the design of most communities in the latter half of the 20th century has contributed to environments that are unsafe and inconvenient for walking and bicycling, thereby influencing decisions not to adopt those behaviors for transportation or recreation (Cambridge Systematics and Killingsworth, 2006). The evidence from many studies on walking and bicycling demonstrate that regular participation in these activities provides a health benefit for people of all ages, genders, and races (Dunn et al., 1999).

Bicycle and pedestrian strategies can improve mobility by providing people with increased travel options, at a lower cost. Bicycle and pedestrian improvements and programs should also increase safety for nonmotorized travelers. At more aggressive levels, however, some bicycle and pedestrian strategies may require compromises in vehicle operating conditions and therefore vehicular mobility, e.g., reduced traffic capacity if general purpose lanes are reduced to create bike facilities, or traffic calming in business districts which slows vehicular movement.

Feasibility

Pedestrian improvements have proven to be popular in many cities, and the benefit of pedestrian-supportive design is gaining fairly wide acceptance. Widespread implementation of such improvements, however, can be a challenge for financially strapped municipalities. The extent to which walk trips can reduce VMT and GHG is primarily driven by the arrangement of land uses, and in particular, having dense, mixed-use environments where people can walk to destinations or to transit.

Bicycle improvements are also gaining in popularity, but still face political, institutional, and technical challenges especially when compromises are required with traditional roadway designs oriented towards motor vehicles. The ability to implement bicycle facilities—whether on-street or off-street—is also often limited by physical constraints on right-of-way availability. The extent to which people will be willing to bicycle for transportation is limited by practical constraints (e.g., need to carry packages, transport children, travel long distances, weather issues) as well as cultural factors, although some European countries have managed to make bicycling a widely acceptable mode of transport.

■ 5.4 Land Use and Parking

Unlike most strategies discussed in this report, which directly involve transportation infrastructure, services, vehicles, or operations, land use indirectly affects the demand for transportation. The spatial arrangement of homes, workplaces, and other activity locations, as well as the design of the built environment, affect the total amount of travel as well as the most efficient means of traveling. Land use policies are largely under the control of local governments and influenced by the private sector (property owners and developers), although regional and State transportation agencies may indirectly influence land use policy. Parking management is also discussed in this section, as parking policies (in particular, off-street parking associated with new developments) are developed within the same local planning framework as other land use decisions.

Land Use

Description

Land Use

Benefits: **Moderate-High**: 24-84 mmt CO_2e in 2030

- Growing over time – potentially double in 2050

Direct Costs: **Low**: < $10 per tonne

Net Included Costs: **Net Savings**: -$700 to -$800 per tonne

Confidence in Estimates: **Moderate**

- Primary uncertainty is ability to achieve significant changes to land use patterns

Key Cobenefits and Impacts: **Positive**

- Mobility benefits to travelers, especially low-income
- Reduced infrastructure investment needs
- Environmental/land consumption benefits

Feasibility: **Low-Moderate**

- Modest changes likely to be supported by market forces
- Political ability to achieve significant changes highly uncertain

Key Policy Options:

- Federal funding incentives/assistance for compact/transportation-efficient land use planning and implementation

This strategy includes coordinated regional transportation and land use planning to develop and implement growth policies, in conjunction with supportive infrastructure investment, to reduce vehicle-travel. The goals of such policies would be to increase the amount of new residential development in attached or small-lot detached units in pedestrian- and bicycle-friendly neighborhoods with sidewalks, bike facilities, good connectivity, mixed-use commercial centers, and high-quality transit; and to locate most jobs in dense, mixed-use activity centers connected by high-quality transit.

Compact, mixed-use, and pedestrian-friendly development contributes to reduced vehicle-travel by: 1) decreasing vehicle trip-lengths, as destinations are closer together; 2) supporting transit, by placing more people and jobs within walking distance of transit stations or stops; and 3) supporting nonmotorized travel, by placing more destinations within walking or bicycling distance and creating a safe and pleasant walking environment. Redevelopment of infill sites in existing urban neighborhoods, as an alternative to new development on far-flung "greenfields," is another component of this strategy that has been demonstrated to reduce vehicle-travel through shorter trip lengths and better access to travel alternatives.

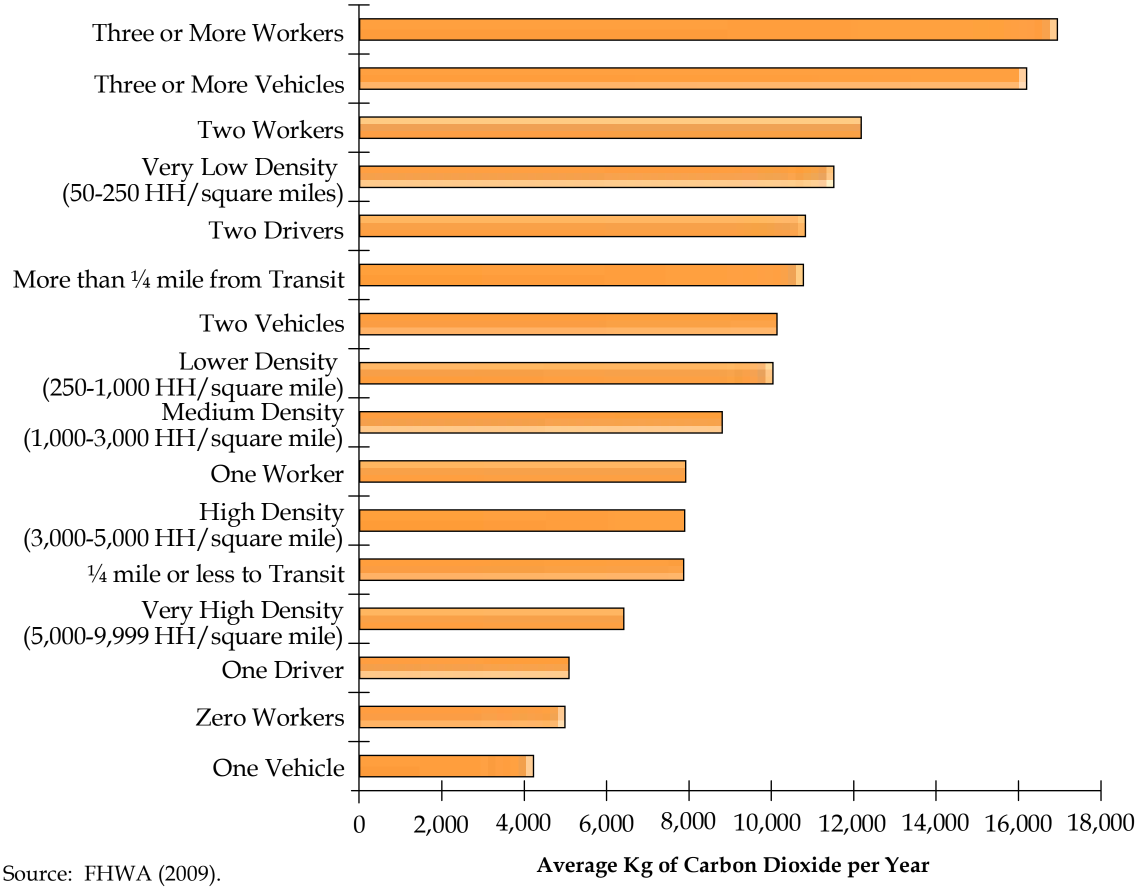
Although land use policies are typically under local authority, regional, State, and Federal agencies can support regional growth objectives through funding policies, fiscal incentives, and technical assistance to local agencies. Some recent examples are described in the sidebar on page 5-53. Additional Federal leverage could be provided through strategies such as:

- Establishing Federal transportation funding programs targeted at land use planning and/or supportive implementation strategies that meet particular objectives (e.g., pedestrian improvements in compact, mixed-use development areas);
- Changing U.S. DOT Statewide and metropolitan planning regulations to require greater consideration of land use (e.g., the development of regional transportation and land use scenarios in long-range planning);
- Expanding technical assistance programs such as EPA's Smart Growth Implementation Assistance program;
- Including "smart growth" criteria in evaluating candidates for grant or loan programs related to transportation, housing, economic development, etc.;
- Providing additional funds, or other incentives such as grant criteria, specifically for brownfields cleanup and redevelopment; and
- Making Federal transportation funding at least partially based on performance or incentive criteria for regional and local achievement of land use planning or implementation objectives.

Magnitude and Timing of GHG Reductions

The impacts of land use patterns at a site or neighborhood level can be significant. A recent review of the literature concluded that vehicle-travel was reduced by approximately 20 to 40 percent for residents of "compact" neighborhoods compared to residents of "sprawl" neighborhoods (Ewing et al., 2007). Infill sites have been shown to reduce VMT by 15 to 50 percent compared to greenfields locations (CCAP, no date). However, the net benefits with respect to GHG reduction are tempered by the long-term nature of land use changes. Land use change can occur as population in a region grows, and as obsolete building stock is replaced. Nelson (2006) estimates that 6 percent of the U.S. housing stock and 20 percent of the commercial building stock is torn down and rebuilt, each decade. Figure 5.5 shows the impacts of population density (as well as other factors) on carbon emissions per household – households in high-density neighborhoods produce about half the annual CO_2 emissions as those in the lowest-density neighborhoods.

Figure 5.5 Household Characteristics and Estimated Annual CO2 Emissions from Travel



Source: FHWA (2009).

This report to Congress analyzed the literature to develop a range of potential GHG reductions from land use strategies. Three studies were particularly instructive: *Growing Cooler*, authored by academic and industry researchers and published in 2008 by the Urban Land Institute; *Moving Cooler*, authored by Cambridge Systematics and published by the Urban Land Institute in 2009; and *Transportation Research Board Special Report 298: Driving and the Built Environment*, published by the National Academy of Sciences in 2009. All three studies, conducted independently and using different assumptions and analysis methods, found GHG reductions from land use strategies of the same order of magnitude. Taking the middle section of the study ranges and adjusting them to the same baseline as that used in this report to Congress, yields a reduction of U.S. transportation GHG emissions of 1.2 to 3.9 percent in 2030 and 2.5 to 7.7 percent in 2050. Table 5.6 below shows a comparison of assumptions and findings of recent studies.

Table 5.6: Comparison of Recent Studies on Land Use and Greenhouse Gas Reduction

	TRB Special Report 298	Moving Cooler	Growing Cooler
% of development on the ground in 2050 that will be developed or redeveloped between present and 2050	41-55%	64%	67% (Population growth plus 6% housing stock and 20% nonresidential redeveloped per decade)
% of new development that is "compact"	25-75%	43-90%	60-90%
Definition of "compact"	1.98 DU/acre (roughly 4 units/ residential acre)	>4000 persons per square mile (roughly > 5 units/residential acre)	Density, diversity, design, destination accessibility, and distance to transit
VMT in compact development	5-25% lower	23% lower	30% lower
Other key assumptions	New development will more likely be on urban fringe, VMT adjusted upward. VMT of those who live in existing housing will remain the same.	VMT of those who live in existing housing will continue to grow.	GHG reduction discounted by 10% to account for increased cold starts and reduced vehicle speeds with compact development.
Overall urban light duty vehicle VMT reduction	1-11%	1.7–12.6%	12-18%
Overall U.S. transportation GHG reduction below baseline (baselines vary)	**0.6-6.5%** (1-11% reduction in light duty GHGs)	**2-3.4%**	**7-10%**

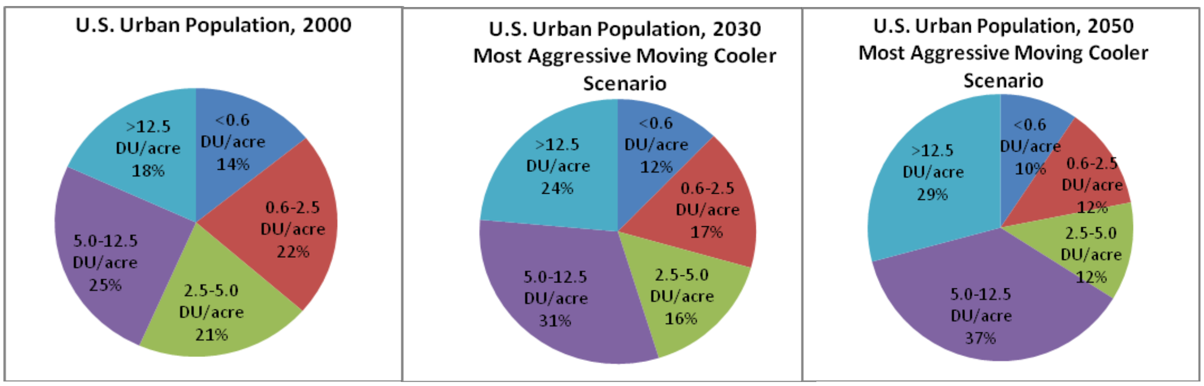
The *Moving Cooler* study found that U.S. transportation GHGs could be reduced by 2 to 3.4% below baseline in 2050 if 43-90% of new urban development occurred in areas of 4,000 persons per square mile or more, which roughly corresponds to 5 dwelling units per residential acre (if half of developed land is devoted to residential purposes) (Cambridge Systematics 2009). Under 1990-2000 trends, 34% of new development took place in these areas. As such the low end of the range considers a scenario with a modest shift, which may be below market demand for this type of housing, while the high end is a significant shift, which may be above market demand for this type of housing.[31] Greater than 4,000 persons per square mile (ppsm) is used as a proxy for "compact" development. Estimated

[31] See feasibility section below for discussion of market trends.

GHG reductions are based on the differences in VMT for individuals living in areas of 4000 ppsm or more versus individuals living in lower density areas, according to the 2001 National Household Travel Survey (NHTS), and modeled by the Center for Urban Transportation Research (CUTR). As such, the proxy only incorporates the current difference in VMT between different density levels and does not incorporate additional policies that could be pursued such as mixing land uses.

The analysis only considers new development in metropolitan areas. It does not assume any changes in rural areas. The pie charts in Figure 5.6 compare the distribution of the U.S. metropolitan area population in 2030 and 2050 under the most aggressive Moving Cooler scenario to the year 2000 actual population distribution.

Figure 5.6 Distribution of U.S. Urban Population



New development in metropolitan areas at greater than 5 units per residential acre could take the form of small lot single family homes, townhomes, apartments, condominiums, or combinations of these with large lot single family homes. The photographs in Figure 5.7 and 5.8 show examples of housing at various numbers of units per acre.

Vehicle miles traveled (VMT) reductions under the scenarios are calculated based on a VMT model developed by the Center for Urban Transportation Research (CUTR) at the University of South Florida. The base data for the model is from the 2001 National Household Travel Survey (NHTS). The VMT reductions in the model are shown in the table below. As shown, those in areas with greater than 5 dwelling units per acre travel 28% fewer miles than those in areas with less than 0.6 dwelling units per acre.

Table 5.7: CUTR VMT Forecasts by Census Tract Density (Annual VMT per Capita)

Persons per square mile (ppsm)	~Dwelling units/ residential acre	2005 VMT	2035	2055 VMT	VMT compared to <500 ppsm
0-499	<0.6	11,422	13,798	16,191	0.0%
500-1,999	.6-2.5	10,083	12,196	14,359	-11.3%
2,000-3,999	2.5-5	9,345	11,345	13,406	-17.2%
4,000-9,999	5-12.5	7,986	9,782	11,651	-28.0%
10,000+	>12.5	4,437	5,651	5,940	-63.3%

Source: Cambridge Systematics, 2009.

The recent *Growing Cooler* study estimated that changes in land use patterns to focus most new development into compact, walkable, transit-accessible communities could reduce total U.S. GHGs from transportation sources by 7 to 10 percent from forecast levels by 2050, or urban VMT by 12 to 18 percent (Ewing et al., 2007). If the VMT reduction is divided by two to represent approximate VMT and GHG reduction benefits in 2030 (assuming that land use benefits increase in roughly linear fashion over time) and applied to the Annual Energy Outlook Reference case forecast, this provides a 4.8 to 7.2 percent reduction in total light-duty VMT in 2030 (assuming 80 percent of VMT in urban areas), corresponding to an emissions reduction of 56 to 84 mmt CO_2e in that year. The *Growing Cooler* estimates were based on 60 to 90 percent of new development being located in "compact" neighborhoods, and findings from literature review and structural equations modeling that VMT per capita with compact development is approximately 30 percent lower relative to sprawl.

The Transportation Research Board's *Special Report 298: Driving and the Built Environment*, released after most of the writing for this report to Congress was complete, found results in the same range. Special Report 298 estimated that the reduction in vehicle miles traveled (VMT), energy use, and CO_2 emissions resulting from more compact, mixed use development would be in the range of less than 1 percent to 11 percent by 2050 (TRB, 2009).

The estimated GHG reduction range in Special Report 298 is based on 25 to 75 percent of new residential development taking place at double the average density of new acres developed between 1987 and 1997. Development between 1987 and 1997 was significantly less dense than existing development. As such, under the low end scenario, average densities would continue to decline. Under the most aggressive scenario, average densities would increase from current levels to densities on the ground in the early 1990s. Committee members for the TRB report disagreed about whether the changes in development patterns and public policies necessary to achieve the high end of these estimates are possible.

Table 5.8: Key Density Data from TRB Special Report 298

Density of average acre: 1987	1.86 DUs/acre
Density of average acre: 1997	1.66 DUs/acre
Density of average new acre developed 1987-1997	0.99 DUs/acre
Study assumption for density of 25% - 75% of new development	1.98 DUs/acre, with remainder at 0.99 DUs/acre
Density of average acre: 2050, study baseline (100% of new development at 0.99 DUs/acre)	1.29 – 1.39 DUs/acre
Density of average acre: 2050, low end	1.43 – 1.49 DUs/acre
Density of average acre: 2050, high end	1.69 – 1.7 DUs/acre

Note: DUs/acre above refers to dwelling units per acre of developed land, including developed land use for residential, commercial, transportation, and other purposes. As such, in a community in which half of the developed land is used for residential purposes, a density of 2 DU/acre would translate into 4 DU/residential acre, or about quarter acre average lot size. The report uses three different methods for calculating density, all of which show the same trends. The method portrayed above uses the U.S. Department of Agriculture's Natural Resources Inventory and the U.S. Census.

Source: TRB, 2009.

Figure 5.7: Examples of Housing Densities

Source: Lincoln Institute of Land Policy, Visualizing Density: Image Gallery Search, http://www.lincolninst.edu/subcenters/visualizing-density/gallery/index.aspx
Photographer: Alex MacLean http://www.alexmaclean.com/

Beauford, SC, 1 unit / acre

Longmont, CO 2.6 units / acre

Levittown, NY, 5 units / acre

Sandusky, OH, 5.4 units / acre

Huntersville, NC, 6.3 units / acre

Fresno, CA 8.1 units / acre

Tampa, FL, 8.6 units / acre

Kansas City, KS, 11.1 units / acre

Longmont, CO, 12.3 units / acre

Detroit, MI 13.7 units / acre

Boulder, CO, 19.7 units / acre

Washington, DC, 21.8 units / acre

Baltimore, MD, 28.6 units / acre

Addison, TX, 55.2 units / acre

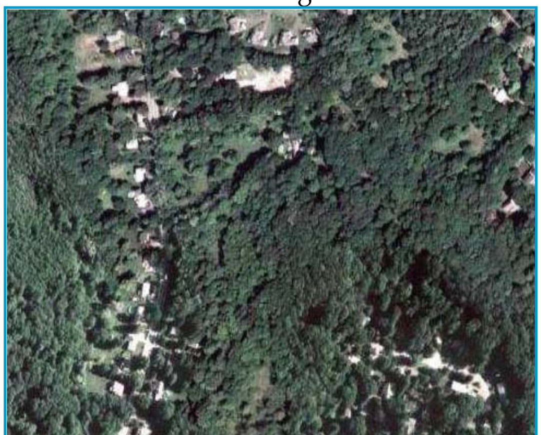
Oakland, CA, 85.3 units / acre

San Francisco, CA, 222 units / acre

Figure 5.8: Examples of Communities at Different Density Ranges

The aerial photographs below provide examples of the different density ranges. Note that even in the highest densities shown below, single family homes dominate the landscape.

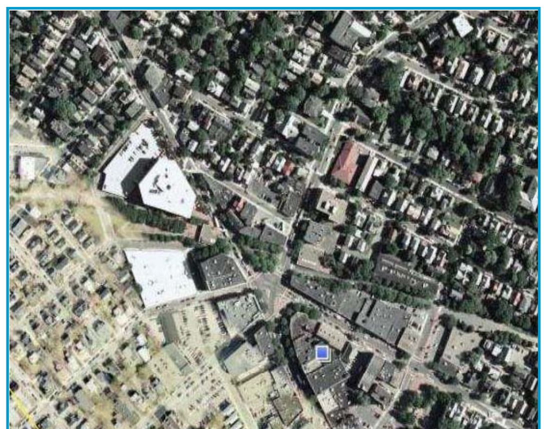
Source: TeleAtlas and GoogleEarth



Concord, MA:
500-2,000 ppsm (0.6 - 2.5 DU/acre)

Lexington, MA:
2,000-4,000 ppsm (2.5 – 5 DU/acre)

Watertown, MA:
4,000-10,000 ppsm (5 – 12 DU/acre)



Somerville, MA:
>10,000 ppsm (>12 DU/acre)

Federal, State, and Local Programs to Influence Land Use

Land use planning may ultimately be a matter of local authority, but regional and State entities have increasingly worked to influence land use patterns through voluntary and incentive-based measures. For example:

- Numerous metropolitan planning organizations (MPOs) and other regional and local public and nonprofit agencies are leading, or have led, "scenario planning" or "visioning" efforts that attempt to achieve a regional consensus on desired future land use and transportation patterns, and work to identify implementation steps and commitments. A recent review for FHWA found 80 examples of scenario planning efforts in more than 50 metropolitan areas nationwide (Bartholomew, 2005). Examples include Denver Metro Vision 2020; the Eastern Planning Initiative in Charlottesville, Virginia; and MyRegion in Orlando, Florida.
- California's Blueprint process is a State-led initiative that provides grants and other resources to support regional scenario planning throughout the State. This process has been further strengthened by Senate Bill 375, adopted in September 2008, which requires the California Air Resources Board to establish GHG emission reduction targets for metropolitan planning areas and for regional transportation plans to include sustainable communities strategies as part of the plan to achieve the emission reduction targets.
- State and regional agencies can support implementation of the visioning and scenario planning outcomes in a number of ways. One is alignment of the long-range transportation plan with the resulting regional vision. Another is through extensive outreach to local governments to encourage implementation of plan objectives in local comprehensive plans and zoning. MPOs have also provided transportation funds for local plan and code revision consistent with the regional plan, or revised project selection criteria to include consistency with the regional land use vision.
- Even without a regional land use vision plan, MPOs have provided funding incentives for local land use plans and transportation projects that support "smart growth" objectives. One example is the Atlanta Regional Commission's Livable Centers Initiative, which has provided \$10 million over 10 years for planning studies and \$500 million for funding of priority transportation projects resulting from these studies.
- At the Federal level, the EPA's Smart Growth Implementation Assistance program is a competitive program that provides a team of technical experts to assist municipalities or other entities with policy analysis or public participatory processes to support "smart growth" implementation. In its first few years of funding, the Federal Highway Administration's Transportation and Community and System Preservation Program (TCSP) supported a number of innovative regional efforts to link transportation and land use planning. In March 2009, the U.S. DOT and the Department of Housing and Urban Development (HUD) announced the creation of a high-level interagency task force to better coordinate Federal transportation and housing investments.

Scenario planning studies using travel forecasting models have estimated that land use changes, combined with supportive transit investments, could reduce metropolitan VMT by a median of 16 percent below forecast levels over a 40-year time horizon (Rodier 2009), which is in the same range as the *Growing Cooler* results. Because land use change occurs slowly over time, the impact over a shorter timeframe will be proportionately less; the Rodier study found a median VMT reduction of 8 percent over a 20-year time horizon. Again applying this result to the AEO reference case, the estimated emission reduction would be 75 mmt CO_2e in 2030. The potential benefits depend upon the projected growth in the region, aggressiveness of assumed land use and transit changes, as well as the forecasting model's capabilities and specific methodological assumptions. Forty-year VMT reductions in the Rodier review ranged from a low of 3 percent to a high of 28 percent across all studies.

Cost-Effectiveness

Land use planning and infrastructure planning activities will incur administrative costs for the development and implementation of incentives, regulations, etc. Based on a review of past and ongoing regional and Statewide planning efforts, the *Moving Cooler* study estimated the costs of a regional visioning and scenario planning effort (planning activities only) to be on the order of $1 million per year in a large metropolitan area or on a Statewide level. Extrapolating to all metropolitan areas and also allowing for municipal code revision, the total planning costs could be on the order of $500 million per year nationwide. It is likely that these costs would need to be sustained over at least a decade, with some additional ongoing costs to support plan implementation. These costs are relatively minor compared to the GHG reductions, and the cost-effectiveness of land use planning, considering administrative costs alone, has been estimated to be in the less than $10 per ton of GHG reduced, considering cumulative costs and GHG reductions over the 2010-2050 period. Considering vehicle operating cost savings, a net savings in the range of -$700 to -$800 is estimated (Cambridge Systematics, 2009).

The calculations cited above did not incorporate other cost savings such as reduced infrastructure expenditures, which are potentially significant, but also subject to a high range of uncertainty. There is good evidence that more compact development can lead to significant savings in infrastructure costs through reductions in the length of local roads and utility connections that must be provided. Burchell (2005) finds a potential 11 percent nationwide reduction in local road and water/sewer costs from a future scenario emphasizing compact development over sprawl, or $126 billion over the 2000-2025 timeframe. Scenario planning studies in locations such as Sacramento, Salt Lake City, and Charlottesville, Virginia, have also shown a significant reduction in regional road investment needs because of reduced traffic, although these savings are partially offset by the need for increased transit investment. For example, Envision Utah (2000) found that a regional "quality growth scenario" would add $1.5 billion over 20 years in transit costs, but save $2.6 billion in regional road costs, for a net savings of $1.2 billion. Additional subregional infrastructure cost savings—including roads, water, and other utilities—would total $3.3 billion or 26 percent. The savings will accrue both to State and regional governments (for regional infrastructure) and to local governments, developers, and consumers (for local infrastructure). However, some public-sector costs will increase—

notably investment in transit and nonmotorized infrastructure. The overall impact on public infrastructure costs will depend upon the specific program of investments in a given metropolitan area.

Achieving the benefits of infill development may in some cases involve the cleanup and reuse of "Brownfields" sites (contaminated) or "greyfields" sites (subject to prior use). Greater short-term costs may be incurred by the public and/or private sectors for Brownfields infill development, compared to a unit of "greenfields" development; median Brownfields cleanup costs run about $57,000 per acre according to a Center for Urban Economic Development study cited in Paull (2008). A U.S. Conference of Mayors survey also cited in Paull (2008) found that an estimated 2.8 million people could be accommodated on Brownfields sites in 82 cities. Extrapolating this estimate to the central city of all 363 U.S. metropolitan areas and assuming a development density of 15 units per acre, the total nationwide cost would be just under $20 billion. Land assembly, demolition of existing structures, and more involved permitting processes can also increase the costs of infill versus greenfields development. Cost differentials may require subsidies or tax incentives by government agencies to stimulate private investment in particular areas. For example, the City of Portland, Oregon, provides a residential tax exemption for qualifying new construction in transit station areas.

Cobenefits

More compact growth patterns have been cited as having a number of cobenefits. In addition to benefits related to reduced VMT, these include improved mobility/ accessibility for populations without access to an automobile, and potentially safety benefits related to lower travel speeds and therefore less severe crashes. One study found that U.S. metropolitan areas with high levels of "sprawl" have higher traffic fatality rates than "nonsprawling" regions (Ewing, Pendall, and Chen, 2003). Another focused on Hawaii found that higher population densities were associated with lower crash rates (Kim and Yamashita, 2002). Dumbaugh and Rae (2009), using data from San Antonio, find that neighborhoods with traditional design features (higher densities, pedestrian-oriented retail uses, interconnected streets) have fewer serious crashes than suburban neighborhoods. Public health benefits may be realized due to higher levels of physical activity as walking and bicycling become more viable options (Frumkin, 2002). Land use planning undertaken with meaningful public participation can also improve the environmental and social quality of an area as perceived by its users. Many of the co-benefits of land use strategies can be summarized in the term "livability," which includes promoting mobility for all users, whether they are children walking or biking to school or commuters riding transit or driving motor vehicles; improved traffic flow; shorter trip lengths; safer streets for pedestrians and cyclists; lower emissions; reduced dependence on fossil fuels; increased trip-chaining; lower household transportation budgets; and independence for those who prefer not to or are unable to drive.

On the other hand, while overall emissions of air pollutants will decrease because of VMT reductions, concentrated land use has the effect of concentrating air and water emissions in areas of potentially greater population exposure.

Compact growth patterns also should reduce land conversion for urban uses, helping preserve agricultural land, forests, open space, wetlands, and species habitat. For example, the Seattle region's VISION 2020, adopted in 1990, was forecast to reduce loss of open space from 750 square miles under trend conditions to 400 square miles under a preferred alternative focusing growth in centers and within an urban boundary (Puget Sound Council of Governments, 1990).

A variety of both social benefits and ills have been assigned to "sprawl" versus "compact" land use patterns (Burchell et al., 1997). For example, some have argued that land use controls could reduce consumer welfare by constraining consumer choice (e.g., requiring smaller dwelling units and/or yards). To the extent that land use policy changes allow development desired by consumers that was previously not legally permitted (many local zoning codes prohibit mixed-use compact development) and simply *accommodate* latent market trends for more compact development, this should not be a concern. However, more aggressive policy changes that restrict development desired by the market, beyond incorporating externalities, could potentially lead to net welfare losses. The factors that influence residential and neighborhood quality are complex and there is not a consensus on the extent to which compact land use may increase or decrease overall social welfare.

To the extent that growth management policies constrain the supply of land, consumers and businesses may experience higher land costs and therefore higher housing and floorspace rents. Some have argued that growth management laws have had significant impacts on affordability. For example, Staley and Gilroy (2002) conclude that Florida's Growth Management Act (GMA) may have contributed to a 15 percent decline in affordability between 1994 and 2000, and that Washington State's GMA may have added about 0.7 percentage points to the housing inflation rate for each year the county had a comprehensive plan in place. Other studies, however, have found that growth management effects are minor after controlling for other factors. For example, an analysis of the urban growth boundary in Portland, Oregon found that the boundary has created upward pressure on housing prices, but the effect is relatively small in magnitude, contributing no more than $10,000 compared to an overall cost appreciation of $144,000 over their study period (Phillips and Goodstein, 2000). A broader literature review concluded that market factors including increased housing demand, increased employment, and rising incomes are much more significant influences; and furthermore, that policy changes to allow increased densities and smaller units have mitigated any affordability impacts by allowing housing supply to be increased within the growth boundary (Nelson et al., 2002).

Effects on the overall economy are unclear. The effects of land use patterns on the economy will depend upon: 1) accessibility benefits – in particular, business access to workers, suppliers, and customers within a given travel time, and the implications for business costs and productivity; 2) land costs, which affect the cost of doing business; and 3) net infrastructure and transportation cost savings. The implications of compact land use for accessibility are not clear as there are two offsetting effects—greater proximity (which will increase accessibility) and greater congestion and lower travel speeds (which will decrease it). Land costs are likely to be higher, but infrastructure and transportation costs lower (as discussed above). Overall the balance of these factors has not been well documented.

Feasibility

In numerous metropolitan areas nationwide, plans to change future patterns of land use and infrastructure investment are already in various stages of development or implementation. For other areas such a process may take five to 10 years to develop because of the time needed to develop the necessary data and analysis tools, conduct outreach, forge public consensus, etc. State and Federal incentives can provide valuable support for such processes, but to be successful they ultimately must reflect locally determined preferences.

The ability to implement changes to land use patterns and infrastructure investment priorities is highly dependent upon local public and political support, which varies from region to region. In most areas, it has been easier to develop a regional vision regarding such priorities than to actually achieve changes at the local level. To date, no State or metropolitan area has been able to fully implement the changes proposed through a regional visioning or scenario planning process. This is due to a variety of factors that inhibit adoption of policy and zoning changes at a local level, such as concerns over density and fiscal impacts; as well as market barriers in some areas (e.g., low land prices and limited demand for higher-density, more urban-style development). One of the few areas—Seattle—that has both adopted and tracked regional policy targets found that continuation of rates of growth from 1990-2000 would lead to the achievement of about 70 percent of planned 2012 targets for population growth in designated "growth centers" by 2020, although the rate of growth in centers was increasing (Puget Sound Regional Council, 2002).

There is evidence that market and demographic trends are supporting a move towards more compact development patterns. Some of these supportive factors include increasing shares of population in households with no children (singles, young couples, "empty nesters," and seniors), a renewed interest in urban living, and transportation constraints (congestion and high fuel prices) that provide incentives to live in walkable or closer-in communities where less driving is needed. Nelson (2006) estimates that current demand for development that could be "compact" in nature (attached and small-lot detached) is estimated at 46 percent of the market and could increase to 60 percent in 2025. A 2004 report by the Center for Transit-Oriented Development estimated that that at least a quarter of all new households—14.6 million households—over the next 25 years could be looking for housing in transit station areas (within a half-mile radius of rail transit), compared to only 6 million households in these areas today (CTOD, 2004). A recent EPA report examined building permit data from 1990 through 2007 in the 50 largest U.S. metropolitan areas and concluded that in several regions of the country there has been a dramatic increase in the share of new construction built in central cities and older suburbs, with a particularly dramatic increase over the past five years (Thomas, 2009). However, the report also found that the trend has not been consistent everywhere. For example, in seven regions, infill development (i.e., in the central city and older suburban communities) accounts for between one-quarter and one-half of new construction (it is greater than one-half in New York). In 13 regions, infill development significantly increased but accounted for less than one-quarter of new residential units, while in 12 regions, there was very little change in the distribution.

Impediments, particularly zoning regulations, have resulted in an apparent undersupply of higher density, mixed use developments (TRB, 2009). Impediments include street designs that emphasize the needs of motorized travel at the expense of other modes, local zoning regulations in many U.S. communities that prevent compact and mixed use development, and minimum parking requirements. Developers report considerable market interest in compact developments but an inadequate supply (Levine and Inman 2004).

One conclusion from these findings is that some level of land use change is likely to be supported by market factors; but more significant change approaching the more aggressive levels assumed in *Growing Cooler* or *Moving Cooler* is likely to require stronger policy intervention.

Parking Management

Definition

Parking management involves changes to parking supply, pricing, or other management techniques to create disincentives to driving. Examples include: reducing parking requirements for new development; designing and locating parking to encourage pedestrian travel for short local trips; charging workers for parking or allowing them to "cash-out" the value of parking if they do not use it; "unbundling" residential parking costs from the cost of a lease or purchase; pricing to encourage "park-once" behavior; pricing to maintain vacant spaces in order to reduce parking search time;[32] reducing on-street parking to make room for wider sidewalks and/or bike lanes; and using information technology to help drivers

Parking Management

Benefits: **Low**: 4 mmt CO_2e in 2030

Costs: Not estimated

Confidence in Estimates: **Low**

- Benefits will depend upon what types of parking management, scale of application, supportive land use context

Key Cobenefits and Impacts: **Mixed**

- Potential cost savings for developers and reduced land consumption for parking
- Mobility losses for drivers if parking is priced or restricted

Feasibility: **Low**

- Very limited applications (e.g., parking reductions in transit station areas) proven feasible
- No mechanism for or U.S. examples of region-wide parking pricing or supply restriction

Key Policy Options:

- Tax policy to discourage parking provision

[32]Studies around the world have found that between 8 and 74 percent of the traffic present in some congested business districts is due to cruising for parking, which can be greatly reduced by pricing parking sufficiently high to ensure availability (Shoup, 2005).

efficiently locate spaces.

Most parking management strategies are under the domain of local government. In most U.S. cities, parking supply is constrained or priced only in the central business district (CBD) and possibly a few other major activity centers, primarily as a result of market forces that establish a strong premium on land costs. Outside of these areas, parking supply is generally plentiful, due to long-established planning and zoning regulations that require developers to provide ample parking, and free (Shoup, 2005). However, some cities, such as Charlotte, Portland, Oregon, and Pasadena, have taken steps to reduce parking supply in transit-oriented developments or other urban neighborhoods. Active management of parking pricing to regulate demand is being tested in New York and Washington, D.C. and considered in other cities including Chicago, Los Angeles, and San Francisco (Nguyen, 2009). Parking cash-out and worksite parking pricing can be implemented by employers or property managers, and are considered a subset of employer commute measures (Section 5.5) in this report.

Magnitude and Timing of GHG Reductions

Both the cost and supply of parking are significant determinants of travel behavior. (These factors tend to be closely related, as parking tends to be priced when – and only when – its availability is limited.) Most studies of parking pricing have focused on commuting behavior. Cervero (1993) found that rail transit mode shares in the San Francisco Bay Area increased by about 50 percentage points (e.g., 64 versus 14 percent transit mode share) if the employee had to pay for parking, compared to those that were given free parking. A study of employers in California found that parking cash-out programs reduced vehicle trips an average of 11 percent (Shoup, 1997).

Information on the potential nationwide GHG reductions from parking pricing or other parking management strategies is very limited. Two recent estimates have focused on commute travel in particular. Nationwide, only 5 percent of employees pay for parking, so in theory there is great potential for expanding the scope of worksite-based parking pricing. On the other hand, market prices for parking usually exist only in CBDs and other densely built activity centers, and, according to data from the 2000 U.S. Census, less than 10 percent of a typical metropolitan area's workforce is located in the CBD. Assuming that an additional 5 percent of workers nationwide could have parking priced at market rates, reducing SOV use per worker by 20 percent, and further assuming that work trips make up 30 percent of total VMT, the total reduction in VMT on a nationwide basis would be approximately 0.3 percent (EEA, 2008). This represents a reduction of 3.5 mmt CO_2e in 2030. A nationwide fee of $5 daily per parking space levied on all worker-utilized parking spaces (or the equivalent, such as a $5 cash-out incentive offered to all workers who choose not to drive) is estimated to reduce emissions much more substantially—by nearly 40 mmt CO_2e in 2030 (Cambridge Systematics, 2009). However, it is not clear how such a broad-based fee would be implemented or enforced.

Some parking management strategies, such as market-rate pricing of on-street spaces or offering a cash-out option to employees, can be implemented within one or two years. However, others (such as reducing parking requirements in zoning) take many years to have widespread effects, because they involve changes to new development which occur over time. The extent to which such zoning changes will have an effect will depend upon the rate of development in an area.

One risk associated with constraining or pricing the supply of parking in limited geographical areas is that activity will shift towards areas in which parking is not constrained. For example, some U.S. cities have adopted policies to expand the supply of parking in their CBDs, to help these areas compete with the suburbs for companies. Achieving the full benefits of parking management will be strongly dependent upon land use strategies to develop attractive high-density activity centers, creating higher land values that support a market for parking and supporting travel alternatives. Since implementing policies to reduce parking supply or increase the price of parking is dependent upon compact, transit-supportive land use environments, it would be difficult to develop unique estimates of the GHG reduction benefits of these parking management strategies.

Cost-Effectiveness

Some parking management strategies, such as changes to minimum and maximum parking requirements, can be implemented with minimal administrative cost. Pricing of parking that was previously free requires the establishment of a system for monitoring parking and collecting revenues; the cost of such a system relative to revenues will depend upon the technology used, parking rates, and other factors. The administrative costs of parking pricing implemented on a widespread basis have not been estimated, and therefore, reliable cost-effectiveness estimates cannot be made.

Parking pricing represents a transfer payment that costs drivers while increasing revenue for local governments and/or property owners. Nondrivers may benefit from lower housing costs if the cost of parking is not included in the lease, or through lower tax rates.

Cobenefits

Parking management will result in some social cost savings. In particular, reductions in parking requirements will reduce costs associated with new development, especially in areas of high land value—benefiting developers as well as tenants. The cost of structured parking typically ranges between $15,000 and $30,000 per space (Johnson, 2006), and nonprofit developers in San Francisco have estimated that parking requirements add 20 percent to the cost of each unit (Shoup, 2005). Surface parking is considerably cheaper, with costs depending upon land values (Shoup, 2005).

Depending upon how they are implemented, parking strategies may lead to improvements or declines in mobility for specific segments of the traveling public. For example, reducing the amount of land devoted to parking will make areas more pedestrian-friendly, supporting pedestrian and transit mobility; but vehicular mobility will be reduced if parking is made more costly or scarce. Pricing and information strategies to manage demand and match demand with supply will have the benefit of reducing local traffic congestion.

Feasibility

Managing demand via parking policies has met considerable political resistance in most locations. Parking is typically priced only in the limited places where there is a market for it (CBDs and other major activity centers), and examples of businesses offering cash-out or residential developers unbundling parking costs are relatively rare. Furthermore, the potential role of the Federal government in encouraging parking management has not been investigated. Incentives (for example, in the form of Federal transportation funding) could perhaps be provided as part of a broader set of incentives for local governments to implement "compact development" land use strategies aimed at reducing vehicle-travel and facilitating alternative mode use. It is also conceivable that the Federal government could implement a tax on parking spaces. However, this would be a major change in U.S. tax policy, which typically leaves property taxes to the local government.

5.5 Commute Travel Reduction

Efforts to reduce commute trips by single-occupancy vehicle (SOV) have long been a staple of transportation demand management (TDM). Commute-focused trip reduction initiatives have included alternative mode information, transit subsidies, ridesharing/ride matching programs and incentives, vanpools, parking management (including pricing and cash-out), telework, and alternative work schedules. This section first discusses general commute-focused worksite trip reduction programs, which are intended to promote a variety of alternatives; and then discusses the potential for specific individual measures such as ridesharing and telework.

Worksite Trip Reduction Programs

Definition

Worksite trip reduction programs may include either requirements for employers to reduce single-occupancy vehicle (SOV) trips by their employees, or outreach, assistance, and incentive programs to encourage them to do so. Transportation agencies began to implement demand management programs in the 1970s, with the energy crisis, and have continued to do so, to varying degrees, since then. Employer trip reduction requirements exist in Oregon and Washington States and in the Phoenix and Tucson, Arizona metropolitan areas; they were introduced in Southern California in the early 1990s but later rescinded. A few cities and counties also require employers to reduce trips or implement TDM programs. A number of State, regional, and local transportation agencies coordinate voluntary demand management programs, with some of the most active programs in the largest, most congested regions such as Atlanta, Washington, D.C., and Southern California.

Worksite Trip Reduction Programs

Benefits: **Low-Moderate**: 2-14 mmt CO_2e in 2030

Direct Costs: **Low to Moderate**: \$30 to \$180 per tonne

- Public sector costs only

Net Included Costs: **Net Savings**: -\$1,000 per tonne

Confidence in Estimates: **Moderate**

Key Cobenefits and Impacts: **Positive**

- Most worksite trip reduction programs will result in additional mobility options for commuters

Feasibility: Moderate to High

- Primary barrier is obtaining widespread employer participation/support

Key Policy Options:

- Targeted funding
- Tax incentives to support commute trip reduction/alternative mode use

A moderately aggressive expansion of worksite trip reduction programs could include the widespread provision of voluntary/outreach-based programs by MPOs and/or State DOTs. A more aggressive expansion could include the nationwide imposition of employer-based trip reduction requirements, combined with supportive programs such as regional ridematching and vanpooling programs and assistance in developing worksite-level trip reduction plans. Of the various worksite-based strategies, financial incentives and disincentives, such as free or discounted transit passes and parking pricing or cash-out, generally have the greatest impact (COMSIS, 1993; VTPI, 2009). This means that programs focused on encouraging employers to offer subsidized or pre-tax transit benefits, parking cash-out, and/or other incentives are likely to have a greater impact than those focused simply on providing information and coordination services. Transit agencies are typically key partners in making transit benefits easily available to employers and employees.

Magnitude and Timing of GHG Reductions

The impacts of worksite-based TDM have generally been modest although not negligible. One review of the literature on commute-focused TDM programs concluded that an overall *areawide* reduction in SOV work trip mode share on the order of 5 percent may be realistic, which translates into net regional VMT impacts of around 1 percent (EEA and Cambridge Systematics, 1999). The U.S. EPA evaluated the effectiveness of the Best Workplaces for Commuters (BWC) program, a program to encourage businesses to offer travel alternatives to their employees. EPA's study estimated that a comprehensive program of employer benefits, including financial incentives, services, and informational campaigns, reduces SOV mode share at the worksite by at least 15 percent (Herzog et al., 2004). A recent report for U.S. DOE (EEA, 2008) estimated that if it reached the entire U.S. metropolitan workforce, a Best Workplaces for Commuters-type program could reduce total nationwide VMT by 0.2 to 1.1 percent, resulting in a reduction of 1.6 to 8.6 mmt CO_2e annually.

The *Moving Cooler* study estimated that a nationwide voluntary outreach program targeted at employers, along with provision of regional support services, could reduce emissions by 6 mmt CO_2e in 2030, while a program that included trip reduction requirements for employers with at least 50 employees (coupled with regional support services) could reduce GHG by 14 mmt (Cambridge Systematics, 2009). These estimates bracket the higher end of the DOE estimate cited above.

Demand management programs can be implemented in a short period (one to two years to develop the administrative and institutional infrastructure), with maximum benefits being realized over the course of a few years with aggressive implementation. Factors such as higher fuel prices could increase the future effectiveness of demand management programs. Commuter demand management strategies overlap with some of the strategies discussed elsewhere in this section (e.g., ridesharing, telecommuting, compressed work week) and therefore the benefits of these strategies are not additive.

Cost-Effectiveness

The costs of demand management strategies include administrative costs to coordinate programs, which will be borne by employers and local or regional agencies; as well as capital costs for telecommuting equipment, vans, etc. Many demand management programs also involve transfer payments, such as transit fare subsidies provided by an employer or regional agency, or additional revenue gathered through parking charges, which may benefit or impact different people in different ways. The FY 2008 budget for the Metropolitan Washington Council of Governments' (MWCOG) regional Commuter Connections program was approximately $5 million, of which the largest expenses were $2.2 million for marketing and $1.0 million for employer outreach; other expenses included ridematching coordination and technical assistance ($0.6 million), a guaranteed ride home program ($0.5 million), a telework program, information kiosks, and evaluation. Other major State and regional TDM programs typically employ five to 10 full-time staff equivalents, in addition to program expenses (Cambridge Systematics for Utah DOT, unpublished data). A 2002 review of the Federal Congestion Mitigation and Air Quality Improvement (CMAQ) Program, which is a common source of funding for trip reduction programs, identified annual costs ranging from $170,000 to $3.5 million per year for eight regional TDM outreach and promotion programs. Costs ranged from $20 million to $376 million per year for regional employer trip reduction requirements such as California's Regulation XV, including private-sector costs (TRB, 2002).

Subsidies or incentives for alternative modes represent a transfer payment rather than a net social cost, but nonetheless represent a public-sector expense. A regionwide program of transit subsidies of $30 per month, reaching 10 percent of the workforce, might incur a public-sector cost on the order of $30 million annually for a metropolitan area with a population of two million.

Cost-effectiveness estimates for employer TDM programs have varied widely, depending upon which costs are included and which types of programs are evaluated. Studies that only include public-sector program costs (and not private costs or transit subsidies) have produced the most favorable cost-effectiveness estimates. The *Moving Cooler* study estimated a direct cost-effectiveness of less than $40 per ton for mandatory trip reduction requirements coupled with regional support services, or a savings of nearly -$1,000 per tonne when vehicle operating cost savings are considered. MWCOG, which has sponsored some of the most rigorous evaluations of its TDM programs, has estimated the cost-effectiveness of the Commuter Connections program to be $0.01 per VMT reduced or $32 per ton CO_2e (MWCOG, 2009). A calculation based on data in the 2002 CMAQ evaluation report developed a median cost-effectiveness estimate for worksite-based TDM projects of $180 per ton, considering only CMAQ program funding (i.e., public sector costs). However, there is considerable uncertainty in this estimate because it was back-calculated from cost-effectiveness data on criteria pollutant reductions, and also because individual project cost-effectiveness ranged from as low as $18 per ton to over $4,300 per ton (Cambridge Systematics, 2009).

Including private sector costs—such as costs to businesses of hiring a transportation coordinator, preparing TDM plans, etc., to comply with a TDM requirement, or hardware and software costs for telecommuting—produces much less favorable cost-effectiveness estimates. A review of studies of California's trip reduction requirements estimated a typical cost-effectiveness of $10.30 per vehicle round-trip avoided, with the vast majority of costs borne by the employer (Apogee, 1994). At the commute average of 24 miles per trip, current vehicle efficiencies, and inflating to 2008 dollars, this translates into about $1,400 per tonne of CO_2e reduced ($2,000 with projected 2030 vehicle efficiencies). A different study that reviewed 22 employer TDM programs nationwide found average costs of $2.66 per vehicle round-trip avoided (COMSIS, 1993); this provides a somewhat more favorable cost-effectiveness estimate of $350 per tonne of CO_2e reduced for current vehicles, or $570 per tonne for 2030 vehicle efficiencies.

Feasibility

The primary barriers to worksite trip reduction are 1) developing and adopting programs that are both politically acceptable and effective; 2) ensuring that information and incentives reach the level of the individual traveler; and 3) factors such as transit availability, work schedules, personal preferences, etc., that make it difficult for individuals to switch modes. Requirements-based strategies such as trip reduction ordinances generally result in a broader base of employers being reached than voluntary and incentive-based demand management strategies, but are politically more difficult to implement. States and local jurisdictions that have adopted trip reduction requirements have typically not assessed penalties for failing to meet targets, although they may penalize employers or property managers for failing to implement an approved plan. This represents a compromise of program effectiveness in order to achieve political acceptability.

Reaching the majority of commuters requires a concerted outreach effort by a State, regional, or local agency, as well as the cooperation of businesses, schools, and other local stakeholders. The extent to which individuals are willing to shift modes will be affected by other factors such as fuel prices and the quality of alternatives provided. The effectiveness of trip reduction measures will therefore depend in part upon future land use patterns, transit investments, and/or pricing policies that support the use of alternative travel modes.

Telework

Definition

Teleworking, also known as telecommuting, is the practice of working from a location other than the regular workplace and using modern telecommunications and computer technology to bridge the resulting distance. In the U.S., the majority of teleworkers work from their homes, while a much smaller number of individuals work from telecenters—smaller offices in closer proximity to the employee's home with direct communications access to the regular workplace (U.S. EPA, 2005).

Telework

Benefits: **Low-Moderate**: 10-13 mmt CO_2e in 2030

Direct Costs: **High**: $1,200-$2,300 per tonne

- Likely to decline in future

Net Included Costs: **Moderate**: $180 per tonne

Confidence in Estimates: **High**

- For benefits only – costs uncertain

Key Cobenefits and Impacts: **Positive**

- Mobility/quality of life benefits for workers (as long as telework is voluntary)

Feasibility: **High**

- Generally supported by private-sector trends

Key Policy Options:

- Employer outreach/technical support programs, tax incentives

Estimates of the proportion of U.S. workers who telework on a regular basis have varied, but this number has clearly been rising substantially as the technology to support teleworking has advanced and fuel prices have risen. According to one recent national survey, the number of employees in the U.S. (i.e., those working for a company) who teleworked at least once a month has more than doubled since 2001, rising from about 8 million in 2001 to 17 million in 2008. Including self-employed and contract workers, this figure has risen from 17 million in 2001 to 34 million in 2008. Of the employee teleworkers, 72 percent – a total of 24.2 million Americans—worked remotely at least once a week in 2008 (WorldatWork, 2009). This figure represents about 18 percent of the employed American workforce. The 2008 State of the Commute survey in the Metropolitan Washington, D.C. region estimated that 19 percent of regional employed workers teleworked at least occasionally, of which 56 percent teleworked at least once a week. Data from King County, Washington suggest that as of 2007, between 1.7 and 4.3 percent of commute trips on an average workday (varying by geographic area) were eliminated by telework, which implies a telework share of between 6 and 14 percent of workers at an average of 1.5 days per week (Washington State DOT, unpublished data). This again represents roughly a doubling since 2000, consistent with the WorldatWork survey, although with a somewhat lower proportion of workers teleworking.[33]

Employers may adopt either formal or informal policies to support telework. Technology investment may be required to support file transfer, home Internet and voice connectivity, and adequate hardware and software for employees, although some employers may work at home occasionally without the need for any additional infrastructure. The growth of telework has primarily been driven by the private sector, although Federal and State government agencies have led the adoption of telework policies.

Magnitude and Timing of GHG Reductions

Employees who telework typically see a considerable decrease in daily VMT as a result of eliminating commute trips. However, evidence suggests that some of this decrease is offset through a "rebound effect." This is because workers may make trips from home on their telework day (e.g., shopping, school drop-off) that were previously chained with their work trip. One review finds a lack of conclusive evidence on the magnitude of this effect, but estimates it to be about six miles per day (Kitou and Horvath, 2003), which would represent about one-quarter of the average worker's round-trip commute distance. Also, VMT reductions may also be offset if teleworkers choose to live farther from their worksite, or continue working in a remote relationship if the employer relocates. Research in the U.K. has found that telework is quite likely to cause individuals to choose a location farther from their employer's premises when moving (Lyons and Hickford, 1998). In general, telework favors more dispersed settlement patterns as well as irregular travel behavior, both of which work to the disadvantage of public transit (Garies and Kordey, 1999). Finally, telework energy and GHG reductions may also be partially offset by

[33] The proportion of workers teleworking is likely to vary by region depending upon the types of jobs and the mix of employers in the region.

increased home energy use; one study suggests that this may represent 11 to 25 percent of the travel energy savings (Handy and Mokhtarian, 1995).

Considering daily "rebound" travel but not considering broader relocation effects, VMT and emission reductions in 2008 attributable to current levels of teleworking by employed workers are estimated to be approximately 28.9 billion VMT and 10 to 13 mmt CO_2e.[34] Telework has the potential to grow further and therefore generate additional GHG reductions. An examination of national survey data as well as surveys in Phoenix, Arizona and metropolitan Washington, D.C. suggests that telework has the potential to approximately double compared to current levels.[35] If this were the case, the potential GHG benefits from additional teleworking would be about 10 to 13 mmt CO_2e in 2030.

While the growth of telework has primarily been the result a result of private sector initiative, a few public sector programs seem to have had some effect on encouraging private sector telecommuting adoption. One recent study in metropolitan Washington, D.C. estimated that telework in the region reduced CO_2 emissions by about 0.5 mmt in 2008, of which about 10 percent could be directly attributed to the Maryland and Virginia Telework program (MWCOG, 2009).

Cost-Effectiveness

The cost of teleworking to employers and employees typically is not negligible. Employers must determine which employees are eligible to telework; provide additional training and technical support for teleworking employees and their managers; provide or share the cost of purchasing computer equipment, communications equipment, and software for teleworking employees; and, in some cases, set up telecenters, or satellite offices for teleworkers' use (U.S. EPA, 1992). According to a recent Federal study that surveyed 18 agencies, the total annual cost of teleworking ranges from $310 to $5,420 per

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[34] This estimate assumes a telecommuting rate of between 12 and 15 percent of employed workers, an average frequency of 1.5 days per week (Cambridge Systematics, 2007; MWCOG, 2008), an average round-trip length of 25 miles, a 75 percent prior SOV mode share, a 25 percent rebound effect, and an employed workforce of 134 million (2007 Bureau of Labor Statistics data).

[35] A 2006 study in Phoenix found that 31 percent of employers currently offer telework options to their employees; among the remaining 69 percent who do not, 37 percent would consider implementing a telework program in the future (WestGroup, 2006). Optimistically assuming that all employers who might consider doing so would actually do so, this would represent an increase from current teleworking levels of 120 percent. The metropolitan Washington State of the Commute survey found that 37 percent of employed nonteleworking respondents said that it would be possible for them to telework at least occasionally; over three-quarters said they would be interested in doing so. These interested respondents represent about 24 percent of all commuters (MWCOG, 2008). Similar to the Phoenix results, this represents a 126 percent increase in teleworking compared to current levels. The WorldatWork survey found that 38 percent of nonteleworkers claimed that at least part of their job could be done from home, and 50 percent rated a high interest in doing so, for a net of 19 percent of nonteleworkers or 16 percent of all employed commuters—slightly less than a doubling.

employee, with a median cost of $1,088 per teleworker and an average cost of $1,920 per teleworker (GSA, 2006). With an estimated 16 to 20 million teleworkers in 2008 consistent with the benefit estimates provided above, this translates into a cost-effectiveness of about $2,300 per tonne CO_2e reduced. In the *Moving Cooler* study, a set of employer TDM strategies that included telecommuting was estimated to cost $1,200 per ton (averaged over the 2010-2050 period) considering only direct costs (including telecommunications equipment and services), or $180 per tonne including vehicle operating cost savings to commuters.

It is likely that teleworking costs will continue to decrease in the future due to technological improvements and the ubiquitous adoption of broadband technology; however, projections of future telework costs could not be identified.

Cobenefits

A variety of cobenefits have been associated with telework, including enhanced worker productivity and morale, improved employee attraction and retention, and reduced overhead expenses (U.S. EPA, 1992; U.S. EPA, 2005; U.S. Congress, 1994). Telework can be considered a mobility enhancement, in the sense that workers have the option to perform activities without incurring the time and cost of travel. To an extent, with handheld devices and wireless-enabled facilities and vehicles, telework can be conducted on trains and in vanpools—thereby enhancing the productivity of travel. Teleworking may contribute to national security by enhancing the ability to operate during emergencies (telework.gov, 2008).

Feasibility

While telework has not yet reached its full potential, a number of barriers will ultimately limit the growth of teleworking. For example:

- Not all jobs are suitable for telework—many require face-to-face communication with clients or co-workers and would therefore be difficult to perform from home or a telecenter (U.S. EPA, 1992; U.S. EPA, 2005). The surveys cited above suggest that about 35 to 40 percent of jobs not currently offered a telework option may be suitable for teleworking.

- For a number of reasons, some employers remain reluctant to offer employees the option of teleworking. Managers, for example, have expressed concerns over whether they would be able to effectively supervise work that is done remotely. Concern over information and data security has also made some employers hesitant to allow employees to telework (GAO, 2001; telework.gov, 2008).

- The additional cost of working from home may be prohibitive for some individuals or employers.

- Some individuals may not be interested in working from home. The surveys cited above, as well as other evidence, suggest that between half and three-quarters of all workers offered the option of telecommuting (and whose job is amenable to it) would be interested in doing so.

Some government agencies have instituted outreach programs, technical assistance, or incentives (such as tax credits or recognition) to encourage and assist private businesses in adopting telework. Examples include Oregon's business energy tax credit (which includes tax credits for telecommuting equipment), the Denver Regional Council of Governments' RideArrangers program, and the Maryland and Virginia Telework program. The EPA's Best Workplaces for Commuters program included telework as one of three "primary" strategies that could be used to achieve certification under the program. The impact of public-sector programs on telework appears to be quite modest, however. For example, the 2007 State of the Commute survey in metropolitan Washington, D.C. found that only 9 percent of telecommuters gained information about telecommuting through a regional program or advertising, compared to 55 percent through their employer and 36 percent on their own or through word of mouth (MWCOG, 2008). The office of Personnel Management has initiated actions to increase teleworking by Federal employees, as only about 5 percent currently telework (Orenstein, 2009).

Compressed Work Week

Definition

Compressed work weeks refers to a scheduling system whereby a regularly scheduled number of hours are worked in a shortened span of time. Often, compressed work weeks refer to 40 hours worked over the course of only four days (4/40) or 80 hours worked over the course of nine days (9/80). Under a compressed work week, each day worked is often longer than a standard 9:00 a.m. to 5:00 p.m. schedule. The 4/40 and 9/80 schedules are among the most common forms of compressed work weeks, and they give employees one day off every week or every other week, respectively. Compressed work weeks have been applied successfully in the commercial, public, and manufacturing sectors for many years (U.S. EPA, 1992). With recent energy cost concerns some agencies and companies have expressed renewed interest in compressed work weeks; for example, in August 2008 the Utah State government implemented a mandatory four-day workweek.

Compressed Work Week

Benefits: **Low**: 3-7 mmt CO_2e in 2030

- Low estimate = government 4-day workweek; high estimate includes doubling of private sector levels

Direct Costs: **Low**: Minimal

- Potential government cost savings from mandatory 4-day week

Net Included Costs: Not estimated

Confidence in Estimates: **Moderate**

- Magnitude of future private sector adoption uncertain

Key Cobenefits and Impacts: **Positive/Mixed**

- Mobility/quality of life benefits if voluntary; potential disbenefits if mandatory

Feasibility: **Moderate**

- Widespread acceptance unclear

Key Policy Options:

- Government "lead by example"
- Tax incentives for private sector adoption

Magnitude and Timing of GHG Reductions

As long as employees drive less on their days off than they otherwise would on their normal commute, compressed work weeks will result in GHG reductions. One study found that workers on 4/40 schedules drove, on average, 20 fewer miles each week than did employees on standard schedules, while employees on 9/80 schedules drove 13 fewer miles (CARB, 1995). Another study reported that employees who had adopted compressed work weeks reduced their total commute VMT by roughly 15 percent (U.S. EPA, 1992). Using a U.S. average commute distance of 24 miles round-trip (from the 2001 National Household Travel Survey) and a "rebound effect" representing day-off travel of 25 percent similar to telecommuting, the average VMT reduced per worker who formerly drove would be 18 miles per week for a 4/40 schedule or 9 miles per week for a 9/80 schedule.

Limited data is available on either the extent of current compressed work week participation or the potential for expanded participation. Surveys in the Phoenix, Arizona metropolitan area (which has a trip reduction ordinance in place) have found that 8 percent of workers work a 4/40 week and 2 percent a 9/80 week (Valley Metro, unpublished data). Monitoring conducted for the Washington State Commute Trip Reduction law in different parts of King County (Seattle and suburbs) show that between 1.6 and 3.1 percent of commute trips were avoided on any given day of the week as a result of workers working a compressed work week; this figure has changed little since the mid-1990s (Washington State DOT, unpublished data). Since 10 percent of workers working a 4/40 week would result in an average daily reduction of 2 percent of all commute trips, this data appears to be roughly consistent with the Phoenix data. If the Phoenix estimates of current participation are assumed, along with the weekly VMT reductions shown above and a prior SOV mode share of 75 percent, it is estimated that current use of the compressed work week reduced nationwide VMT by 7.0 billion and GHG emissions by 3.1 mmt CO_2e in 2006.[36]

While compressed schedules could in theory be implemented very quickly, the extent to which compressed schedules might be further adopted—and the policy mechanisms or incentives for bringing this about—have received little study. Currently it is estimated that between 33 and 44 percent of private employers offer compressed work weeks.[37] If this amount were doubled and employees participated at the same rate, 14.0 billion VMT would be reduced each year leading to a greenhouse gas reduction of 4.4 mmt CO_2e in 2030. Compressed work weeks may be easier to implement in the public sector, which represents 14 percent of employment nationwide. If 75 percent of all government employees were required to take a 4/40 workweek, the resulting reduction would be 9.5 billion VMT annually or 3.0 mmt CO_2e in 2030. There may be a combined upper limit to

[36]This may be an overestimate, if companies in Phoenix and King County were more likely to implement compressed work weeks due to trip reduction requirements.

[37]Based on survey data from Mellon Financial Corporation (2003) and Society for Human Resource Management (2005), as cited in Canadian Telework Association (2009).

the number of employees that can either take advantage of a compressed work week or telework.

Cost-Effectiveness

The cost of implementing compressed work weeks to employers is typically minimal. Program development and administration typically make up the largest portion of the total cost. Compressed work weeks may also lead to increased facility and energy costs if the workplace remains open over longer hours (U.S. EPA, 1992; U.S. EPA, 1998; VTPI, 2008), but may lead to decreased costs if an agency-or company-wide policy is implemented that allows facilities to close entirely on certain days.

Cobenefits

Offering the option of a compressed work week can provide employees more flexibility in scheduling work and personal commitments. This can lead to increased job satisfaction, reduced stress, shorter commute time, and more free time on weekdays for employees. Employees may use this time to become more engaged in their families and communities, leading to stronger family support and a deeper level of civic engagement. However, not all employees will prefer longer work days or have compatible personal schedules. Therefore, if compressed work weeks are made mandatory, some employees are likely to be made better off while others are worse off.

Compressed work week schedules can support mobility objectives by relieving traffic congestion during peak periods, since participating employees work longer hours than a traditional 9 to 5 schedule. For example, peak-hour commuters saved an average of 1.08 minutes in travel time on certain roadways after one large employer in the area implemented a 9/80 schedule for 260 of its employees (Kelley, 2006).

Feasibility

While some companies have successfully applied compressed work weeks for many years, there may be barriers to further adoption of compressed work weeks on both an individual and a firm level. The extent to which there is potential for additional adoption of compressed work weeks has not been widely studied, and may depend in part upon other factors such as fuel costs and congestion that drive interest in travel alternatives. Some particular barriers include:

- Increased facility and energy costs when workplaces need to operate or remain open over longer hours.

- Perception or evidence that employee productivity may decrease as a result of working longer days (U.S. EPA, 1992; U.S. EPA, 1998; VTPI, 2008).

- Incompatibility with some occupations, where employees are needed most during normal business hours and on every work day.

- Perception or evidence that offering compressed work week scheduling will not yield emissions benefits in all cases. As with telework, it is possible that reductions in commute VMT will be offset by an increase in nonwork travel on the day-off or in-home energy use; or that over the longer term, employees with compressed work weeks will choose to move farther from their place of employment (U.S. Congress, 1994; VTPI, 2008).

- Lack of interest in compressed schedules if employees do not want to work longer hours on fewer days or find it disruptive of their schedules. As a result, mandatory policies may meet greater resistance than simply providing the option of a compressed schedule.

While Federal and State government agencies could take a leadership role in promoting compressed work weeks by offering such schedules to their own employees, there has been little investigation of potential incentives for encouraging greater adoption in local government or the private sector. Some options may include leading by example (government agency adoption); outreach and promotion, such as through broader employer TDM outreach programs; and tax credits or other incentives (such as recognition programs) for businesses who adopt or allow compressed work weeks.

Flexible Work Schedules

Definition

Flexible work schedules refer to employer-facilitated alternatives to a standard 9:00 a.m. to 5:00 p.m. work schedule for commuting employees. Employees are given more discretion over when they work so that they can accommodate other obligations and/or commute during less congested off-peak periods. Typically, so long as they are working a set number of hours each day, week, or month, employees with flexible work schedules are allowed to choose the times they begin and end work each day. Often employers that offer flexible work schedules require all employees to be present in the office for pre-specified "core" hours. Historically, employees in managerial and professional occupations have been the most likely to have flexible work schedules (Beers, 2000; BLS, 2005a).

Flexible Work Schedules

Benefits: **Unknown**

Direct Costs: **Low**: Minimal implementation cost

Net Included Costs: Not estimated

Confidence in Estimates: **N/A**

- No quantitative estimates developed

Key Cobenefits and Impacts: **Positive**

- Mobility/quality of life benefits

Feasibility: **Moderate**

- Ability to implement beyond current levels unclear

Key Policy Options:

- Government "lead by example"
- Tax incentives for private sector adoption

Magnitude and Timing of GHG Reductions

The potential contribution of flexible work schedules to GHG mitigation in the transportation sector is determined by three factors: 1) the number of commuters who can adopt flexible work schedules; 2) mode shift achieved through deployment of flexible work schedule arrangements; and 3) the potential fuel savings these commuters would achieve by commuting off-peak as a result of flexible work schedule opportunities.

1. **Number of Commuters –** An estimated 27.5 percent of all full-time workers in the U.S. report having some flexibility in their work hours, down from 28.6 percent in 2001 (BLS, 2005b). Given that the types of employees who can take advantage of flexible work schedules is limited, the emissions reduction potential is also limited until more categories of employees can gain flexibility through either technologies that facilitate remote work or new and emerging industries that can accommodate flexible work schedules. In the long term, as the economy becomes more and more service-oriented and handheld telecommunications and computer devices become more powerful and prevalent, more employees will likely be able to take advantage of flexible work schedules.

2. **Modal Shift –** In some cases, offering flexible work schedules appears to have increased transit use and/or ridesharing, ostensibly because workers were better able to coordinate their schedules with transit schedules or with others for ridesharing (FHWA, 2003; U.S. EPA, 1992; VTPI, 2008a). However, sometimes flexible work schedules have led to a decrease in the use of public transit and ridesharing among employees who had flexible work schedules, as existing ridesharing arrangements and transit schedules could no longer accommodate the employees' new (e.g., perhaps earlier) schedules (FHWA, 2003; U.S. EPA, 1992; VTPI, 2008a). To minimize these impacts, employers, transit agencies, and rideshare organizations need to coordinate to attract and retain commuters with new schedules. Quantitative data on the magnitude or direction mode shift impacts of flexible work schedules is not available.

3. **Potential Fuel Savings per Commuter –** Employees who start work either earlier or later in order to avoid the worst peak period traffic congestion should experience a modest reduction in the duration of their commute trips, gasoline consumption, and GHG emissions. For example, three studies found savings of 5 to 9 minutes per trip for commuters with flexible schedules (Picado, 2000; U.S. EPA, 1998; Kelley, 2006). If the shift in trips due to flexible work schedules is significant enough to measurably affect congestion, fuel use by other commuters should be reduced as well. One study estimated that the first 3 percent reduction in peak period vehicular volume results in a 35 percent decrease in minutes of delay per vehicle per mile resulting in associated fuel savings and GHG emissions reductions (Ungemah, 2008).

Because of the uncertainty in associating delay reductions with fuel savings, as well as the uncertainty in the potential future increase in the use of flexible work schedules, an estimate of GHG reductions could not be generated for this study. Furthermore, it is possible that workplaces may see an increase in building energy consumption and therefore GHG emissions after implementing flexible work schedules, if employees are present over longer hours. The potential magnitude of this increase has not been estimated.

Cost-Effectiveness

The net cost of offering flexible work schedules to employers and the U.S. Government is minimal. The most significant cost typically incurred is the time required to develop and administer the program (U.S. EPA 1992).

Cobenefits

Flexible work schedules offer a potential host of cobenefits to employers, employees, and society as a whole. Documented benefits include reduced absenteeism and tardiness; improved employee attraction, retention and morale; lower overtime costs; and, in some cases, increased employee productivity (U.S. EPA, 1992; VTPI, 2008a). One workplace, for example, saw employee productivity increase by 3 percent and average annual sick time decrease by 3.5 days per employee after it began offering flexible work schedules (U.S. EPA, 2003).

Feasibility

Thousands of government agencies, private sector companies, and organizations already offer flexible work schedules without problems. However, there may be significant barriers to further expansion of flexible work schedules, including:

- Commitments outside of work, such as driving children to and from school, prevent a significant portion of the labor force from changing their work schedules from the standard 9 to 5 (Picado, 2000);

- Resistance by management to offer flexible work weeks also prevents widespread implementation of flexible work schedules. Workplaces may also see an increase in facility and energy costs after implementing flexible work schedules if employees are present over longer hours; and

- Incompatibility with occupations that require that work begin and end at set times, such as teaching, nursing, emergency response, and manufacturing (Beers, 2000).

While Federal and State government agencies could take a leadership role in promoting flexible work schedules by offering such schedules to their own employees, there has been little investigation of potential incentives for encouraging greater adoption of flexible schedules in local government or the private sector. Some options may include leading by example (government agency adoption); outreach and promotion, such as through broader employer TDM outreach programs; and tax credits or other incentives for businesses who adopt or allow flexible schedules.

Ridematching, Carpool, Vanpool

Definition

Ridematching, carpooling, and vanpooling—which may collectively be termed "ridesharing"—are typically commuter-oriented strategies that seek to reduce VMT by increasing vehicle occupancies for work trips. Carpooling involves formal or informal arrangements between two or more people to share a ride in a private vehicle. Vanpools generally consist of 5 to 15 people, including a volunteer driver-member, that elect to commute together in a van. Ridematching involves assisting travelers with finding suitable partners for carpooling or vanpooling through on-line databases or other mechanisms. New technologies utilizing the Internet and mobile phones are facilitating the expansion of ridesharing to nonwork trips, by allowing people to find suitable ride-sharing partners for trips that do not follow regular patterns. The concept of forming carpools on very short notice is known as "dynamic ridesharing." Guaranteed ride home (GRH) programs, which reimburse employees for the cost of a taxi ride or rental car if they need to stay late or leave early in an emergency, are an important strategy to support ridesharing.

Ridematching, Carpool, Vanpool

Benefits: **Low**: 1-5 mmt CO_2e in 2030

Direct Costs: **Moderate**: $80 per tonne (areawide rideshare matching)

- Higher for vanpools

Net Included Costs: Not estimated

Confidence in Estimates: **Low-Moderate**

Key Cobenefits and Impacts: **Positive**

- Mobility benefits through expanded commute options for workers

Feasibility: **High**

- Primary ridesharing barrier is providing adequate incentives (financial or otherwise) for commuters to participate
- Vanpooling market is limited

Key Policy Options:

- Funding for program support

Carpooling represents the second most common commuting mode in the U.S., with a mode share of 12.2 percent according to the 2000 Census. However, the majority of carpooling is informal—over 60 percent is in two-person carpools with family members (Pisarski, 2006). Vanpooling has a much lower mode share, at 0.3 percent, and is primary done only in niche markets serving relatively long-distance commuters to large employers (the average vanpool trip length according to the 2001 National Household Travel Survey was 20.4 miles, compared to 12.2 miles for all work trips). Carpooling and vanpooling both reached a peak in the late 1970s with the oil crisis, then declined after 1980 as gasoline once again became cheap and less emphasis was placed on ridesharing programs (Evans and Pratt, 2005). The 2000 carpool commute mode share represents a decline from 13.6 percent in 1990 and 19.8 percent in 1980.

Formal carpool and vanpool programs with the objective of increasing carpooling and vanpooling were implemented in the 1970s and widely studied in the 1970s and 1980s. Public sector support for these programs has varied, with more aggressive programs typically implemented in larger metropolitan areas with significant congestion problems. Regional vanpooling and ridematching programs are sometimes operated by MPOs, State DOTs, or transit agencies. Local programs may be operated by municipalities, transportation management organizations (nonprofit employer associations focused on a particular geographic area), or large employers.

Magnitude and Timing of GHG Reductions

While program-specific evaluations have been conducted more recently, some of the most comprehensive and rigorous assessments of rideshare programs were performed in the late 1970s when these programs were being implemented as an energy reduction measure. An early evaluation of over 100 Federally funded carpool demonstration projects found that approximately one out of six employees exposed to a program submitted applications for carpool assistance; of these, 16 percent were influenced to join or expand carpools as a result of carpool matching efforts – representing just under 1 percent of total areawide employment. Including others who were influenced by marketing and promotion campaigns, 2.8 percent of the areawide commuter population in six evaluated areas had formed or expanded rideshare arrangements. These impacts translated into an estimated reduction of 0.3 percent of areawide work trip VMT for carpool matching, or 1.2 percent for broader programs (Wagner, 1978). Considering that work trips are just under one-third of total VMT, this represents a reduction in areawide passenger VMT of 0.1 to 0.4 percent. A more recent literature review found that areawide ridesharing programs have led to a reduction in regional VMT ranging from 0.1 to 2.0 percent, with the authors developing a "maximum reasonable estimate" of 0.4 percent (Apogee, 1994). Considering that metropolitan VMT represents about four-fifths of total U.S. VMT, the cited range of 0.1 to 0.4 percent would translate into a nationwide reduction in GHG from automobiles of about 0.9 to 3.7 mmt CO_2e in 2030.

Vanpooling programs have been effective at reducing VMT in niche markets. At its peak in the late 1970s, about 15,000 vanpools operated in the U.S., with perhaps 10,000 operating recently. The five largest U.S. transit provider programs in 2002 had from 204 to 686 vanpools each, serving 2,400 to 7,200 average weekday passenger trips, with average vehicle loadings of 5.2 to 7.0 passengers (Evans and Pratt, 2005). Vanpooling is currently most prevalent in the Puget Sound region, where 2 percent of workers commute by vanpool, although this is in part a result of unique geographic and institutional factors, including water crossings with ferries with priority vanpool access, an extensive HOV lane system, and employer trip reduction mandate. One study estimated the theoretical market potential of vanpooling, based on the number of employees working for larger employers and commuting longer distances, to be about 5 percent (COMSIS and ITE, 1993, in Evans and Pratt, 2005).

Estimates of GHG emission benefits of vanpools must account for not only the reduction in single-occupancy VMT but also the increase in GHG emissions from van operations and the additional circuity of the trip. Furthermore, not all vanpool passengers are drawn out of single-occupant vehicles. When vanpools serve central area employment in corridors with heavy transit service, a substantial proportion of the vanpoolers may be drawn away from carpools or transit use. One study of an early program in Massachusetts found an average reduction in fuel use of 66 percent per participant (Evans and Pratt, 2005). The State of Connecticut's vanpool program registered over 3,000 commuters in 2006, 68 percent of whom are new to carpooling and transit. The State estimates that over 2.8

million passenger miles were reduced, resulting in the reduction of 1,250 tons of GHG emissions (State of Connecticut, 2007) or 0.42 tons per vanpooler. If this benefit were extrapolated to a hypothetical participation of 2 percent of the workforce in the 50 largest metropolitan areas, and netting out the current participation of 0.3 percent, the result would be 1.22 million new vanpoolers and a reduction in greenhouse gas emissions of 0.5 mmt CO_2e at current vehicle efficiencies. An alternative calculation using the same hypothetical 2 percent participation rate, combined with other generic assumptions about participation, mileage, and trips displaced, yields an estimated reduction of 1.3 mmt CO_2e.[38]

Ridesharing and vanpooling programs can be established quickly, within less than a year to develop appropriate ridematching tools and marketing/outreach materials. Successful programs should grow over time; however, maximum benefits should be realized within a few years.

Cost-Effectiveness

Ridesharing program costs consist primarily of administrative expenses along with marketing and outreach to promote the program. Results of carpool program evaluations from the 1970s found a project cost of $47 per new carpooler captured, or $0.024 per vehicle-mile reduced over the project life (Wagner, 1978), or $0.08 per mile in 2008 dollars. The 1994 literature review estimated a cost-effectiveness of $0.60 per vehicle round-trip avoided for areawide ridesharing programs (Apogee, 1994), which at an average of 12 miles per one-way trip and inflating to 2008 dollars translates into $0.04 per vehicle-mile reduced. Based on this estimate the cost-effectiveness of areawide ridesharing programs would be about $80 per ton CO_2e reduced. A net cost savings would be realized if private vehicle operating cost savings are included.[39] The administrative costs associated with rideshare matching programs are quite small compared to the costs that are required for a broadly effective marketing and outreach campaign, and are likely to have declined further with the advent of Internet technology.

Vanpool costs include purchase and operating costs for the vehicle as well as administrative expenses. Costs are offset by vehicle operating cost savings to individuals, meaning that vanpool programs can cover most, if not all, of their costs through

[38]The alternative calculation assumes an average vanpool occupancy of six persons, one-way vanpool trip length of 35 miles versus 20 miles for previous solo drivers, average mpg of 12.0 for a van versus 20.6 for a car, 75 percent prior SOV mode share, and four days per vanpooler per week. The fuel savings per occupant is about 50 percent of their daily commute fuel use (0.97 gallons per vanpooler per day).

[39]At a round-trip length of 24 miles and a cost of $0.55 per mile per current Internal Revenue Service (IRS) guidance (as of January 2009), the typical commuter could theoretically save about $13 per day (although the actual savings may be less as this includes some fixed costs such as insurance). Even at half the IRS value per mile, user cost savings are still considerably greater than the $0.04 per-mile cost estimate.

subscription fees (Winters and Cleland, no date). Some State and regional agencies have subsidized vanpools to increase viability and ridership. For example, the Denver Regional Council of Governments' FY 2009 budget includes about $500,000 for vanpool subsidies, and the Washington State DOT allocated $8.6 million to vanpool programs in the 2005-2007 biennium. A review of vanpool programs found a median operating cost of about $10 per vehicle-mile in 1995 (Winters and Cleland, no date), which translate into a cost-effectiveness of over $20,000 per tonne CO_2e reduced; including vehicle operating cost savings to former drivers would reduce this figure somewhat but not entirely.[40]

Cobenefits

Ridesharing and vanpooling can constrain schedules and lengthen commutes, which may be considered a reduction in mobility. As long as participation is voluntary, however, travelers will not be made worse off by the program (i.e., the benefit of reduced costs more than offsets the additional travel time). The typical vanpooler sacrifices 10 to 12 minutes of travel time compared to driving alone, trading time off against other attributes such as reduced travel cost and stress (Evans and Pratt, 2005).

Feasibility

One significant barrier to ridesharing and vanpooling is the inconvenience to travelers associated with identifying appropriate travel partners and undergoing longer commutes. The popularity of ridesharing and vanpooling over time has been directly related to energy prices. As gasoline becomes more expensive, travelers are more willing to trade commuting time for reduced vehicle operation. The need for flexibility in work schedules, as well as to travel to other activities outside of work, also limits the potential for ridesharing; many ridesharers only do so a limited number of days per week when they are traveling from home to work and back.

The market for vanpooling is limited to longer-distance commuters at large employers or in large employment centers; as of the early 1990s less than 8 percent of the U.S. workforce both worked for a company with at least 100 employees and lived at least 15 miles from work (COMSIS and ITE, 1993). Employer vanpools would in most cases be operated by employers with hundreds or thousands of employees at a single location.

Another barrier involves ensuring that information about programs make it to the level of the individual traveler. An aggressive, regionally coordinated marketing and outreach program is generally required in order to ensure that information and programs are

[40] The cost-effectiveness calculation assumes 2.8 billion new vanpool vehicle-miles per year (1.22 million new vanpoolers * 80 percent utilization (4 days/week) * 250 days/year operation/ 6 persons/vanpool), or $28 billion in total new vanpool operating costs. Assuming 7.3 billion annual displaced VMT by auto drivers (1.22 million new vanpoolers * 75 percent former SOV * (250 * 0.8) days/year * 40 miles/round-trip), the vehicle operating cost savings would be $4.4 billion at an average cost of $0.55 per mile, for a net cost-effectiveness of $18,800 per tonne.

targeted at a broad population of workers. Financial incentives have been found to be a significant benefit in promoting ridesharing and vanpooling. For example, the San Diego Association of Governments and Pima Association of Governments (in Tucson, Arizona) provide $400 in monthly subsidies for vanpools meeting 80 percent occupancy. Other agencies have noted that providing gas cards has been an effective incentive for new riders to join carpools or vanpools.

■ 5.6 Public Information Campaigns

Public information campaigns have been directed at affecting a number of aspects of consumer transportation behavior that influence GHG emissions. Information has been directed at affecting not only travel choices, but also driving habits, maintenance habits, and vehicle purchase decisions. Three sets of strategies are discussed in this section:

1. General mass marketing and individualized marketing campaigns, directed at affecting travel behavior;
2. Provision of information directed at affecting vehicle purchase decisions;[41] and
3. "Eco-driving" efforts to teach efficient driving and vehicle maintenance practices.

Consumers make large and small decisions regarding transportation every day based on millions of messages they absorb from a variety of sources. These sources provide information that is largely biased and intended to sway opinion and behavior toward specific modes and products. Providing the public with unbiased, factual information on the full cost of driving and flying, as well as providing comprehensive information about the range of travel alternatives available and how to use them, may affect transportation choices and behavior in a way that reduces greenhouse gas emissions. For example, by raising public awareness of the full costs of transportation choices (not just the upfront costs associated with retail fuel prices or tickets for driving or flying, respectively), the public may elect to avoid trips or use alternate modes. In addition, people who are used to traveling by car may be unfamiliar with the alternatives available to them; for example, they may not be familiar with how to ride transit, or may not realize that they could reach their destination just as quickly on a bicycle as by driving. Finally, people may be unaware that they could easily save fuel by driving more smoothly or keeping their vehicle maintained properly.

Better informing the public of the costs of their choices, as well as the full range of alternatives available and how to use them, may influence consumer behavior in a way that leads to emissions reductions. Examples of how behavior may be affected include traveling by alternative modes; "chaining" trips together; forgoing trips altogether or shifting them out of highly congested periods; purchasing more efficient vehicles; and driving more efficiently.

[41] Vehicle purchase is not technically a "travel activity" strategy but is included in this section for convenience.

Information on Travel Choices

Information on Travel Choices
Benefits: **Low**: 6 to 9 mmt CO_2e in 2030
Direct Costs: **Moderate-High**: \$90 to \$270 per tonne
Net Included Costs: **Not estimated**
Confidence in Estimates: **Low**
• Benefits of mass marketing difficult to quantify; individualized marketing still in demonstration stages
Key Cobenefits and Impacts: **Positive**
• Improved awareness and understanding of travel options
Feasibility: **High**
• Primary barrier to mass marketing is funding
• Broad-scale acceptance of individualized marketing unproven
Key Policy Options:
• Larger-scale demonstration programs for individualized marketing

Description

Two programs—*It All Adds Up to Cleaner Air* and *Best Workplaces for Commuters*—are directed at affecting travel choices to reduce fuel consumption and emissions. *It All Adds Up to Cleaner Air* emphasizes simple and convenient actions that consumers can take. The *Best Workplaces for Commuters* program (discussed in Section 5.5, Commute Travel Reduction) provides public recognition for employers that offer their employees commuter-related benefits. Public information has also been an important component of local and regional commuter TDM programs. Mass marketing campaigns have been used to inform commuters about the availability of travel alternatives and incentives and direct them to more specific information on options for their commute.

A new form of public information campaign, known as individualized marketing, shows promise for reducing GHG emissions through travel behavior changes. Individualized marketing programs utilize survey tools to identify individuals who are open to alternative modes of transportation, and provide individualized contact and customized information on modes favored by targeted respondents. The concept of individualized marketing was first developed and tested in Europe and Australia. U.S. pilot projects have been undertaken in selected neighborhoods in a number of cities including Bellingham, Washington; Cambridge, Massachusetts; Cleveland, Ohio; Durham, North Carolina; Portland, Oregon; and Sacramento, California (FTA, 2006; ACT, 2008).

Magnitude and Timing of Greenhouse Gas Reductions

Public information campaigns directed at travel behavior have had mixed success, with individualized marketing showing somewhat greater promise than mass marketing as a travel and GHG reduction strategy. The benefits of mass marketing programs are difficult to quantify, but appear to be modest. Two factors must be determined – how many people recalled the message of the campaign; and of those, how many switched changed their travel behavior as a result. Public information campaigns that have focused solely on better informing the public of the environmental costs of their transportation choices (such as driving alone) have not always produced noticeable behavioral changes (Tordella, 2007). Providing motorists in The Netherlands with information on the environmental and economic costs of driving had no effect on their travel behavior over an eight-week period, although it was found to have increased their general environmental awareness (Tertoolen et al., 1998). Program staff have been unable to document the benefits of *It All Adds Up to Cleaner Air*, in part because of the difficulty of separating the campaign's effects from the many other factors that affect people's travel behavior. A public information campaign in Atlanta in 1998, designed to raise awareness of air pollution and its health consequences and decrease the amount of driving on ozone alert days, was found to significantly reduce VMT on these days (Henry and Gordon, 2003), although it is not clear that such short-term changes could be sustained into longer-term behavior changes that reduce GHG.

At least one study has examined the impact of mass marketing campaigns specifically on commuter behavior. An evaluation of the Commuter Connections program in the Washington, D.C. region used a regional survey to examine the impacts three public information strategies – a mass marketing campaign, information kiosks, and a Commute Operations Center to provide information and other tools (ridematch lists) for alternative modes (MWCOG, 2009). The Mass Marketing campaign was estimated to result in 35 percent recall and 0.1 percent mode shift for those who recalled the message (this mode shift compares with a 1 percent mode shift in an earlier 2004 survey). The survey further found that only 19 percent of shifters permanently shifted modes. The result was an estimated regional emissions reduction of 8,200 tons of CO_2 in 2008. InfoExpress kiosks in the District of Columbia and Northern Virginia were estimated to reduce CO_2 emissions by 6,200 tons, and the Commute Operations Center was estimated to reduce CO_2 emissions by 83,000 tons. Despite the uncertainty in survey results it probably can be concluded that the annual regional impacts of all information strategies were on the order of 0.1 mmt CO_2e. If this impact were extrapolated to the 50 largest metropolitan areas in the U.S. (representing just over half the country's population), the benefits would be approximately 3.0 mmt CO_2e annually.

Individualized marketing shows potentially greater promise as a travel and GHG reduction strategy. Pilot individualized marketing programs that target both work and nonwork travel have reported VMT reductions in the U.S. of 2 to 8 percent for targeted populations (FTA, 2006), and GHG reductions should correspond. The net effect across the entire population will depend upon the proportion of the population that is: 1) willing to participate in individualized marketing programs, and 2) willing and able to make meaningful and permanent travel behavior shifts. No evidence is currently available on these parameters. However, if individualized marketing campaigns could effect a 5 percent VMT reduction in between 5 and 10 percent of the U.S. population, the net effect would be an 0.25 to 0.5 percent reduction in VMT or 3 to 6 mmt CO_2e in 2030. Combining the individualized marketing and mass marketing impacts provides an overall estimate of 6 to 9 mmt CO_2e annually.

As noted, public information campaigns can be implemented in a short timeframe but must be sustained over time in order to have a lasting impact. There impact is likely to be greater under conditions of higher fuel prices, where travelers have more of an incentive to change their behavior in a way that reduced fuel consumption and emissions.

Cost-Effectiveness

The costs of public information campaigns can be modest in relation to investment in transportation infrastructure or services. Costs for broadcast advertising are not insignificant, however, and costs for individualized marketing may also be significant if expanded to a broad population base. Campaign developers must know their audience well enough so that they can deliver a message that will be understood and that is capable of impacting behavior, which requires a substantial time investment. The FY 2008 budget for MWCOG's Commuter Connections program included $2.2 million for mass marketing, nearly half the total program budget. With an estimated emissions reduction of 8,200 tons, this works out to a cost-effectiveness of about $270 per ton. Other major metropolitan areas have invested similar amounts in marketing—for example, the Atlanta Regional Commission budgeted $2.6 million in FY 2009 for "advertising and public relations" to support its regional TDM program.

For individualized marketing campaigns, one source describing Portland's SmartTrips program suggests that a typical 20,000-household program costs $570,000, or $29 per household (Pedestrian and Bicycle Information Center, no date). An individualized marketing program in Seattle cost $10-19 per participant (ACT, 2008). Assuming a program cost of $15 per participant, a VMT reduction of 5 percent per participant, and 7,500 annual per-capita VMT,[42] cost-effectiveness can be estimated to be approximately $0.03 per VMT reduced or $90 per ton CO_2e.

Cobenefits

Public information campaigns will provide benefits to travelers and consumers by helping them make more informed choices, which should increase welfare. Individualized marketing helps travelers better understand the travel options available to them, meaning that it may help improve mobility as well as reducing the costs of travel for individuals. Documented air quality benefits from regional mass marketing campaigns include a reduction of 0.032 tons per day NO_x and 0.017 tons per day VOC in the Washington, D.C. region (MWCOG, 2009).

Feasibility

Public information campaigns have been implemented in the past and do not face any significant feasibility constraints. For individualized marketing campaigns, institutional capability (as well as potential customer interest) to implement this type of program on a broad scale, reaching a large segment of the population, has not yet been determined.

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[42] A number lower than the national average of about 10,000 VMT per capita was selected to reflect that these programs have been conducted in more densely populated urban neighborhoods which are likely to exhibit lower VMT per capita.

Information on Vehicle Purchase

Description

Information on Vehicle Purchase

Benefits: **Low**: 2-5 mmt CO_2e in 2030

- Based on quantified benefits of existing campaigns

Costs: Not estimated

Confidence in Estimates: **Moderate**

Key Cobenefits and Impacts: **Positive**

- Improved information for consumers resulting in potential cost savings

Feasibility: **High**

Key Policy Options:

- Funding for education/outreach programs

The U.S. EPA and Department of Energy (DOE) have spearheaded a number of the Federal government initiatives aimed at influencing consumer decision-making behavior related to consumer products, including vehicles (EEA, 2008). Transportation-focused programs include:

- *SmartWay*, a voluntary collaboration between EPA and the freight industry to reduce greenhouse gases and air pollution by conferring a special designation to vehicles that perform well;
- EPA's Green Vehicle Guide, first launched in 2001 to give consumers information about the environmental performance of different vehicles using a rating system; and
- The DOE's Web site, www.fueleconomy.gov, a similar effort that provides visitors with readily accessible, nontechnical information on fuel economy ratings and fuel economics, estimated annual petroleum consumption, GHG emissions data, air pollution scores, and gas-saving tips for vehicles 1985 through the present. The site also contains a variety of fact sheets explaining why fuel economy is important.

Magnitude and Timing of Greenhouse Gas Reductions

Public information campaigns appear to have had some success at reducing fuel consumption. Fuel economy data has, in the past, had more of an impact on behavior than information on other environmental concerns (ORNL, 2003). DOE credits www.fueleconomy.gov with inspiring behavior changes that reduced U.S. petroleum consumption by about 200 million gallons in 2006, which would have resulted in a 2 mmt reduction in CO_2 emissions for the year (DOE, 2007). EPA has also quantified the success of its *SmartWay* program. Nationally, over 2500 partners, including ones with large trucking operations like Wal-Mart Stores and Tyson Foods, have joined the *SmartWay* program. According to EPA, since 2004, SmartWay Partners have saved a total of 16 million metric tons of CO_2, 1.4 billion gallons of diesel fuel, and $3.5 billion in fuel costs. Most public information campaigns can likely be implemented within one or two years or less, but must be sustained over time to have a lasting impact. Programs that affect vehicle purchases will have an impact that starts low but grows over time, with most benefits being realized within a 15- to 20-year timeframe as the vehicle fleet turns over.

Cost-Effectiveness

The costs of public information campaigns can vary widely, but can be modest in comparison to emissions reduction strategies that require investment in infrastructure or services. Costs are dependent on how the information is disseminated. If the information can be distributed on a web site that has already been established (such as www.fueleconomy.gov), then overall costs will be relatively low. Broadcast advertising is more expensive. Establishing a channel to deliver information to the public on the real costs of travel is useful for delivering new or different messages to the same audience later. Once a campaign becomes known and establishes trust with the public, then it can be adapted and enhanced with marginal effort. Programs such as *SmartWay* and *Best Workplaces for Commuters* have relied on direct outreach to target populations (shippers, employers) which requires somewhat more significant program resources, primarily to support the staff time required to conduct the targeted outreach.

Cobenefits

Public information campaigns will provide benefits to travelers and consumers by helping them make more informed choices, which should increase welfare and reduce transportation-related costs. EPA's SmartWay program has been credited with saving truckers money and reducing fuel consumption and air pollution. EPA estimates that in 2004–2005, *SmartWay* projects saved 298 million gallons of fuel per year, saving truckers $850 million in fuel costs, and reduced NO_x emissions by 25,000 tons and PM by 841 tons.

Feasibility

Public information campaigns have been implemented in the past and do not face any significant feasibility constraints.

Driver Education/Eco-Driving

Definition

Eco-driving programs are directed at increasing vehicle fuel efficiency by affecting both driver behavior and vehicle maintenance.

Driver Education/Eco-Driving

Benefits: **Moderate-High**: 18-94 mmt CO_2e in 2030

Direct Costs: **Not estimated**

Net Included Costs: **Net Savings:** $0 to -$230 per tonne

Confidence in Estimates: **Low-Moderate**

- Benefits will depend upon widespread and sustained implementation over time

Key Cobenefits and Impacts: **Positive**

- Reduction in air pollutants and vehicle operating costs

Feasibility: **Moderate**

- Unproven ability to implement widespread education/training campaigns

Key Policy Options:

- Requirements for in-vehicle feedback instrumentation and revisions to driver education curricula
- Funding for education programs

- **Driver Behavior –** Driver training programs are used to teach new or experienced drivers how to alter their driving behavior to increase their fuel efficiency and thus reduce greenhouse gas emissions. This includes measures such as avoiding rapid accelerations and braking, avoiding speeding, proper gear shifting, and the usage of cruise control. In-vehicle instrumentation to provide real-time feedback on fuel economy can be used as a stand-alone eco-driving strategy, or in combination with driver training programs.
- **Vehicle Maintenance and Equipment –** Public awareness campaigns or other methods can be used to teach drivers how to properly maintain and equip their vehicle to achieve the greatest fuel efficiency and to lower greenhouse gas emissions. Such measures include proper tire inflation, lower rolling resistance tires, and lower viscosity motor oil.

Eco-driving programs are becoming common in Europe, with some of the most extensive programs being implemented in the Netherlands due to their lack of compliance with European air quality standards. The Netherlands program is called the New Driving Campaign, and was started in 2000 by the Ministry of Transport, Environment, and Economic Affairs. It aims to increase fuel efficiency through driver training and energy usage labels for tires and vehicles (ICF, 2008). In Sweden, eco-driver training became mandatory in driver education program for new drivers starting in 2006, and for taxi-drivers' licenses in 2007. There are no known mandatory eco-driving training programs in the U.S., although there are some public education campaigns such as www.DriveSmarterChallenge.org, which is being led and evaluated by the Alliance to Save Energy. Also, the Michigan Department of Environmental Quality (DEQ) is currently evaluating a proposed eco-driving program.

Driving practices can also have an impact on truck fuel economy. Even highly experienced drivers can enhance fuel economy using techniques such as cruise control, coasting whenever possible, limiting use of cab accessories, smooth and gradual acceleration, progressive shifting (up shifting at the lowest rpm possible), reducing maximum freeway speeds, and limiting truck idling and stops. Driver training can reduce fuel consumption by 5 percent or more, saving more than $1,200 in fuel costs and eliminating about eight metric tons of greenhouse gas emissions per truck each year. Driver training may generate larger efficiency gains for vehicles in urban service, where shifting practices have more influence on fuel economy (U.S. EPA, 2004).

Magnitude and Timing of GHG Reduction

Two U.S. studies have been performed comparing fuel consumption under standard versus more aggressive driving cycles. One, by the U.S. EPA, found that aggressive driving can reduce gas mileage by 33 percent at highway speeds. Another, by the California Air Resources Board, found an increase in fuel consumption of 5 to 14 percent for a more aggressive urban driving cycle (IEA, 2005). However, these studies did not assess the actual effects of eco-driving campaigns on driver behavior.

Eco-driving campaigns have been directly evaluated in Europe. Short-term savings have been found to be higher than long-term savings, since effects of education wear off over time. An eco-driving course in Europe found that reductions in fuel consumption of 15–25 percent were quite possible for drivers in the first year. However, this improvement typically decreases as old driving habits return, so subsequent years had an average of 6.3 percent reduction in fuel consumption (Ecodrive, 2007). Evaluation of the Netherlands program found a 10 percent overall long-term reduction from the program (Lucke and Hennig, 2007). Another European source suggests an overall potential reduction from cars, buses, and trucks of 5 to 15 percent. This source suggests a reduction of 5 percent over the long term only through education programs, or 5 percent only with in-car instrumentation to provide driver feedback; combined effects will be greater (Crist, 2008). Results from European studies may not be directly transferable to the U.S., however. Since "upshifting as soon as possible" is one eco-driving strategy, U.S. benefits are likely to be lower than European benefits because of the greater prevalence of automatic transmissions in the U.S. The effects of other factors, such as different engine technologies, vehicle weights, and driving conditions, have not been investigated in such a way as to inform how European study results could be adjusted to U.S. conditions.

Regarding the benefits of maintenance and equipment practices, the U.S. EPA and DOE cite fuel savings of 4 percent for keeping an engine properly tuned, 3 percent for keeping tires properly inflated, and 1 to 2 percent for using the recommended grade of motor oil (DOE and EPA, 2009). IEA (2005) estimates that properly inflating tires could reduce total U.S. fuel consumption from road transport use by 1.6 percent, accounting for program implementation effectiveness.

The IEA source suggests a "consensus estimate" of a 5 percent reduction in total on-road fuel use in the U.S., as a result of eco-driving campaigns aimed at both driving and maintenance habits (IEA, 2005). This would equate to 94 mmt CO_2e in 2030. Another national estimate of potential benefits in the U.S. suggests that eco-driver training programs could reduce GHG emissions by 11 to 53 mmt CO_2e and that public education campaigns to encourage proper vehicle maintenance could reduce emissions by 7 to 17 mmt CO_2e annually by the year 2020 (Cambridge Systematics, 2009).[43] The combined results for both programs would be a range of 18 to 70 mmt CO_2e reduced.

Eco-driving programs can begin immediately and can be modeled after current programs already in place in Europe. Depending on the methods of implementation, it may take some time to reach all drivers and gain the maximum amount of benefits. For example, if eco-driver training programs are provided only to new drivers it is possible to reach about 2 percent of the driving population each year. The benefits are proportional to the number of drivers reached and providing training to existing drivers will greatly speed the realization of benefits. While in-vehicle feedback instrumentation will increase the effectiveness of eco-driving programs (and likely provide some benefit even in the absence of such programs), the benefits will only be realized over a 15- to 20-year period as policies are adopted to require instrumentation in new vehicles, and the vehicle fleet turns over. Currently, only a few vehicles, primarily hybrids, provide in-vehicle feedback to drivers on the efficiency of their driving habits.

Cost-Effectiveness

According to one European study (Lucke and Hennig, 2007), cost-effectiveness may range from 17 to -128 euros per tonne CO_2e ($22 to $-163 per tonne) for eco-driving programs and 5 to -98 euros per tonne CO_2e ($6 to $-124 per tonne) for optimal tire pressure measures. This range is mainly a cost savings because the benefits of reduced fuel usage outweigh the costs of the programs. Another European source (Crist, 2008) concurs with this range and gives a cost savings of 69 euros per tonne CO_2e ($88 per tonne) for providing eco-driver training to new drivers and 45 euros per tonne CO_2e ($57 per tonne) by providing it to existing drivers.

The Michigan Climate Action Council and Center for Climate Strategies (2008) estimate that an eco-driver training program that reaches about 3 percent of the Michigan driving population per year will cost $93.3 million per year to implement. Including fuel savings they estimate a cost-effectiveness of -$211 per tonne CO_2e by 2020. A public information campaign to encourage proper tire inflation that reaches 1.2 percent of the Michigan driving population per year would cost $2.7 million per year to implement, which yields a cost-effectiveness of -$233 per tonne CO_2e by 2020.

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[43] The eco-driving estimates assume 10-50 percent of the population is reached, half of those that are reached will implement the new driving behaviors, and those that do will realize a 19 percent individual fuel use reduction. The range of population reached accounts for different levels of implementation, such as requiring eco-driver training courses to only half of newly licensed drivers versus requiring the courses to all new drivers and some current drivers. The vehicle maintenance estimates account for different mixes of implementation methods, such as public awareness campaigns, new driver education, and working with the tire industry, oil change shops, and refueling stations. These calculations assume 12.5 percent individual fuel use reduction, 20-50 percent of the population is reached, and 25 percent of those that are reached will implement the vehicle maintenance suggestions.

Cost-effectiveness considering direct implementation costs alone was not estimated in the *Moving Cooler* study. Considering vehicle operating cost savings, cost-effectiveness was estimated to range from -$50 to -$190 per tonne, cumulatively over the 2010-2050 period. These estimates are in the same range as the European and Michigan estimates.

Cobenefits

Eco-driving can have benefits for reducing air pollution, both as a result of smoother driving patterns with less hard acceleration, and improved vehicle maintenance. The focus of eco-driving studies has been primarily on fuel savings and GHG reductions, and air pollutant emission reductions have not been quantified.

Feasibility

Eco-driving programs are very feasible and have no technological barriers. European programs have already demonstrated the feasibility and effectiveness of these programs. Outreach to the driving public can be in the form of training courses, which become a portion of mandatory driver education before new drivers can obtain a driver's license or before existing drivers can renew their licenses. Outreach to the driving public for vehicle maintenance can be incorporated into the training courses mentioned above, but more often takes the form of a public information campaign. In the U.S., EPA's SmartWay has included information on eco-driving practices targeted at truck operators.

The primary barriers to eco-driving programs in the U.S. are likely to be institutional; in particular, revising State driver training curricula to incorporate eco-driving practices, and working with automobile manufacturers to incorporate in-vehicle feedback systems in new cars. Incentives may be needed to encourage private truck fleet operators to promote eco-driving practices by enrolling drivers in training programs and providing information and feedback. UPS is undertaking an initiative to test the use of vehicle instrumentation to provide feedback to drivers on how to reduce fuel use and otherwise improve their driving practices (e.g., for greater safety) (UPS, 2009).

No data is available on the effectiveness of training new versus existing drivers, but as previously noted, education must be continuously provided or habits can erode over time. It is therefore not clear whether it will be feasible to sustain the initial gains observed from eco-driving programs. The interest in consumers in making use of this information on a broad scale also has not been determined.

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Appendix A. Methodological Issues

This Appendix provides a discussion of some key methodological issues underlying the data and conclusions presented in this report, including:

- Criteria for inclusion of literature in this report—how the research team determined which sources to use and cite;
- Basis for calculating greenhouse gas emission reductions;
- Treatment of cost-effectiveness—what is included and not included in the cost and cost-effectiveness estimates;
- Analysis of life cycle emissions from fuels;
- Induced demand——the phenomenon of increased travel in response to improvements in transportation conditions, which affects the reported benefits of some of the system efficiency and travel activity strategies;
- Price elasticities and vehicle operating costs—the parameters used to estimate the impacts of transportation system pricing measures; and
- The rebound effect—the extent to which increased travel (due to reduced cost per mile of driving) may offset vehicle fuel efficiency gains.

Criteria for Inclusion of Literature in This Report

This report draws from over 400 references that provide information either directly or indirectly related to the impact of transportation strategies on greenhouse gas emissions. A broad range of literature is available on transportation GHG emissions and related topics (such as vehicle travel reduction, air pollutant emissions reduction, and energy savings), which is of varying usefulness and validity. The research team that produced this report applied its professional judgment to select studies that appear to have sound, unbiased methodology and credible results. Sources include:

- Peer-reviewed academic articles published in journals or as conference proceedings;

- Research documents prepared for research programs such as the National Cooperative Highway Research Program (NCHRP), Transit Cooperative Research Program (TCRP), or Transportation Research Board (TRB);
- Government reports and other publications prepared by Federal, state, or local agencies such as U.S. Department of Transportation (DOT), U.S. Environmental Protection Agency (EPA), U.S. Department of Energy (DOE), or State DOTs;
- Internet sites that are credible sources (such as a government agency or think-tank) and have data than can be validated; and
- Research reports from private and non-profit organizations, as long as they appear to be of sound methodology and unbiased.

It is difficult to assert than any source is truly unbiased, since all authors and research sponsors work from a particular personal or organizational viewpoint. However, it is important that the methodology used in the source is presented in a transparent manner, so that any potential biases can be determined and the results of the analysis appropriately caveated if necessary. The research team excluded any sources that appear to make unreasonable assumptions or apply questionable methodologies. Sources which are not peer-reviewed received particular scrutiny.

A Note on the Moving Cooler Study

A number of the strategies discussed in the system efficiency and travel behavior chapters cite results from the *Moving Cooler* study. This study (Cambridge Systematics, 2009) conducted a comprehensive evaluation of a broad range of transportation measures that influence greenhouse gas emissions by reducing the amount of driving, reducing fuel consumption, and improving the performance of the transportation system. It was intended as a complement to previous studies, such as the 2007 McKinsey & Company and Conference Board report, *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost*?, which primarily focused on technology and fuels strategies in the transportation sector.

The *Moving Cooler* study is not the only study to address travel activity and system efficiency strategies, and other literature is cited in this report as available. However, it does help to fill a critical knowledge gap and is unique in its comprehensive and consistent treatment of these strategies. The report was developed between August 2008 and July 2009 through a collaborative process that included extensive review by a wide range of stakeholder groups, including the Environmental Protection Agency, Intelligent Transportation Society of America, Shell Oil, Urban Land Institute, Federal Transit Administration, Natural Resources Defense Council, Federal Highway Administration, American Public Transportation Association, and the

Environmental Defense Fund. In addition, the study was peer-reviewed by a panel of three leading transportation researchers.

Moving Cooler developed GHG reduction estimates for each of 50 strategies for the years 2020, 2030, and 2050, as well as cumulative reductions over the 2010 to 2050 period. In addition, costs were estimated for each year and cumulatively over this period. Both direct implementation costs and vehicle operating cost savings were estimated. In some cases, more detailed data developed as part of the *Moving Cooler* study was referenced or utilized in this report that was not presented in the final *Moving Cooler* report. However, the findings referenced are consistent with those presented in the final *Moving Cooler* report.

In addition, the cost-effectiveness results (measured in $/tonne GHG reduced) in this Report to Congress that reference the *Moving Cooler* study data were not presented as cost-effectiveness numbers in the *Moving Cooler* report, but rather were obtained by dividing total costs by total GHG benefits. These cost-effectiveness figures must be interpreted with caution, as discussed below in "treatment of cost-effectiveness." Finally, *Moving Cooler* uniquely accounted for induced demand effects. These are also discussed in more detail below under "induced demand."

One difference between the *Moving Cooler* study and this report is that rather than using the Annual Energy Outlook (AEO) 2009 Reference case as a baseline for future transportation GHG emissions (as described below), the *Moving Cooler* study developed its own baseline GHG forecasts for on-road sources using projections of annual fuel efficiency and VMT increases. Total on-road transportation GHG emissions in 2030 are forecast in *Moving Cooler* to be 1,688 million metric tons carbon dioxide-equivalent (mmt CO_2e) emissions under the baseline scenario, compared with 1,593 mmt CO_2e based on the AEO 2009 Reference Case—a difference of six percent. Since most of the *Moving Cooler* results were developed on a percentage basis (i.e., a percent reduction in VMT and emissions was estimated, then applied to the total baseline emissions), the implication is that if the *Moving Cooler* methodologies were applied to the AEO baseline GHG emissions used in this report, the GHG benefits (tons reduced) would be about six percent smaller. This is not true for certain strategies that do not affect VMT, such as truck idle reduction, for which emission reductions were calculated on an absolute basis.

Basis for Calculation Emission Reductions

For all strategies analyzed in this report, baseline GHG emissions and the baseline level of alternative fuel use through 2030 are taken from the April 2009 Annual Energy Outlook (AEO) Reference case developed by the DOE. The AEO forecast accounts for the expected impacts of the Renewable Fuels

Standard (RFS) established under the Energy Independence and Security Act (EISA) of 2007, as well as the Corporate Average Fuel Economy requirements promulgated under EISA in November 2008, but not any changes to either of these standards that were being discussed during 2009. Adjustments were made to the Reference case by Cambridge Systematics to account for greenhouse gas emissions in addition to CO_2, including nitrous oxide (N_2O), methane (CH_4), and hydrofluorocarbons (HFC). The effect is to increase total CO_2e by about six to seven percent from the AEO Reference case. Forecast emissions through 2030 as based on the AEO Reference case are presented in Volume 1, Section 2.0. In cases in which 2050 benefits are presented, the transportation sector's 2030 baseline emissions per the AEO Reference case are used as a baseline.

Market penetration, GHG reductions, and fuel savings for low-carbon fuels and vehicle energy efficiency strategies are all calculated incremental to any vehicle technology and alternative fuel penetration already included in the Reference case. All vehicle modification and fuel costs are calculated relative to conventional vehicle/fuel combinations. Cost estimates attempt to account for the volume production levels and associated economies of scale for the time period in question.

It is generally agreed that cumulative GHG emissions reductions over a future time period (for example, 2010 through 2050) are the most important measure of a strategy's success, rather than emissions in any particular year. Since cumulative emission benefits are not available for all the strategies in this report, however, common "snapshot" years are presented instead. The year 2030 is viewed as a reasonable "average" representation for the 2010-2050 period for strategies whose benefits increase over time (such as land use change or new vehicle technologies that are phased in).

Treatment of Cost-Effectiveness

The text and summary tables of this report include quantitative estimates of the cost-effectiveness (cost per tonne of GHG emissions reduced) for each strategy for which such estimates are available. Cost-effectiveness can potentially include a very narrow or wide range of costs, including:

- **Monetary implementation ("direct") costs**. These include the cash outlay needed to put in place a strategy—infrastructure construction costs, capital costs, ongoing maintenance and operations costs, program administrative costs, etc. This category defines the funding levels that public agencies or the private sector will need to achieve in order to implement these GHG reduction strategies.

- **Monetary user costs**. These are the costs or savings to private vehicle operators. These include fuel costs (savings), vehicle maintenance, and other vehicle ownership costs for private modes.

- **Non-monetary user costs.** The value of time to the traveler is a primary non-monetary user cost, which is often monetized for transportation project cost/benefit calculations. Travelers may also receive additional welfare benefits or disbenefits (e.g., improved access to destinations, reduced vehicle functionality).

- **Externalities.** These include non-monetary costs that are more difficult (or controversial) to monetize, such as health benefits, fatality reductions, air quality improvements, energy security, impacts from land use changes, etc.

Taxes, fees, and rebates are not included in cost-effectiveness calculations, since they are regarded as a transfer payment (from the private sector to the public sector). However, the imposition of taxes, fees, and rebates may create welfare changes that are difficult to monetize but nonetheless represent a real cost or benefit to consumers. If taxes and fees are used for financing transportation or other GHG reduction strategies, they may have secondary effects on GHG emissions.

For vehicle and fuel technology strategies, both the implementation costs and the monetary cost savings are borne primarily by the same group—the vehicle purchaser/owner. An automotive manufacturer or fuel producer will pass on development and production costs through the purchase price of the vehicle or fuel. The owner will also realize the benefits of fuel cost savings from more efficient vehicles, or incur increased fuel costs for alternative fuels. Therefore, only one set of cost-effectiveness estimates is shown for these strategies. Welfare impacts may be significant in some cases, but are difficult to measure or monetize and are not included in the cost-effectiveness estimates shown in this report.

For system efficiency and travel activity strategies, both the direct implementation cost (as usually borne by the public sector), and the net social cost/benefit (including private sector costs or savings) are of interest. However, estimating and presenting net social costs or benefits can be problematic, because the non-monetary costs and benefits of many of these strategies (e.g., time savings, increased or decreased mobility) can be quite significant in comparison to the monetary user costs or savings. Direct implementation costs have been estimated for most strategies discussed in this report, and monetary user cost savings have been estimated for some, but non-monetary user costs or savings have rarely been quantified and monetized. Therefore, for the system efficiency and travel activity strategies, this report presents two separate cost-effectiveness estimates:

- Direct (implementation) cost per tonne—for most strategies, an indicator of the GHG benefit that will be achieved with a given level of public-sector investment; and
- "Net included cost" per tonne. This includes both direct costs and whatever other costs or cost savings the references cited in the report have chosen to monetize—usually vehicle operating costs.

With some exceptions, costs in this report are expressed in present-year real dollars (as cited in the data source or reference) without any inflation or discounting. In a few cases, when cost estimates were particularly old (e.g., prior to year 2000), the consumer price index was applied to inflate values to current year dollars. When calculating cost effectiveness, future-year operating cost savings for on-road vehicles (but not for off-road vehicles) were discounted using a discount rate of seven percent. The cost-effectiveness estimates computed from the *Moving Cooler* study data are also based on discounting future vehicle operating cost savings at a rate of seven percent. Cost-effectiveness estimates from other studies cited in this report that included future cost savings may have used other discounting assumptions.

The cost-effectiveness estimates should be read with caution because they reflect monetary costs only, and in many cases may not reflect other very significant benefits or disbenefits to consumers.

Life-Cycle Fuel Emissions Analysis

The analysis of fuel emissions presented in Volume 2, Section 2.0 considers "well-to-wheel" (WTW) emissions, which includes all three stages of the life cycle of a transportation fuel (first, feedstock extraction and distribution, and second, fuel production and distribution, which are collectively known as "upstream" or "well-to-pump" emissions; and third, vehicle operation, also known as "downstream" emissions).

The proportion of GHG use associated with vehicle operation versus upstream emissions can vary significantly be the type of fuel. For example, hydrogen fuel cells and electric vehicles have no operating emissions since there is no fuel combustion in the vehicle. The properties of selected fuels and GHG emissions by life cycle stage are shown in Table A.1. The results shown in the table are based on an analysis using the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) model, version 1.8b (released May 2008). This model, developed at Argonne National Laboratory, is one that is commonly used by EPA and DOE to assess total fuel cycle emissions of alternative fuel vehicles. The GREET model calculates WTW emissions, which takes into account emissions from all phases of production, distribution, and use of transportation fuels (Chien, 2009). A strength of GREET is that the user can match a vehicle technology with a variety of different fuel options. In fact, GREET includes more than 100 fuel production pathways and more than 70 vehicle systems. The GREET model is based solely on fuel type and vehicle technology, whereas other transportation models (such as TAFV, MiniCam, and NEMS) project transportation emissions based on an expected economic situation and/or likely consumer behavior.

This analysis uses the default values found in GREET in order to assess the lifecycle impacts of alternative fuels relative to conventional gasoline and diesel. The grams per vehicle mile traveled values in Table A.1 account for key GHGs, converted to CO_2 equivalents using a 100 year (default) global warming potential (GWP). Results from the model vary significantly depending on various assumptions related to fuel production technology and end-use. In addition, GREET does not account for indirect land use changes or other indirect effects that may significantly impact final results for biofuels in particular. Other key limitations of GREET's "direct attributional approach" include (U.S. EPA, 2009a):

- The economic impact of biofuel coproducts on other sectors, such as livestock feed markets and associated indirect GHG impacts, were not adequately assessed;
- Specific policy measures could not be evaluated in detail as a function of different production targets, especially with regard to agricultural sector impacts;
- Fuel replacement impacts were assessed on an average gallon of fuel basis, rather than evaluating the specific alternative fuel production and conventional fuel replacement emissions at the margin; and
- The RFS1 evaluation methodology did not account for the effects of falling U.S. petroleum demand on world fuel prices, and subsequent increases in international petroleum consumption.

Depending upon the nature of the analysis, GREET grams per mile outputs were frequently converted to equivalent grams per gallon values, in order to compare the potential GHG impacts of alternative fuels compared with conventional gasoline and diesel. In this way the impact of changing fuel efficiencies over time could be accounted for without having to re-run the GREET model for each time period of interest. In addition, in most cases this analysis assumes that alternative fuel vehicles accrue fuel efficiency improvements at the same rate over time as the comparable conventional baseline vehicle. This simplifying assumption is not made for fuel cell and battery electric vehicles, as the source of motive power and drive train configurations can be fundamentally different than conventional internal combustion engine vehicles.

Table A.1 Energy Content and Life Cycle GHG Emissions for Selected Transportation Fuels

	Heating Value (Btu/gal unless noted)		Carbon Content (% by wt)	g CO2e per VMT for LDVs, by Life-Cycle Stage (GREET 1.8b)			
	Lower	Higher		Feedstock	Fuel	Operation	Total
Gasoline	116,090	124,340	86.3%	29	71	384	484
No. 2 Diesel	128,450	137,380	86.5%	30	45	330	405
Compressed Natural Gas(CNG)	20,268 Btu/lb.	22,453 Btu/lb.	72.4%	60	33	316	410
Liquefied Natural Gas (LNG)	74,720	84,820	75.0%	42	50	318	410
Liquefied Petroleum Gas (LPG)	84,950	91,410	82.0%	38	22	341	401
Liq H2 at Central Plant[b]	51,585 Btu/lb	61,013 Btu/lb	0%	18	316	0	334
Gaseous H2 at Central Plant[b]				18	239	0	257
Liq H2 at Refueling Station[b]				25	432	0	457
Gaseous H2 at Refueling Station[b]				25	232	0	257
Gaseous H2 at Refueling Station-electrolysis w/ avg grid				719	0	0	719
Gaseous H2 at Central plant (Nuclear)				10	52	0	62
Liq H2 at Central plant (Nuclear)				10	5	0	15
Electricity (U.S. avg grid)	3,414 Btu/kWh	3,414 Btu/kWh		20	303	0	323

[b] Results are for steam reforming of natural gas.

Price Elasticities and Vehicle Operating Costs

An "elasticity" is a percent change in one value with respect to a percent change in another. For measures that affect the cost of travel, one important elasticity is the percent change in fuel use with respect to a percent change in the cost of that travel (e.g., cents per mile). The value of the elasticity will be different depending upon whether the change in travel cost is measured relative to just one component of travel (e.g., fuel price) or all relative to the full cost of travel (including vehicle operating costs, user-borne crash costs, and time savings). Elasticities were used in this report to estimate response to some travel pricing measures, using a methodology consistent to that applied in the *Moving Cooler* study.

There is an extensive body of literature on elasticities for travel costs. Much recent work has focused on responses to changes in motor fuel prices, since motor fuel prices have been highly volatile, and since overall prices for travel are less volatile. While there is an extensive body of literature on transportation price elasticities, Small and Van Dender (2007) provide a review of previous studies as well as recent estimates using data through 2004. The authors estimate elasticities of VMT, fuel intensity (gallons/mile), and total fuel consumption (VMT multiplied by fuel intensity) with respect to fuel price changes. Elasticities are estimated both over a historical time period (1966 to 2004) and within the past few years (2000 to 2004) to examine how elasticities might be changing. These findings are shown in Table A.2.

Table A.2 Historical and Recent Long-Run Elasticities With Respect to Fuel Price

Calculated Long-Run Price Elasticities With Respect to Fuel Price of:	Elasticity 1966 to 2004	Elasticity 2000 to 2004
Vehicle Miles Traveled	-0.210	-0.057
Fuel Intensity	-0.193	-0.191
Fuel Consumption	-0.363	-0.237
Rebound Effect (Percentage)	**21.0%**	**5.7%**

Source: Small and Van Dender (2007). The values shown in this table are "long-run" elasticities—i.e., response over a multi-year period after the price change. Long-run elasticities will be greater than the immediate or short-term response since travelers are able to make more fundamental adjustments to their activity patterns, such as changing residence or worksite locations or changing the number and types of vehicles owned. The rebound effect is discussed in the following section.

The findings imply, for example, that based on data from the 1966 to 2004 period, a 100 percent increase in fuel price should lead to a 21 percent reduction in VMT, and 19 percent increase in the fuel efficiency of vehicles, for an overall net decrease in fuel consumption of 36 percent. For the more recent period of 2000 to 2004, the elasticity of VMT with regard to fuel price declined substantially, such that a 100 percent increase in fuel price would lead to only a 6 percent long term decline in VMT. For the pricing measures analyzed in Volume 2, Section 5.0, which apply charges based on distance traveled rather than fuel consumed, it is the VMT response that is of interest. Table A.2 shows that historically, about half of the impact of a fuel price increase would be on VMT reduction and the other half on fuel efficiency; but that in recent years, the VMT response to price increases has become much lower—less than one-third the magnitude of the fuel efficiency effect.

Another recent review of elasticities by Sperling (2008) suggests that elasticity values are higher, but also reaches a similar conclusion that elasticities with respect to VMT have declined in recent years. Sperling found that long run elasticities of fuel consumption with regard to fuel price "may be as low as -0.2."

The Small and Van Dender and Sperling studies provide the most recent estimates of those in the literature, and therefore are used as the primary basis for this report and the *Moving Cooler* study. Depending on the basis on which elasticities are applied, such as to "total operating costs" or to estimated "out of pocket costs" or to fuel costs, different elasticity values will be appropriate. FHWA includes in its Highway Economic Requirement System (HERS) model estimates for the operating costs of light duty and heavy duty vehicles. The latest HERS costs for 2006 included operating costs of 40 cents per mile for all vehicles and crash costs of 15 cents per mile for all vehicles. The crash costs include both insurance costs and uncompensated accident costs. Travel time costs for all vehicles were 54.5 cents per mile, and taxes paid were 2.4 cents per mile. Using the HERS estimates of only the monetary costs, the 2006 number would be 40 cents plus 15 cents plus 2 cents or 57 cents. Adjusting for fuel price to 2008 ($2.27 per gallon in 2006 versus $3.25 per gallon in 2008, at a fleet average of 17 mpg) would add 6 cents to the HERS estimate, making it 63 cents per mile. HERS also uses lower safety costs such as a lower cost of lives lost than is used by other agencies such as EPA and that adjustment would add several cents per mile.

The cost assumptions underlying the analyses present in the *Moving Cooler* study and this report were developed during a time in which costs have changed. The IRS had estimated costs of 58.5 cents per mile for light duty vehicles in 2008, and lowered that estimate to 55 cents when fuel prices dropped. It is expected that this figure will be adjusted again. Using the 2008 IRS allowed operating cost of 58.5 cents per mile, future light duty vehicle operating costs were estimated at 60 cents per mile, based upon an assumption of somewhat higher future fuel prices (starting at $3.70 per gallon and increasing over time) than the average fuel price for 2008.

Future total fleet operating costs were estimated at 69 cents per mile. The latter figure is based on the impacts of heavy trucks on the total operating costs of the vehicle fleet. Heavy trucks have over twice the operating cost per mile of light duty vehicles and including them in the calculations increases the average operating costs by 15.4 percent, according to the HERS operating cost factors. This yields 60 cents times 1.15 equals 69 cents per mile. Of this element, with fuel prices of $3.70 per gallon for the AEO high case in 2008 and a fleet overall average of 17 mpg, fuel costs would be about 22 cents per mile, or about one third of total estimated costs.

For the purposes of the *Moving Cooler* study and this report, converting the Small and Van Dender long term elasticity for VMT or the Sperling elasticity for fuel prices to an elasticity for overall operating expenses would imply about a three or four times higher elasticity (since fuel cost represents only about one-third to one-fourth of total operating costs), or up to around three to four times -0.057 (-0.17 to -0.23) for Small and Van Dender and up to around three to four times -0.2 (-0.6 to -0.8) for Sperling. No representation is made that the referenced researchers agree with this conversion. The overall elasticity selected for *Moving Cooler* and this study was -0.45, which is in the middle of these calculated conversions. This elasticity is close to the long-run fuel price elasticity of about -0.4 used in a 2008 Congressional Budget Office analysis of gasoline price effects. The -0.45 elasticity was applied for the response of VMT to total vehicle costs for all pricing measures. This elasticity is also comparable to the long-term elasticity used in the HERS model. The HERS input elasticities total to -0.65, but because of the way HERS is set up this results in a total elasticity of about -0.8. This applies to the total of all costs, including travel time costs. Since HERS assumes travel time costs of about 50 percent of total costs (54 cents out of $1.07 per mile), the -0.45 elasticity is just slightly higher than the equivalent in HERS.

The Rebound Effect

The "rebound effect" can be characterized as the extent to which fuel savings (and corresponding GHG reductions) from vehicle fuel efficiency improvements are offset by increased travel, because travel is made cheaper per-mile due to reduced fuel costs. It is related to the price elasticity effect discussed above. In particular, it is the same magnitude as the elasticity of VMT with respect to fuel price—only it works in the opposite direction, i.e., reflecting an increase in the amount of driving in response to a price decrease, rather than vice-versa.

The National Highway and Traffic Safety Administration (NHTSA), in its preliminary regulatory impact assessment for the CAFE standards rulemaking, reviewed 22 studies of the rebound effect and found effects ranging from 10 to 30 percent (i.e., the gains from regulated vehicle efficiency improvements would be reduced by this amount over the long run due to increased travel) (NHTSA, 2008). Table A.1 also shows Small and Van Dender's estimate of the rebound effect. Consistent with the NHTSA review, they estimate that this effect is about 21 percent historically; however, they also find a significant reduction (to about 6 percent) based on data from the most recent time period. Small and Van Dender note that the estimates of the rebound effect are very sensitive to the time period considered and treatment of CAFE regulations, and further, that there is no agreement on how to control for CAFE standards in these studies.

The NHTSA study also acknowledges and places credibility on the findings that the rebound effect has become smaller over time. The NHTSA used a 10 percent rebound effect in its analysis of fuel savings and other benefits from higher CAFE standards for MY 2012-2016 vehicles. The Agency's judgment is that the apparent decline over time in the magnitude of the rebound effect justifies using a value for future analysis that is lower than historical estimates, which average approximately 25 percent. Because the lifetimes of vehicles affected by the alternative CAFE standards considered in the rulemaking will extend from 2012 until approximately 2050, a value that is significantly lower than historical estimates appears to be appropriate. Recognizing the uncertainty surrounding the 10 percent estimate, the Agency analyzed the sensitivity of its benefits estimates to a range of values for the rebound effect from 5-to-15 percent (NHTSA, 2009).

Induced Demand

Induced travel demand can be defined as *any increase in travel resulting from improved travel conditions* (Hunt, 2002). These improved conditions include reduced travel time, reduced costs, improved safety, or improved comfort. Since most roads are empty at most times of day—the average density of traffic on all U.S. roads over 24 hours per day is one vehicle per lane every 90 seconds—induced demand is an issue that is applicable to a small minority of road miles and only during a portion of the day. These capacity issues, however, are important because they arise on the most heavily traveled roads at the most heavily-traveled times.

Induced demand is related to the basic economic concept of *elasticity*: if the price of something falls, its consumption will increase. Thus, if congestion is reduced (for example, because highway capacity is increased, or some people have chosen to work from home instead of commute), travel times and travel-time costs will decrease, and an induced increase in vehicle miles traveled (VMT) will result. The induced VMT is likely to come partly from shifts of travelers from other modes (particularly transit) and partly from changes in travel patterns (more trips and longer trips). Also, in some cases, there may be shifts in the time of travel from off-peak periods to peak periods.

There are two basic types of transportation GHG reduction measures that can result in induced demand:

- System efficiency improvements that reduce congestion and delay, thereby improving travel times (as well as reducing fuel consumption and GHG related to delay); and
- Travel behavior strategies that reduce VMT by increasing the attractiveness of alternatives to auto travel (or single-occupancy-vehicle travel).

For example, policies that cause diversion to transit reduce highway congestion and thereby reduce highway travel times, making highway travel more attractive to non-transit users who, in turn, increase somewhat the number and/or length of their highway trips. Travel behavior strategies will only result in induced demand to the extent that they reduce VMT during congested travel periods, and therefore reducing delay and decreasing travel times. This is sometimes referred to as a "rebound effect," since traffic volume rebounds as the traffic that is diverted off the road is partially replaced by new traffic from other sources. (Strategies that reduce VMT by making highway travel more expensive—such as mileage-based fees or increased gas taxes—do not produce a rebound effect, since they apply comprehensively to all highway travel.)

The offsetting effects of induced demand apply to any VMT or congestion/delay-related metric such as fuel consumption or criteria pollutant emissions. The magnitude of these effects depends upon the elasticity of travel demand with respect to a change in travel time or travel cost—i.e., the percent change in travel for a given percent change in time/cost. Both short-term (about one year) and long-term (multi-year) elasticities have been estimated, since rebound effects can be greater over the long term as people make more significant changes to their travel habits such as living farther from work.

The magnitude of the induced demand effect from both system efficiency and travel activity strategies was estimated in work performed for the *Moving Cooler* study. The effects are quite different:

- For travel activity strategies, the system-wide "rebound effect" was estimated to be about 14 percent, using the Federal Highway Administration's (FHWA) Highway Economic Requirements System (HERS) model. That is, for any measure that would reduce VMT by making alternatives to auto travel (or single occupancy vehicle travel) more attractive, the initially estimated reduction in VMT and GHG is reduced by 14 percent to reflect the rebound effect. This reduction is reflected in the travel activity strategy results cited from the *Moving Cooler* study for transit, land use, non-motorized travel, and employer trip reduction.
- For system efficiency strategies, the increase in GHG emissions resulting from increased VMT (as a result of reduced congestion and delay) is relatively more significant. In fact, the net effect in the *Moving Cooler* study was to essentially offset the cumulative GHG benefits of bottleneck relief strategies over the 2010-2050 period, and to significantly reduce the benefits of traffic management strategies (by up to 90 percent or more in 2030). Some benefit would be seen in the short- to mid-term (10-20 years), but over

time the induced demand effects would increase and in later years, more than offsetting the benefits of delay reduction. Again, the induced demand effects were modeled using the same relationships contained in FHWA's current version of the HERS model.

As noted, the analysis used the same elasticity for induced demand as that used in the HERS model. The HERS model includes a demand elasticity that quantifies the response of total VMT to a general increase or decrease in the cost of road travel. The negative value for this elasticity reflects that the demand for road travel declines in response to an increase in "generalized cost" per mile of travel. Similarly, demand for road travel increases in response to a decrease in costs (induced demand). The generalized cost sums the average per mile costs associated with travel time, road crashes, and vehicle operation (fuel, maintenance, etc.).

Evidence suggests that response of VMT to a sustained increase in generalized cost - due, say, to a permanent increase in the federal gas tax- grows over time as people have more time to adjust—for example, by relocating their residence to be closer to the workplace. Similarly, a long term decrease in the cost of travel because of improved conditions such as shorter travel times leads to an increase in demand that is larger over the long term as people have more time to adjust. For the HERS model, the FHWA accordingly specifies separate demand elasticities for the short run and long run. These elasticities were derived from a review of estimated elasticities of travel demand with respect to fuel prices and other components of travel cost (Federal Highway Administration 2005). In 2004, HERS used values of -0.6 for the short run elasticity and -1.2 for the long run. These were reduced in the 2006 and 2008 HERS model runs to -0.4 for the short run (meaning that a 10 percent increase in the generalized cost reduced VMT by approximately 4 percent) and -0.8 for the long run because of new evidence suggesting that travel demand responses were smaller than previously thought.

The HERS elasticity is for VMT with respect to total travel costs. To compare this elasticity to elasticities in the literature of VMT with respect to fuel costs (or any other portion of total travel costs) one must account for the share of total travel costs represented by fuel (or other subset of cost). FHWA estimates the different component shares of total highway travel costs as shown in the table below.

Component Shares in Total Price

Component	Low Share	High Share
Fuel	8%	36%
Maintenance	9%	48%
Accidents and Insurance	7%	37%
Vehicle wear & ownership	18%	54%
Tolls and fees	0%	10%
Parking	1%	10%
Travel time	40%	62%

Source: Federal Highway Administration 2005, *Highway Economic Requirements System—State Version*, Technical Report, FHWA-HIF-08-017.

To compare an elasticity for fuel prices to an elasticity for total travel costs, one would need to multiply the fuel price elasticity by a factor of three to ten, since fuel cost represents only about a tenth to a third of total operating costs, as shown in the table above.

Based on the earlier literature review, FHWA estimated the elasticity of VMT with respect to fuel prices at -0.17 for the short run and -0.33 for the long run. In contrast, the Congressional Budget Office (2008) relied on alternative estimates from Small and Van Dender (2007) of a near-zero elasticity for the short-run (between -0.02 and -0.03) and of an elasticity between -0.11 and -0.15 for the long-run. For short- to medium-run responses of VMT to changes in fuel prices, Ewing et al. (2008) estimated an elasticity of -0.17 using data for U.S urban areas from 1985 through 2005. The question of how strongly VMT responds to changes in fuel prices is far from settled, with ongoing research continuing to produce new estimates.

A number of uncertainties are noted regarding the induced demand impacts. In particular, there is considerable uncertainty and debate over the magnitude and timing of induced demand. A range of plausible estimates from the literature could produce results that show either a net increase or decrease in GHG emissions over time. Furthermore, the estimates were performed using delay—fuel consumption relationships for today's vehicle fleet. The evolution of vehicle technology in the future could lead to very different effects. For example, the widespread adoption of electric-drivetrain vehicles (hybrid-electrics, battery-electrics, or fuel cells) would greatly reduce the fuel and GHG reduction benefits of delay reduction, since these vehicles are much more efficient in low-speed operation.

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