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Fuel-Cycle Greenhouse Gas Emissions Impacts of Alternative Transportation Fuels and Advanced Vehicle Technologies

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Abstract

At an international conference on global warming, held in Kyoto, Japan, in December 1997, the United States committed to reduce its greenhouse gas (GHG) emissions by 7% over its 1990 level by the year 2012. To help achieve that goal, transportation GHG emissions need to be reduced. Using Argonne's fuel-cycle model, I estimated GHG emissions reduction potentials of various near- and long-term transportation technologies. The estimated per-mile GHG emissions results show that alternative transportation fuels and advanced vehicle technologies can help significantly reduce transportation GHG emissions. Of the near-term technologies evaluated in this study, electric vehicles; hybrid electric vehicles; compression-ignition, direct-injection vehicles; and E85 flexible fuel vehicles can reduce fuel-cycle GHG emissions by more than 25%, on the fuel-cycle basis. Electric vehicles powered by electricity generated primarily from nuclear and renewable sources can reduce GHG emissions by 80%. Other alternative fuels, such as compressed natural gas and liquefied petroleum gas, offer limited, but positive, GHG emission reduction benefits.

Among the long-term technologies evaluated in this study, conventional spark ignition and compression ignition engines powered by alternative fuels and gasoline- and diesel-powered advanced vehicles can reduce GHG emissions by 10% to 30%. Ethanol dedicated vehicles, electric vehicles, hybrid electric vehicles, and fuel-cell vehicles can reduce GHG emissions by over 40%. Spark ignition engines and fuel-cell vehicles powered by cellulosic ethanol and solar hydrogen (for fuel-cell vehicles only) can reduce GHG emissions by over 80%. In conclusion, both near- and long-term alternative fuels and advanced transportation technologies can play a role in reducing the United States GHG emissions.

Key Words

Greenhouse Gases, Fuel Cycles, Emissions, Alternative Fuels, Transportation Technologies

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Introduction

Concern about the potential effects of greenhouse gases (GHGs) on global warming has led to increased recognition of the need to reduce anthropogenic GHG emissions worldwide. At the global warming Conference, held in December 1997 in Kyoto, Japan, the United States provisionally committed to reduce its GHG emissions by 7% from 1990 levels by the year 2012. If no efforts are made to reduce them, GHG emissions generated by the U.S. transportation sector, which account for 29% of the nation's total GHG emissions (EPA 1998), may continue to grow as population and vehicle miles traveled (VMT) increase. In order to meet the Kyoto goal, the trend of increasing GHG emissions in the U.S. transportation sector must be reversed — not an easy task.

Alternative transportation fuels have historically been promoted for helping solve urban air pollution problems and reduce the U.S. reliance on petroleum fuels. Use of these fuels, especially those produced from renewable sources, may help reduce transportation GHG emissions as well. Because the processes for producing different transportation fuels vary, the impacts of GHG emissions from each transportation fuel must be evaluated on a full fuel-cycle basis. Beginning in 1995, Argonne National Laboratory has developed a spreadsheet-based model for estimating fuel-cycle energy and emission impacts of alternative transportation fuels and advanced transportation technologies (Wang 1996). The intention of creating such a model was to allow researchers to readily test various parametric assumptions that affect fuel-cycle energy use and emissions. The model, called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation), has since been expanded and upgraded. The most recent GREET version – GREET1.4 – incorporates additional fuel cycles and vehicular technologies, revised modeling approaches for up-stream fuel production activities, and new parametric assumptions. This paper presents the most recent results of fuel-cycle GHG emissions that are estimated with GREET1.4.

Past Studies

This section summarizes several major past studies on fuel-cycle emissions; the summary is intended to provide some historical background of transportation fuel-cycle analyses and put this study into perspective. Because parametric assumptions change frequently from studies to studies or from time to time with a same study, comparison of quantitative results among studies are less meaningful. Thus, the summary below focuses on methodologies and coverage of individual studies rather than on their quantitative results.

In 1991, Delucchi completed a study to estimate fuel-cycle emissions of GHGs for various transportation fuels (Delucchi 1991; 1993). GHGs considered in that study were carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), nitrogen oxides (NO_x), and nonmethane organic gases (NMOG). Emissions of these gases were combined with their global warming potentials (GWPs). Delucchi estimated not only the fuel-cycle energy use and emissions, but also the energy use and emissions associated with manufacturing motor vehicles. He included the following fuel cycles: petroleum to gasoline, petroleum to diesel, petroleum to liquefied petroleum gas (LPG), natural gas (NG) to methanol, NG to compressed natural gas (CNG), NG to liquefied natural gas (LNG), NG to LPG, coal to methanol, wood to methanol, corn to ethanol, wood to ethanol, nuclear energy to hydrogen, solar energy to hydrogen, and electricity generation from various fuels.

Delucchi developed a spreadsheet-based model to estimate energy use and emissions. Using the model, he estimated GHG emissions for the year 2000 from a baseline gasoline car with a fuel economy of 30 miles per gallon (MPG). He generally assumed improvements in energy efficiency for alternative-fuel vehicles (AFVs) relative to gasoline vehicles (GVs). To address uncertainties in future energy production processes and vehicle technologies, Delucchi designed various scenarios representing potential improvements in fuel production efficiencies, GWPs of GHGs, vehicular efficiencies of AFVs, and regional differences in fuel production.

Delucchi's study was the most comprehensive study of fuel-cycle GHG emissions then. The study was widely cited. The early work on GREET development at Argonne, as documented in Wang (1996), relied heavily on methodologies used and data presented in Delucchi's 1991 study.

Delucchi has continued to revise and upgrade his model. The most recent report published by Delucchi is the one in 1997 (Delucchi 1997). That report presented updated fuel-cycle emissions results, changes in parametric assumptions, addition of new fuel cycles, and use of economic damage indices in place of GWPs to combine GHGs together.

Ecotraffic, AB, a Swedish company, estimated fuel-cycle emissions and energy consumption of producing and using various transportation fuels in Sweden (Ecotraffic, AB 1992). That study — probably the most comprehensive one conducted outside of the United States — included the following fuel cycles: petroleum to gasoline, petroleum to diesel, petroleum to LPG, NG to CNG, NG to methanol, biomass to methanol, biomass to ethanol, rapeseed to vegetable oil, solar energy to hydrogen (via electrolysis of water), NG to hydrogen, and electricity generation from various fuels. Fuel-cycle emissions of three criteria pollutants (HC, CO, and NO_x) and six GHGs (CO_2, CH_4, N_2O, NO_x, CO, and HC) were estimated for three vehicle types: cars, medium-duty trucks, and buses.

Ecotraffic concluded that use of non-fossil fuels could result in a greater-than-50% reduction in GHG emissions compared with use of petroleum-based fuels. However, use of diesel and vegetable oils produced the highest NO_x emissions. Because almost all electricity in Sweden is generated from hydropower and nuclear energy, use of electric vehicles (EVs) reduced emissions of criteria pollutants and GHGs drastically. The study was conducted using only Swedish data of emissions and energy efficiencies, so its conclusions may be applicable only to Sweden.

Darrow conducted two separate fuel-cycle studies: one for the Gas Research Institute (GRI) to analyze fuel-cycle emissions of alternative fuels (Darrow 1994a) and the other for the Southern California Gas Company to compare fuel-cycle emissions from EVs and compressed natural gas vehicles (CNGVs) (Darrow 1994b).

In his GRI study, Darrow included the following fuel cycles: petroleum to conventional gasoline, petroleum to reformulated gasoline (RFG), petroleum to LPG, NG to CNG, NG to methanol, NG to LPG, corn to ethanol, and electricity generation from various fuels. The study included five criteria pollutants (reactive organic gases [ROG], NO_x, CO, sulfur oxides [SO_x], and particulate matter with a diameter of less than 10 microns [PM_{10}]) and three GHGs (CO_2, CH_4, and N_2O).

Darrow analyzed fuel-cycle emissions for the United States and California in two target years: 1994 and 2000. For the United States, he analyzed emissions data from various areas of the country and aggregate U.S. data on emissions and energy efficiencies. For California, he included emissions occurring only within the state. Over 50% of electricity in the United States is generated from coal, while natural gas, hydropower, and nuclear plants are the primary sources of electricity generation in California. Consequently, EV fuel-cycle emissions in California were significantly lower than those in the United States.

In his study for the Southern California Gas Company (Darrow 1994b), Darrow compared fuel-cycle emissions from CNGVs and EVs in Southern California. He concluded that, while urban emissions from EVs were generally lower than those from CNGVs, total emissions (emissions occurring in all the locations) of NO_x from EVs were slightly higher than those from CNGVs. However, EVs always generated lower total ROG and CO emissions than CNGVs did.

Acurex Environmental Corporation (1996) conducted a study for the California Air Resources Board (CARB) to estimate fuel-cycle emissions of various transportation fuels. The study included these fuel cycles: petroleum to conventional gasoline, petroleum to RFG, petroleum to clean diesel, NG to LPG, NG to methanol, NG to CNG, NG to LNG, coal to methanol, biomass (including corn, woody and herbaceous biomass) to methanol, biomass to ethanol, electricity generation from various fuels, and hydrogen from electricity via electrolysis of water. The study estimated emissions of three criteria pollutants (NO_x, NMOG, CO) and two GHGs (CO_2 and CH_4). NMOG emissions from different fuel production processes and from vehicles using different alternative fuels were adjusted to account for their ozone-forming potentials.

Through that effort, Acurex established a database for estimating fuel-cycle emissions in California between 1990 and 2010. Emissions regulations applicable to this timeframe in California were taken into account. In particular, Acurex considered the reductions in stationary source emissions brought about by the adoption of emissions regulations by the South Coast Air Quality Management District (SCAQMD). Given the uncertainties involved in emission controls and fuel economy improvements from the present to 2010, Acurex established three scenarios in 2010 to reflect varying degrees of stationary emissions controls and vehicle fuel economy.

In its study, Acurex thoroughly characterized emissions of various fuel production processes in California, especially in the South Coast Air Basin. Acurex collected extensive emissions data — its established fuel-cycle database contains detailed emissions data for California. The study did not include N_2O, PM_{10}, and SO_x emissions. Researchers' ability to apply the Acurex database to other regions outside of California is limited.

There are two other separate efforts that were not documented in publicly available reports. One is a fuel-cycle model developed by Eco-Balance, a consulting company located in Rockville, Maryland. The Eco-Balance's model was used by the National Renewable Energy Laboratory for recently completed fuel-cycle studies on biodiesel and cellulosic ethanol. The other is a study that A.D. Little, based in Cambridge, Massachusetts, completed for the Ford Motor Company. The report prepared by A.D. Little for Ford is not available to the public.

Many other individual fuel-cycle studies have also been completed to evaluate specific transportation fuels; those studies are not summarized here.

Methodologies Used and Fuels Included in This Study

The use of motor vehicles involves two different energy cycles: production and use of motor fuels (fuel cycle) and production and use of motor vehicles (vehicle cycle). The *fuel cycle* for a given transportation fuel includes the following processes: energy feedstock (or primary energy) production, feedstock transportation and storage (T&S); fuel production; fuel transportation, storage, and distribution (T&S&D); and vehicle operations that involve fuel combustion or other chemical conversions (Figure 1). The processes that precede vehicle operations are often referred to as up-stream activities; vehicle operations are referred to as down-stream activities. In Figure 1, the processes enclosed in rectangles are production- or combustion-related activities, and those enclosed in ovals are transportation-related activities. Energy use and emissions of the former are far greater than those of the latter.

The *vehicle cycle* includes raw material recovery and fabrication, vehicle production, vehicle operations, and vehicle disposal/recycling. (Note that vehicle operations are included in either the fuel cycle or vehicle cycle). In general, the contribution of the vehicle cycle to per-mile vehicle energy use and emissions is much smaller than that of the fuel cycle or vehicle operations.

The GREET model comprises three series of sub-models. The Series 1 sub-model (GREET 1.0, 1.1, 1.2, 1.3, and so on) calculates fuel-cycle energy use and emissions for light-duty vehicles (passenger cars, vans, and light trucks). The Series 2 sub-model, which was developed through Argonne's effort on a total energy cycle analysis for hybrid EVs, calculates vehicle-cycle energy use and emissions for light-duty vehicles. The Series 3 sub-model estimates fuel-cycle energy use and emissions for heavy-duty vehicles (class 2b to class 8 trucks). The series 2 and 3 sub-models are linked to the series 1 sub-model. Running of the former two requires the series 1 model available.

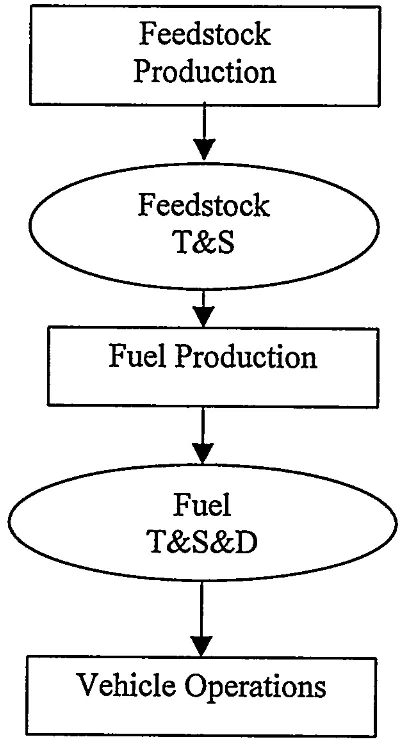

Figure 1 Stages of a Fuel Cycle

GREET calculates Btu-per-mile (Btu/mi) energy use and grams-per-mile (g/mi) emissions by taking into account energy use and emissions of fuel combustion and non-combustion sources such as fuel leaks and evaporation. The model calculates total energy use (all energy sources), fossil energy use (petroleum, natural gas, and coal), and petroleum use. It includes emissions of three major GHGs (CO_2, CH_4, and N_2O) and five criteria pollutants (volatile organic compounds [VOCs], CO, NO_x, PM_{10}, and SO_x). The three GHGs were specified in the 1997 Kyoto Protocol for GHG emissions reductions by developed countries.

Because of space limitation, this paper presents GREET-estimated fuel-cycle emissions of the three GHGs for combinations of transportation fuels and vehicle propulsion systems. Emissions of the five criteria pollutants and energy use are not presented in this paper. Detailed methodologies, assumptions, and results of energy use and emissions of criteria pollutants and GHGs are presented in an on-going report, which will be available soon.

In this study, emissions of the three GHGs were combined with their global warming potentials (GWPs). I used IPCC-recommended GWPs for the 100-year time horizon (IPCC 1996): 1 for CO_2, 21 for CH_4, and 310 for N_2O. The choice of a time horizon affects GWP values considerably. For example, the IPCC estimated GWP values of 1, 56, and 280 for CO_2, CH_4, and N_2O for a 20-year time horizon; and 1, 6.5, and 170 for a 500-year time horizon. Some researchers — such as Delucchi — maintain that economic damage indices for GHGs should be used to aggregate GHGs (Delucchi 1997). Economic damage indices take, in principle, into account the assertion that future global warming effects are worth less the current warming effects.

While GREET includes over twenty-five fuel cycles, this study focuses on nineteen major fuel cycles that produce twelve transportation fuels. Table 1 presents the fuel cycles included in this study.

Table 1. Fuel Cycles Included in This Study

Feedstock	Fuel
Petroleum	Conventional gasoline (CG) Reformulated gasoline (RFG) Conventional diesel (CD) Reformulated diesel (RFD) Liquefied petroleum gas (LPG) Electricity via residual oil
Natural gas	Compressed natural gas (CNG) LPG Methanol (MeOH) Fischer-Tropsch diesel (FTD) Hydrogen (H_2) Electricity
Corn Biomass	Ethanol (EtOH)
Soybeans	Biodiesel
Solar energy	H_2
Coal Nuclear energy Renewable energy	Electricity

Various vehicular propulsion systems have been studied and proposed for use of the twelve transportation fuels. Table 2 presents the combinations of transportation fuels and vehicle technologies evaluated in this study. The table separates the technology/fuel combinations into near- and long-term options. The near-term options are available in the marketplace now; the long-term options will require additional research and development (R&D) efforts and could become available around 2010. Although the included near- and long-term technology options can be applied to passenger cars and light-duty trucks, this study evaluates their applications only to passenger cars.

Table 2. Near- and Long-Term Technology Options of Alternative Fuels and Vehicular Propulsion Systems

Near-Term Options (Model Year 2000)	Long-Term Options (Model Year 2010)
GVs: RFG (baseline)	GVs: RFG (baseline)
CNGVs: bi-fuel	CNGVs: dedicated
CNGVs: dedicated	LPGVs: OEM, dedicated
FFVs: M85	M95 dedicated vehicles
FFVs: E85	E95 dedicated vehicles
LPGVs: converted, dedicated	EVs
EVs	Grid connected HEVs: RFG
Grid-connected HEVs: RFG	Grid indep. HEVs: RFG
Grid-independent HEVs: RFG	Grid indep. HEVs: RFD
Grid-independent HEVs: CD	FCVs: hydrogen
Conv. CI vehicles: CD	FCVs: methanol
CIDI vehicles: CD	FCVs: RFG
	FCVs: ethanol
	SIDI vehicles: RFG
	CIDI vehicles: RFD
	CIDI vehicles: FTD50
	CIDI vehicles: BD20
	CIDI vehicles: DME

Notes:
GVs – gasoline vehicles; CNGVs – compressed natural gas vehicles; FFVs – flexible-fuel vehicles; LPGVs – liquefied petroleum gas vehicles; EVs – battery-powered electric vehicles; HEVs – hybrid electric vehicles; CI – compression ignition; CIDI – compression ignition, direct injection; FCVs – fuel-cell vehicles; SIDI – spark ignition, direct injection; OEM – original equipment manufacturer; RFG – reformulated gasoline; M85 – 85% methanol and 15% gasoline by volume; E85 – 85% ethanol and 15% gasoline; M95 – 95% methanol and 5% gasoline; E95 – 95% ethanol and 5% gasoline; CD – conventional diesel; RFD – reformulated diesel; FTD50 – 50% Fischer-Tropsch diesel and 50% conventional petroleum diesel; BD20 – 20% biodiesel and 80% conventional petroleum diesel; DME – dimethyl ether.

Key Assumptions

This section presents key assumptions for each of the fuel cycles included in this study. Because of limited space in this paper, not all the assumptions made in this study are presented here. Detailed assumptions for each cycle are documented in an ongoing GREET report.

Petroleum-Based Fuel Cycles

As Table 1 shows, there are six petroleum-based fuel cycles. For these cycles, petroleum refining consumes the largest amount of energy, and consequently generates the most CO_2 emissions. A key parameter for these cycles is refining energy efficiencies. Based on review of past studies, I assumed the following refining efficiencies: 85% for CG, 83% for RFG, 88% for CD, 86% for RFD, 94% for LPG, and 95% for residual oil. The refining energy efficiencies among these fuels reflect the required refining intensity for producing each fuel. RFG here is the federal phase 2 RFG to be available in year 2000. CD is the currently available low-sulfur diesel.

There is no RFD available in the U.S. yet. Because of the increased interest in advanced diesel engines, some type of RFD will probably have to be in place in order to reduce emissions of diesel engines. I assumed an RFD with a sulfur content of 100 parts per million (ppm).

The amount of process fuels used for refining petroleum into each of the fuels is estimated using the assumed refining efficiencies. GREET calculates CO_2 emissions generated during combustion of process fuels; the model also accounts for the CO_2 emissions that are generated from non-combustion processes of refining crude into crude products.

During crude extraction and oil separation in the oil fields, CH_4 emissions (about 60 grams per million Btu [mmBtu] of crude produced) result from venting associated gas. Also, some CO_2 emissions are produced from flaring of associated gas. These emissions are considered in GREET.

NG-Based Fuel Cycles

Among the six NG-based fuel cycles (Table 1), production of methanol, FTD, DME, and H_2 consumes the largest amounts of energy. In evaluating the near-term technology options, I assumed these fuel production energy efficiencies: 65% for methanol, 57% for FTD, 65% for DME, and 68% for H_2. For the long-term technology options, I assumed the following efficiencies: 70% for methanol, 60% for FTD, 70% for DME, and 70% for H_2. As one can see, improvements in energy efficiencies are assumed over time. Compression of NG at refueling stations consumes a significant amount of energy; I assumed an efficiency of 95% for NG compression.

I assumed that production plants for methanol, DME, FTD, and H_2 are near NG fields, and transmission of NG is not needed for these fuels. On the other hand, transmission and distribution of NG are necessary for CNG and NG-fired electric power plants. A considerable amount of NG is leaked during transmission and distribution. This amount was taken into account in this study for these two cycles.

There is a carbon deficiency during conversion of NG to methanol and DME. I assumed that the deficiency is made up within production plants by carbon contained in some additional amount of NG. On the other hand, there is a large amount of carbon released in the form of CO_2 during conversion of NG to H_2. Some have maintained that the generated CO_2 will be sequestered to underground NG wells or will be collected as a commercial product (Williams 1996). If hydrogen is massively produced from natural gas for motor vehicle applications, and if the U.S. commits itself to stabilize or reduce its total GHG emissions, CO_2 from hydrogen plants could be sequestered for commercial uses (such as enhanced oil and NG recovery) and/or for achieving additional CO_2 emissions reductions. Since hydrogen is assumed only as a long-term fuel in this study, I assumed that in 2015, 50% of NG-based hydrogen plants will sequester the CO_2 emissions generated during hydrogen conversion. Without this assumption, GHG benefits of using NG-based H_2 in FCVs are reduced by about 10%.

LPG is produced from crude and NG. I combined the two cycles by assuming that 60% of LPG is produced from NG and the remaining 40% from crude. This is about the current average split for U.S. LPG production.

Corn and Biomass to Ethanol Cycles

The key activities for the corn-to-ethanol cycle are corn farming and ethanol production. The productivity of U.S. corn farming has increased continuously over the past 30 years — by over 50% — to a level of about 125 bushels per harvested acre. The U.S. Department of Agriculture (USDA) predicts that corn yield will continue to increase at about 1.5% per year from now until 2010 (Price et al. 1998). On the other hand, fertilizer and energy inputs per acre of cornfield have stabilized or declined slightly. Consequently, energy and chemical usage intensity in Btu and grams per bushel of corn harvested has declined in the past 30 years. This trend will probably continue for the foreseeable future. Using corn farming data in sixteen major corn-growing states, I estimated that in 1996 (an average year in terms of weather and corn yield), the energy and chemical usage intensity for U.S. corn farming was 21,100 Btu of farming fuels, 489 grams of nitrogen fertilizer, 184 grams of phosphate fertilizer, and 220 grams of potash fertilizer per bushel of corn harvested. I reduced these rates by 10% to approximate usage intensities for year 2005. The reduced rates remain the same for year 2015.

As shown above, a large amount of nitrogen fertilizer is used for corn farming. Some of the nitrogen in the applied fertilizer eventually becomes N_2O emissions, either directly from soil or indirectly from runoff water, both through nitrification and denitrification processes. Following a detailed review of studies for U.S. Midwest cornfields, Wang et al. (1997) concluded that about 1.5% of the nitrogen in nitrogen fertilizer applied to cornfields becomes nitrogen in N_2O emissions to the atmosphere. This value was adopted in this study.

At present, the United States produces about 1.5 billion gallons of corn ethanol a year, consuming about 6% of annual U.S. corn production. A substantial increase in ethanol production will require a larger amount of corn available. The additional corn could come from (1) increased corn production through increased corn yield per acre, switching of cropland from other crops (such as soybeans) to corn, and/or use of idled cropland and/or pastureland; (2) reduced U.S. corn and corn product exports to other countries; and/or (3) reduced use of corn for other applications, such as animal feed. If land use patterns are changed by increased ethanol production, a different profile of CO_2 emissions may result, because biomass production can be different for different crops and vegetation, and growing different crops and vegetation can change the original soil carbon content in land.

To estimate potential land use changes, the USDA's Economic Research Service simulated the changes in production and consumption of major crops caused by corn ethanol production (Price et al. 1998). USDA's simulations were based on an increase in corn use for ethanol production of 50 million bushels per year, beginning in 1998. By 2010, 650 million more bushels of corn a year would be used for ethanol production to double ethanol production from the current level. On the basis of USDA simulation results, Wang et al. (1998) estimated a net CO_2 emission rate of 390 grams per bushel of corn harvested from potential land use changes in both U.S. and grain-importing countries to accommodate increased U.S. ethanol production. This emission rate was included in the calculations for this study.

Ethanol plants are the largest energy-consuming stage of the entire corn-to-ethanol fuel cycle. I included both dry and wet milling ethanol plants in this analysis. Ethanol production R&D efforts in the last two decades have concentrated on increasing ethanol yield and reducing plant energy use. Consequently, newly built ethanol plants are generally more energy efficient than old plants, but energy use in older ethanol plants has also been reduced through process integration. Wang et al. (1997) estimated energy use of 41,400 and 40,300 Btu per gallon of ethanol produced in current dry and wet milling ethanol plants, respectively. For near-term future ethanol plants in operation around 2005, they estimated energy uses of 36,900 and 34,000 Btu per gallon for dry and wet milling plants, respectively. I reduced these energy use rates by 10% for the year 2015.

While dry mills produce ethanol and distillers' grains and solubles (DGS), wet mills produce corn gluten feed, corn gluten meal, and corn oil, together with ethanol. I estimated the GHG emission credits from the co-products with the following procedure: (1) estimate the amount of co-products produced in the ethanol plant; (2) identify the products to be displaced by the co-products; (3) determine displacement *ratios* between co-products and displaced products; and (4) estimate energy use and emissions for producing the displaced products (see Wang et al. [1998] for parametric details).

Both woody biomass (e.g., hybrid poplar) and herbaceous biomass (e.g., switchgrass) can be used to produce cellulosic ethanol. Based on data provided by Marie Walsh (1998) of Oak Ridge National Laboratory, I assumed that production of one dry ton of woody biomass requires 234,770 Btu of farming fuels, 709 grams of nitrogen fertilizer, 189 grams of phosphate fertilizer, and 331 grams of potash fertilizer; and production of one dry ton of herbaceous biomass requires 217,230 Btu of farming fuels, 10,633 grams of nitrogen fertilizer, 142 grams of phosphate fertilizer, and 226 grams of potash fertilizer. Transportation of biomass from farms to ethanol plants was estimated to require 308,400 Btu per dry ton of woody biomass and 179,300 Btu per dry ton of herbaceous biomass.

Farming of biomass in marginal land increases the amount of aboveground biomass, underground biomass, and soil carbon content, all of which cause carbon sequestration. According to Delucchi (1998), the carbon sequestration rate is about 225,000 grams per dry ton of woody biomass produced and 97,000 grams per dry ton of herbaceous biomass produced.

At cellulosic ethanol plants, the unfermentable biomass components, primarily lignin, can be used to generate steam (needed in ethanol plants) and electricity in cogeneration systems. Recent simulations of cellulosic ethanol production by National Renewable Energy Laboratory indicated an ethanol yield of 76 gallons per dry ton of hardwood biomass for ethanol plants to be in operation around year 2004 (Wooley 1998). Such ethanol plants consume 2,719 Btu of diesel and generate 1.73 kWh of electricity per gallon of ethanol produced. For cellulosic ethanol plants in operations in year 2010, the simulations indicated an ethanol yield of 98 gallons per dry ton of hardwood biomass. The plants will consume 2,719 Btu of diesel and generate 0.56 kWh of electricity per gallon of ethanol produced. The results for year 2010 plants were used in this study to simulate long-term cellulosic ethanol. While combustion of lignin undoubtedly produces CO_2 emissions, these emissions come from the atmosphere through the photosynthesis process during biomass growth. Thus, CO_2 emissions from lignin combustion at ethanol plants were treated as being zero. For the same reason, CO_2 emissions from ethanol combustion in ethanol vehicles were treated as being zero.

The electricity generated in cellulosic ethanol plants was assumed to be exported to the electric supply grid to offset electricity generation from conventional electric power plants. Energy and emissions credits for the electricity credit were calculated within GREET by taking into account the emissions associated with electricity generation in electric power plants. One key question is what electric power plants would provide electricity in the absence of cellulosic ethanol electricity. The answer depends on the location (region) of ethanol plants, scale of cellulosic ethanol production, and many other factors, which all are subject to speculations. I assumed that cellulosic ethanol electricity would displace grid electricity generation under the average U.S. electricity generation mix, in which over 50% of electricity is generated from coal (see Table 3).

Soybeans to Biodiesel Cycle

While biodiesel can be produced from vegetable oils and animal fats, I examined production of biodiesel only from soybeans in this study. This production pathway includes: production of chemicals (i.e., fertilizers and pesticides), transportation of chemicals, soybean farming, soybean transportation to soy oil plants, soy oil production, transesterification of soy oil to biodiesel, transportation of biodiesel to bulk terminals for blending with petroleum diesel, and distribution of biodiesel blend to service stations.

The assumptions regarding biodiesel in this study were primarily from Sheehan et al. (1998). Based on farming data from fourteen major soybean production states, Sheehan et al. estimated energy and chemical usage intensity for soybean farming of 35,710 Btu for farming fuels, 132 grams for nitrogen fertilizer, 414 grams for phosphate fertilizer, and 705 grams for potash fertilizer per bushel of soybeans harvested in 1990. I reduced the values by 10% to approximate energy and chemicals usage for years 2005 and 2015.

Production of biodiesel involves two major steps: soy oil extraction and transesterification. For year 2015, energy use was estimated to be 5,867 Btu per pound of soy oil produced during soy extraction. During this stage, a large amount of soy meal is produced with the soy oil. GHG emission credits need to be estimated for the produced soy meals. One of three approaches can be used to determine the credits: the weight-based, the market value-based, or the displacement-based approach. In theory, the displacement-based approach should be used; however because not enough data are available to allow use of this approach to accurately estimate emission credits, I used the market value-based approach to approximate the GHG emission credits for soy meals. With this approach, 66.4% of revenue of soybeans is from soy meal and 33.6% from soy oil.

Sheehan et al. (1998) estimated that soy oil transesterfication requires about 2,909 Btu per pound of biodiesel produced. Glycerine, a specialty chemical, is produced with biodiesel during transesterification. Again, the market value-based approach is used to approximate glycerine emission credits. Based on this approach, 29.9% of revenue of soy oil is from glycerine and 70.1% from biodiesel.

Electric Power Generation

Electricity is used in battery-powered EVs and grid-connected HEVs and during upstream fuel-cycle stages. GHG emissions of electricity generation are determined mainly by the type of fuels used. The marginal electric generation mix for charging EVs should be used in estimating their GHG effects. The marginal mix is determined by the regions where EVs will be introduced, the number of EVs to be introduced, and the type of new electric power plants to be added, all of which are case-specific and subject to uncertainties. Instead, I used average generation mix in this study. Because the mix is the most important factor in determining GHG emissions of EVs, I analyzed their GHG effects with three different electric generation mixes — the U.S. generation mix, the California generation mix, and the Northeast U.S. generation mix. Table 3 presents the three generation mixes. On the other hand, I used the U.S. generation mix for evaluating grid-connected HEVs and for determining GHG emissions of up-stream fuel-cycle activities.

Table 3 Electric Generation Mixes Used in This Study[a] (%)

	Coal	Oil	NG	Nuclear	Others[b]
Year 2005					
U.S.	53.8	1.0	14.9	18.0	12.3
California	7.0	0.2	30.6	14.1	48.1
Northeast U.S.	28.2	2.5	31.6	26.3	11.4
Year 2015					
U.S.	54.0	0.8	21.1	12.4	11.7
California	7.0	0.2	30.6	14.1	48.1
Northeast U.S.	26.3	1.6	44.4	17.0	10.7

[a] The U.S. and the Northeast U.S. mixes were based on Energy Information Administration's projections (EIA 1997); the California mix was based on the California Energy Commission's projections (California Department of Finance 1996).
[b] Others here include hydroelectric power plants, geothermal power plants, and wind power plants. They are treated as zero-emission plants.

In the electric utility industry, advanced, efficient combustion technologies are being introduced to NG- and coal-fired power plants to reduce plant fuel costs. I assumed that the combined-cycle turbine technology, with an energy efficiency of 50%, would account for 30% of the NG power plant capacity nationwide by 2005 and for 45% by 2015. For coal-fired power plants, I assumed that advanced coal technologies, such as pressurized fluid bed combined-cycle and integrated gasification combined-cycle technology, with an energy efficiency of 38%, would account for 5% of the coal power plant capacity by 2005 and for 20% by 2015.

Vehicle Fuel Economy

Fuel economy of alternative-fueled and advanced vehicles is the most significant factor determining their fuel-cycle GHG emissions. After examining fuel economy performance of existing alternative-fueled vehicle technologies and potential improvements in the future, I assumed their fuel economy changes relative to baseline gasoline vehicles, except for CI engine vehicles, where their fuel economy changes are relative to the fuel economy of diesel vehicles (Table 4).

Table 4 Fuel Economy Changes of Alternative-Fueled and Advanced Vehicle Technologies (Relative to Gasoline Vehicles, except as Noted)[a]

Near-Term Options (Model Year 2000)		Long-Term Options (Model Year 2010)	
Technology	MPG Change (%)	Technology	MPG Change (%)
Bi-fuel CNGVs	-7%	Dedicated CNGVs	5%
Dedicated CNGVs	-5%	Dedicated LPGVs	10%
Dedicated LPGVs	0%	M95 dedicated vehicles	10%
M85 FFVs	5%	E95 dedicated vehicles	10%
E85 FFVs	5%	EVs	300%
EVs	250%	Grid-connected HEVs: RFG	
Grid-connected HEVs: RFG		Grid operation	300%
Grid operation	250%	ICE operation	75%
ICE operation	50%	Grid-independent HEVs: RFG	75%
Grid-indep. HEVs: RFG	50%	Grid-indep. HEVs: RFD	75%
Grid-indep. HEVs: CD[b]	50%	H_2 FCVs	100%
Conven. CI vehicles: CD	10%	MeOH FCVs	85%
CIDI vehicles: CD[b]	25%	RFG FCVs	75%
		EtOH FCVs	75%
		SIDI vehicles: RFG[b]	25%
		Conventional CI vehicles: RFD	10%
		CIDI vehicles: RFD[b]	25%
		CIDI vehicles: DME[b]	25%
		CIDI vehicles: FT50[b]	25%
		CIDI vehicles: BD20[b]	25%

[a] Fuel economy changes are based on gasoline-equivalent fuel economy. A positive number means an increase in fuel economy (i.e., less fuel consumption), a negative number means a decrease in fuel economy, and zero means no change in fuel economy.
[b] Fuel economy changes of CI technologies are relative to fuel economy of conventional CI vehicles fueled with diesel. Gasoline-equivalent fuel economy of conventional CI vehicles is about 10% higher than that of conventional gasoline vehicles.

I assumed a fuel economy of 28 mpg for 2000 model-year baseline GVs and 30 mpg for 2010 model-year baseline GVs, which were projected by EIA (1997). For grid-connected HEVs, I assumed a VMT split of 30% and 70% between grid-powered VMT and vehicle engine-powered VMT, which was based on Argonne simulations of HEV designs and operations.

Results

Near-Term Technologies

Figure 2 presents per-mile GHG emission changes for near-term technologies relative to baseline GVs fueled with RFG. M85 FFVs have virtually the same emissions as GVs, despite the fact that tailpipe GHG emissions from FFVs are lower than those from GVs mainly because of the greater fuel economy of FFVs. Methanol production, with an energy efficiency of 65% in the near term, produces far greater GHG emissions than petroleum refining does.

The next group of near-term technologies achieves around a 10% reduction in GHG emissions. This group includes conventional CI vehicles fueled with CD, bi-fuel CNGVs, dedicated CNGVs, and after-market converted LPGVs. The reduction in GHG emissions achieved by CI vehicles is attributable to their 10% improvement in gasoline-equivalent fuel economy (see Table 4). The emissions reductions for CNGVs and LPGVs result from reduced GHG emissions during upstream stages.

The third group, which includes CIDI vehicles fueled with CD and E85 FFVs, achieves about 25% reduction in GHG emissions. Significant improvements in fuel economy account for the emissions reduction for the CIDI vehicles. The reduction by E85 FFVs is attributable to carbon sequestration during corn farming, which more than offsets GHG emissions during corn farming and ethanol production.

The fourth group achieves 30-40% reductions in GHG emissions. The emissions reductions for this group, which includes EVs with the U.S. generation mix and the three HEV types, result from their greatly improved fuel economy.

The fifth group includes EVs with the California and the Northeast U.S. electric generation mix. Powered with electricity from the Northeast U.S. generation mix, EVs achieve a near 60% reduction in GHG emissions, and powered with electricity from the California generation mix, a near 80% reduction. In both cases, reductions are caused by the EVs' greatly improved fuel economy and the fact that over 60% of electricity is generated from nuclear power and renewable sources in California and that a smaller amount of electricity is generated from coal in the Northeast United States than in the rest of the country.

Figure 3 shows GHG emissions of near-term technologies by fuel-cycle stage. For most internal combustion engine vehicles, emissions from vehicle operations account for the majority of the total fuel-cycle emissions. For EVs under the three electric generation mixes, as expected, electricity generation accounts for the majority of the total emissions. Electricity generation also accounts for a large portion of the total emissions for grid-connected HEVs. For E85 FFVs, ethanol production accounts for a large portion of the total emissions. In general, upstream GHG emissions for different fuels are distinctly different. This figure clearly shows that comparison of vehicular GHG emissions only among different technologies can be misleading in trying to rank GHG reduction potentials of the technologies.

Figure 4 presents the contributions of the three GHGs to total GHG emissions. Note that emissions of CH_4 and N_2O, as presented in the figure, are already CO_2-equivalent emissions by adjusting actual emissions of the two with their GWPs. In all the cases, CO_2 emissions dominate the total GHG emissions. CH_4 emissions are considerable for bi-fuel and dedicated CNGVs. N_2O emissions for E85 FFVs, which are mainly from nitrification and denitrification of nitrogen fertilizer, are significant. In general, the contribution of N_2O emissions to total GHG emissions is larger than that of CH_4 emissions, primarily because of the much greater GWP for N_2O than for CH_4 (310 vs. 21).

Long-Term Technologies

Figure 5 shows fuel-cycle GHG emission reductions for long-term technology options relative to long-term baseline GVs fueled with RFG. In terms of the level of GHG emissions reductions, there are three distinct groups. The first group — SIDI vehicles fueled with RFG; conventional CI vehicles fueled with RFD; CIDI vehicles fueled with RFD, FTD50, BD20, and DME; dedicated CNGVs; dedicated M95 vehicles; and OEM produced LPGVs — achieves GHG emissions reductions of 10-30% (CIDI vehicles fueled with BD20 achieve a reduction of more than 35%). Emissions reductions by SIDI and CIDI vehicles are mainly caused by their significantly improved fuel economy. The additional reduction by BD20 relative to the other three fuels for CIDI vehicles results from the carbon sequestration that occurs during soybean farming. Improved fuel economy and reduced upstream emissions (for CNGVs and LPGVs) account for the emission reductions for dedicated CNGVs, M95 vehicles, and LPGVs.

The second group — dedicated E95 vehicles, EVs with the U.S. and northeast U.S. generation mix, the three HEV types, and FCVs fueled by methanol, RFG, and NG-based hydrogen — achieves 40–60% reductions in GHG emissions. The emissions reduction by E95 vehicles is caused primarily by carbon sequestration during corn farming. The reductions by other vehicle types are caused by their greatly improved fuel economy.

The third group, including EVs with the California electric generation mix, E95 dedicated vehicles fueled with cellulosic ethanol, and FCVs fueled with solar hydrogen and cellulosic ethanol, achieves over 80% reductions in GHG emissions. Additional GHG emission reductions by EVs with the California generation mix are attributable to the fact that over 60% of electricity is generated from nuclear and renewable sources under this mix. Use of cellulosic ethanol achieve GHG emission reductions greater than 90% because (1) production of cellulosic ethanol in ethanol plants produces zero CO_2 emissions (carbon in lignin burnt in ethanol plants is from the atmosphere), and (2) the produced electricity from cellulosic ethanol plants displaces some electricity generation in fossil fuel electric power plants, which offsets GHG emissions in those plants. The more than 100% reduction by cellulosic ethanol FCVs is caused by emissions credits from electricity credits generated in cellulosic ethanol plants. By nature, solar hydrogen FCVs almost eliminate GHG emissions of baseline GVs.

Figure 6 shows the contribution of each fuel-cycle stage to the total fuel-cycle GHG emissions. Again, emissions from vehicle operations account for the majority of the total emissions for most of the internal combustion engine-based technologies and for FCVs fueled with RFG and methanol. Emissions from fuel production account for the majority of the total emissions for corn-based ethanol (used in both E95 dedicated vehicles and FCVs), EVs, grid-connected HEVs, and hydrogen FCVs. For cellulosic ethanol, the production of feedstocks and fuels generates GHG emission credits (negative emissions because the electricity produced in cellulosic ethanol plants displaces electric generation in fossil fuel electric power plants).

Figure 7 presents the contribution of the three GHGs to the total GHG emissions. For all the technology options, CO_2 emissions account for the majority of the total GHG emissions. For corn and cellulosic ethanol, N_2O emissions are considerable. For dedicated CNGVs, CH_4 emissions are significant. Note that for FCVs fueled with cellulosic ethanol, while N_2O emissions are positive, CO_2 emissions, greater than N_2O emissions, are negative. The negative CO_2 emissions are caused by the displacement effect of the electricity generated in cellulosic ethanol plants.

A comparison of Figures 2 and 5 reveals significantly greater GHG emission reductions by the long-term technologies than the near-term technologies. In this study, while parametric assumptions regarding near-term technologies are based mostly on actual performance data of the technologies already in place, the assumptions regarding long-term technologies are based primarily on their speculative target performance goals. Significant R&D efforts are needed to achieve these target goals. Because of these, there are large uncertainties involved in the results for the long-term technologies. These results should be used with caution. Furthermore, some of the long-term technologies (e.g., CIDI vehicles) must meet stringent emission standards for criteria pollutants. If that challenge is not met, these technologies may not be implemented. Although the GREET model is capable of estimating emissions of criteria pollutants as well as GHGs, estimation of criteria pollutant emissions is beyond the scope of this paper. Results of criteria pollutant emissions are presented in an on-going report, which will be available soon.

The GREET model assesses energy and emission impacts of various alternative transportation technologies as if they were displacing a mile that is otherwise traveled by baseline GVs. The per-mile results themselves provide information about technological potentials of the evaluated technologies in terms of energy and emission effects. These data, an approximation of the actual energy and environmental benefits if the technologies are introduced into the marketplace on a massive scale, are helpful for setting priorities to deal with energy and environmental issues. Once introduced into the marketplace, a technology is judged on the basis of its energy and emission benefits as determined by the per-mile results and its success in displacing baseline gasoline and diesel technologies. Some researchers argue that the actual displacement ratio between alternative technologies and baseline technologies may not be one-for-one mile, because the addition of alternative technologies may cause the prices of existing technologies to go down, inducing additional use of existing and new technologies. The price effect is generally not considered in the GREET model, nor in many other fuel-cycle models. To address the full price effects and the technological potentials, some type of economic general equilibrium models need to be run together with the so-called "technology assessment" models such as GREET; that kind of study would allow a more precise estimate of quantitative changes in energy use and emissions caused by introduction of new technology.

However, the amount of good delivered with the introduction of the new technology is changed as well. While a general equilibrium model can estimate changes in energy use and emissions, it typically does not address the monetary and non-monetary benefits of the increased use of a given technology. In the case of alternative transportation technologies, one change is vehicle miles traveled. Thus, each modeling approach has its limitations. The extent of these limitations depends partly on what the researcher hopes to achieve in evaluating a given technology.

Conclusions

The estimated per-mile GHG emissions results from this study show that introduction of alternative transportation fuels and advanced vehicle technologies can help reduce transportation GHG emissions. Of the near-term technologies evaluated, EVs, HEVs, CIDI vehicles, and E85 FFVs reduce fuel-cycle GHG emissions by more than 25%. EVs powered by electricity generated primarily from nuclear and renewable sources can reduce GHG emissions by 80%. Other alternative fuels such as CNG and LPG offer limited, but positive, GHG emissions reduction benefits.

Many of the long-term technologies evaluated can reduce GHG emissions by over 40%; some by over 80%. These technologies include EVs, HEVs, FCVs, and E95 vehicles fueled with cellulosic ethanol. The large GHG reduction potentials offered by these technologies warrants the largely public R&D efforts that are necessary to overcome their technological hurdles for their introduction into the marketplace. For example, the on-going efforts of developing and commercializing HEVs and FCVs by the Partnership for a New Generation of Vehicles will undoubtedly advance HEV and FCV technologies. On the other hand, near-term technologies are needed for two primary reasons. First, U.S. VMT continues to grow in the foreseeable future, so reductions in transportation-related GHG emissions through technology improvements are needed immediately. The near-term technologies, already available in the marketplace, offer immediate benefits. Second, even as long-term transportation technologies may become mature sometime in the future, the supporting infrastructure may not be developed as quickly and may not be in place to support the new technologies. Introduction of some near-term technologies can help ensure that the infrastructure for long-term technologies be gradually established. That is, near-term technologies that can help bridge the gap between existing and long-term technologies present an opportunity for potential energy and environmental gains over the long term. Both near- and long-term technologies, then, can contribute to achieving the GHG emissions reduction goal that the United States committed to in Kyoto.

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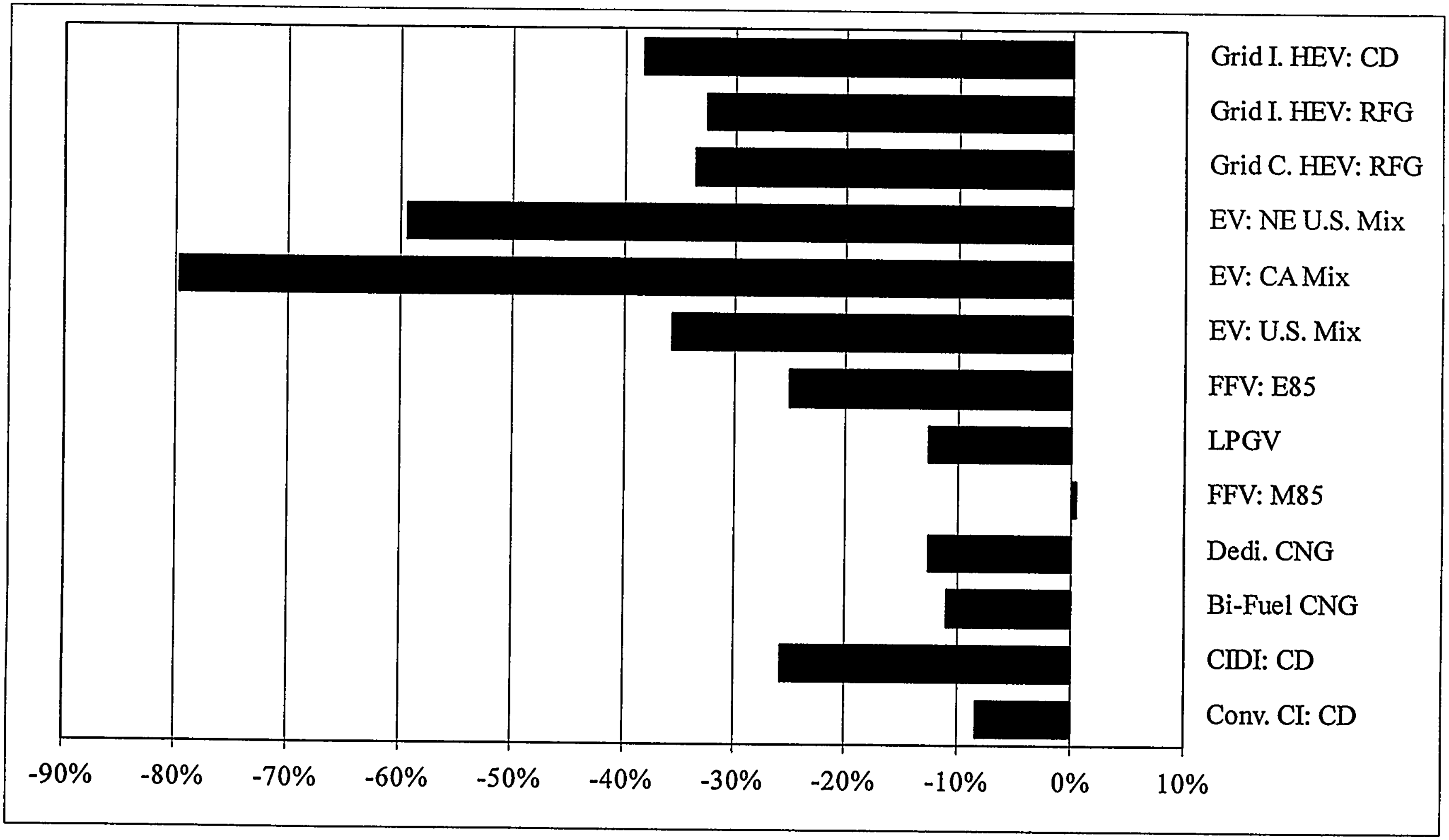

Figure 2 Per-Mile GHG Emissions Reductions by Near-Term Alternative Transportation Technologies (% relative to GVs fueled with RFG)

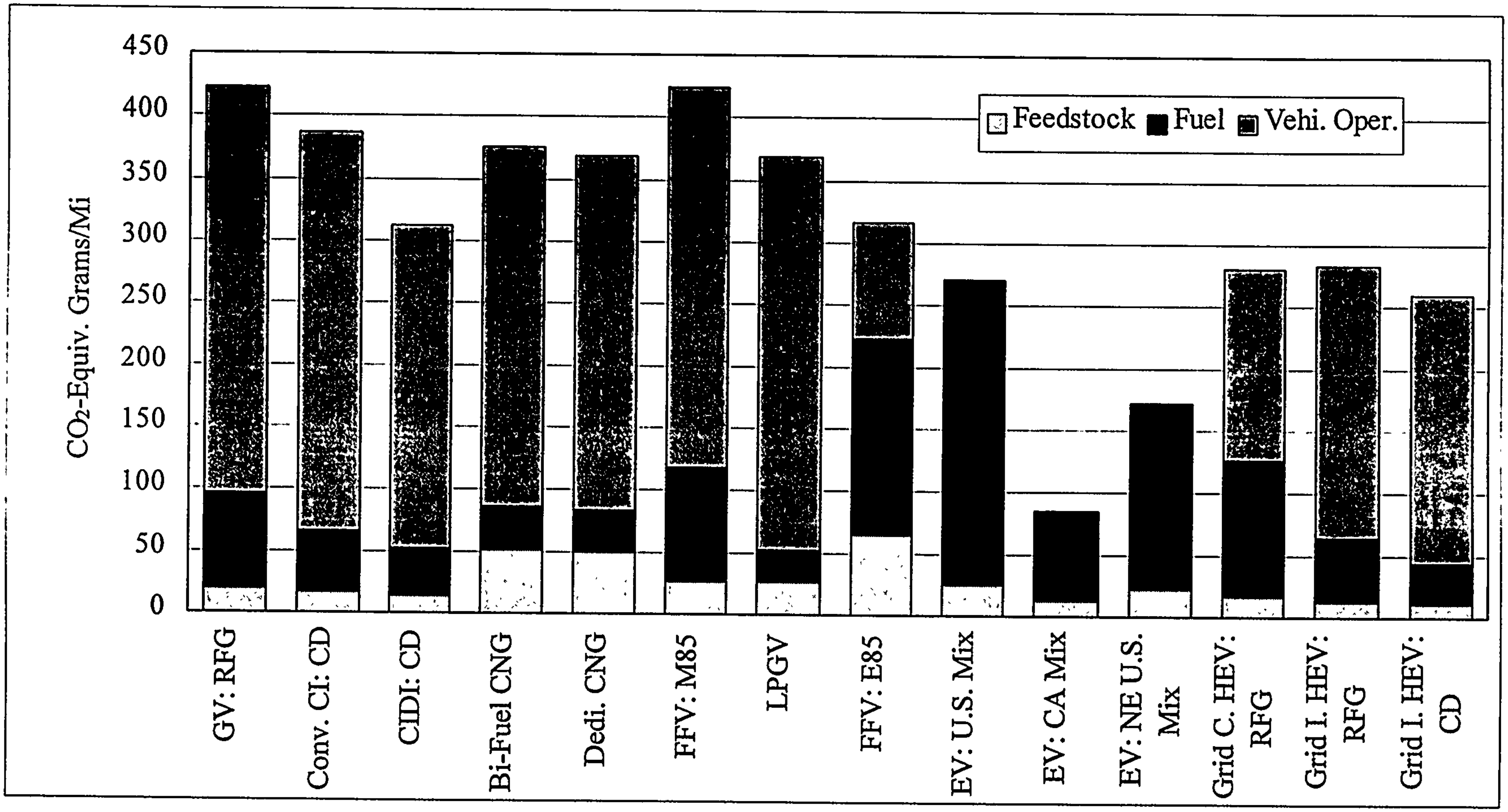

Figure 3 Per-Mile GHG Emissions of Near-Term Transportation Technologies by Fuel-Cycle Stages

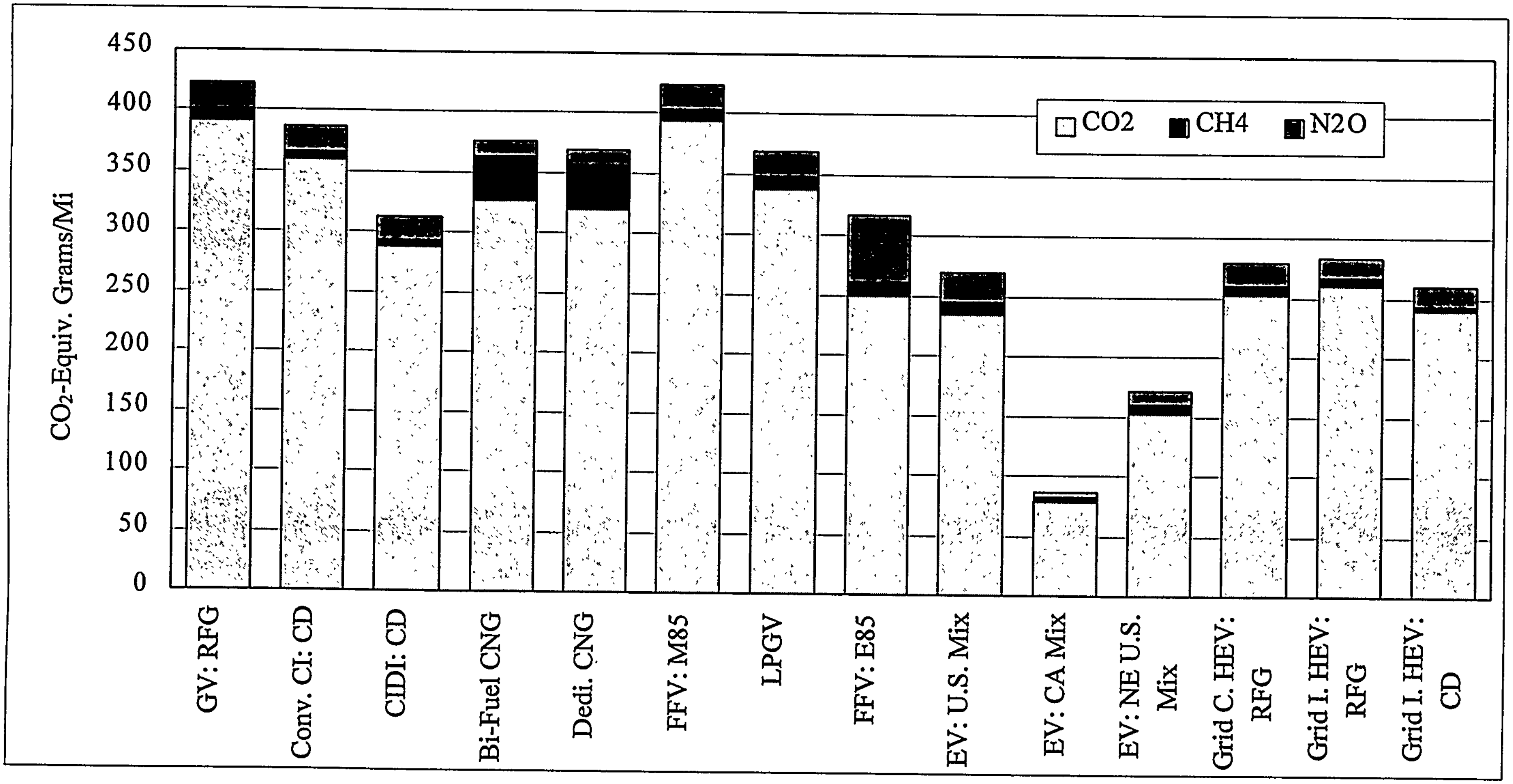

Figure 4 Per-Mile GHG Emissions of Near-Term Transportation Technologies by GHG

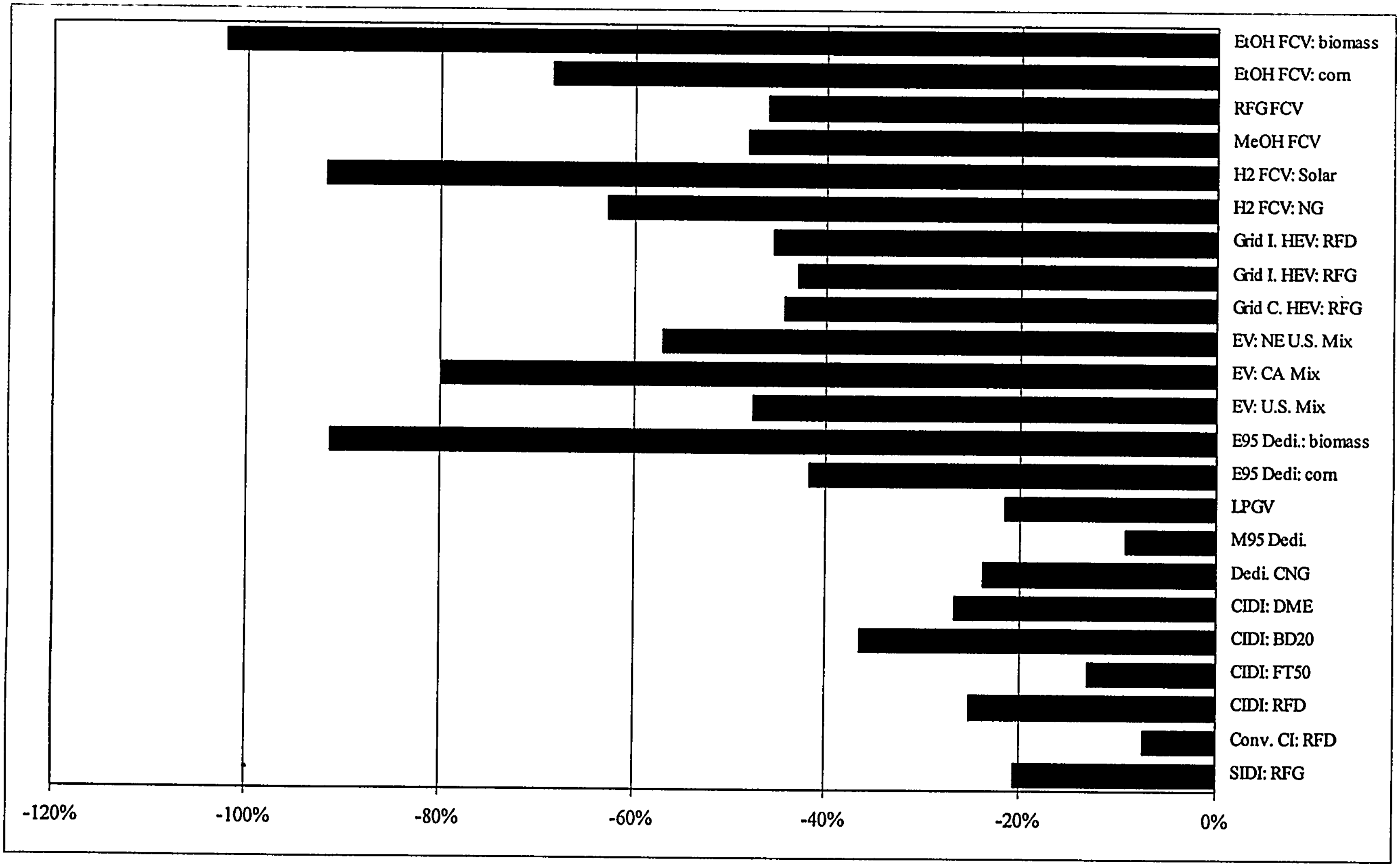

Figure 5 Per-Mile GHG Emissions Reductions by Long-Term Alternative Transportation Technologies (% relative to GVs fueled with RFG)

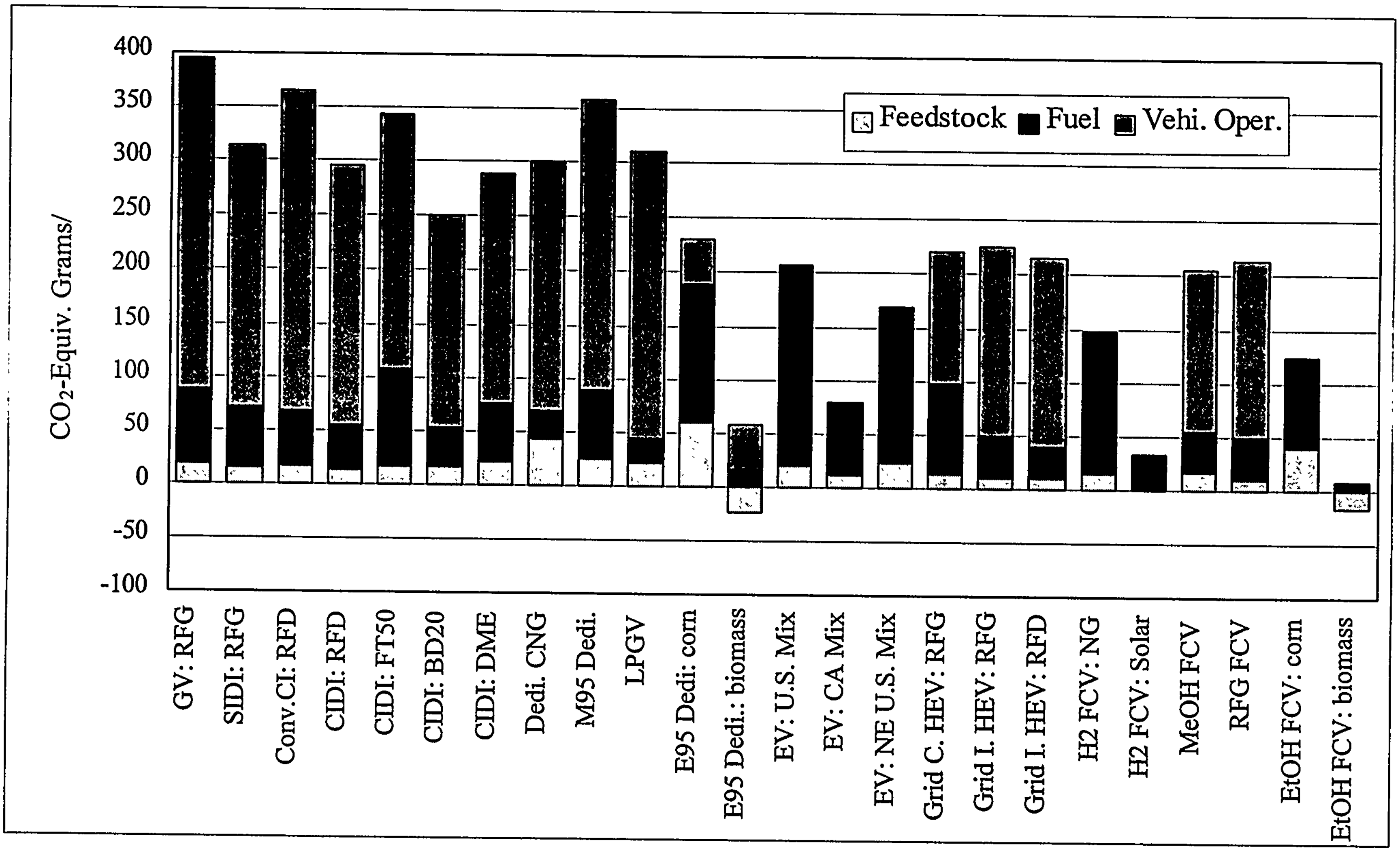

Figure 6 Per-Mile GHG Emissions of Long-Term Transportation Technologies by Fuel-Cycle Stages

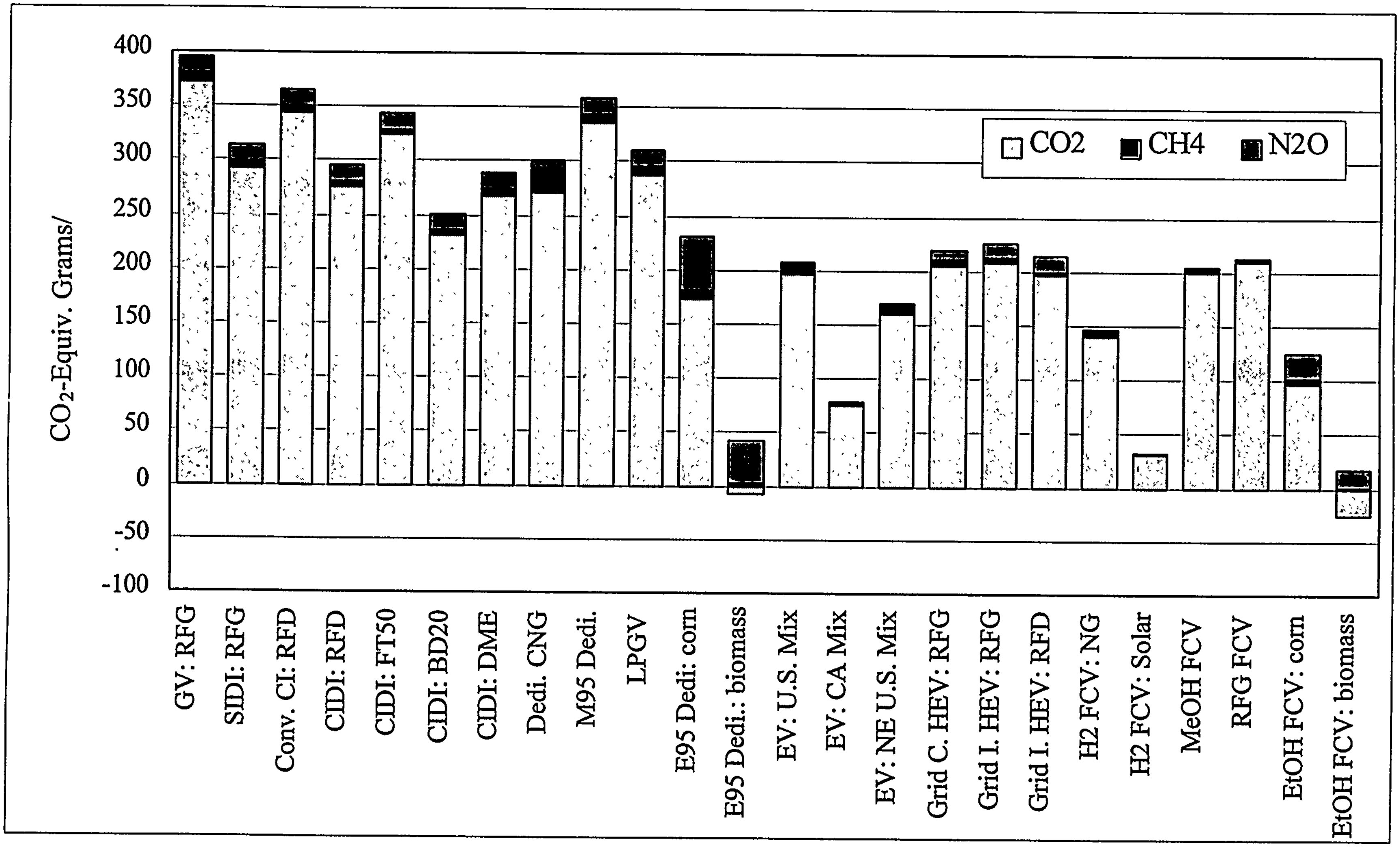

Figure 7 Per-Mile GHG Emissions of Long-Term Transportation Technologies by GHG