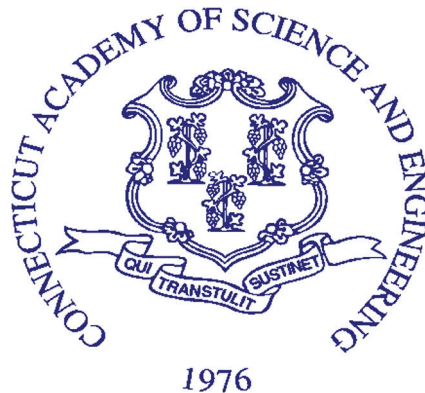


SUSTAINABILITY STRATEGIES TO MINIMIZE THE CARBON FOOTPRINT FOR CONNECTICUT BUS OPERATIONS

FEBRUARY 2018

A REPORT BY

THE CONNECTICUT
ACADEMY OF SCIENCE
AND ENGINEERING



FOR

CONNECTICUT DEPARTMENT OF
TRANSPORTATION

SUSTAINABILITY STRATEGIES TO MINIMIZE THE CARBON FOOTPRINT FOR CONNECTICUT BUS OPERATIONS

A REPORT BY

THE CONNECTICUT ACADEMY
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SUSTAINABILITY STRATEGIES TO MINIMIZE THE
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16. Abstract: The objective of this study is to identify a strategy to minimize the carbon footprint for CTDOT-contracted bus operations in Connecticut, bus systems owned by CTDOT and branded as <i>CTtransit</i> , including resulting benefits and challenges. The economic value of investments necessary to achieve strategy goals in terms of initial capital costs, ongoing operating costs including life-cycle costs, and overall benefits/savings were considered and presented in an easy-to-read and comprehensible format. The carbon footprint was calculated/estimated for all CTDOT-contracted bus operations. This analysis looked at the carbon footprint associated with day-to-day operations of equipment and facilities. The recommendations are consolidated into four categories: rolling stock, facilities, resilience, and monitoring. The primary conclusion is as follows: the most effective strategy for minimizing the carbon footprint of CTDOT-contracted bus operations is to reduce greenhouse gas (GHG) emissions through the replacement of the existing fleet with battery electric buses over the next 12 years. Battery electric buses outperform existing and alternative fuel technologies with respect to the reduction of GHG emissions and provide the additional benefit of having the second lowest expected life-cycle cost of alternative fuel technologies. Additionally, CTDOT can effect further reductions by adopting recommendations and standards for retrofitting existing bus facilities and constructing new bus facilities that are designed to reduce GHG emissions and energy consumption. In adopting these strategies, CTDOT should consider the resilience of the fleet and its operations, and institute a practice of monitoring, and modifying as needed, the assumptions of this analysis and updating these strategies accordingly.			
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GLOSSARY

APTA	American Public Transportation Association
BEB	Battery Electric Bus
BCA	Benefit-Cost Analysis; alternatively denoted as Cost-Benefit Analysis
CH ₄	Methane
CNG	Compressed Natural Gas
CO ₂	Carbon Dioxide
CO _{2e}	Carbon Dioxide Equivalent
COBRA	EPA's Co-Benefits Risk Assessment Screening Model
DEEP	Connecticut Department of Energy and Environmental Protection
EPA	US Environmental Protection Agency
FCB	Hydrogen Fuel Cell Bus
FTA	Federal Transit Administration
GHG	Greenhouse Gas(es)
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LBT	Long Beach Transit
LCCA	Life-Cycle Cost Analyses
LDV	Light-Duty Vehicle
MT	Metric Ton
MMT	Million Metric Tons
MWh	Megawatt Hours
N ₂ O	Nitrous Oxide
NREL	National Renewable Energy Laboratory
NYMTA	New York Metropolitan Transit Authority
TCRP	Transit Cooperative Research Program
USDOE	US Department of Energy
VMT	Vehicle Miles Traveled
VTA	Martha's Vineyard Transit Authority
VTPI	Victoria Transport Policy Institute

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EXECUTIVE SUMMARY

This study was conducted for the Connecticut Department of Transportation (CTDOT) by the Connecticut Academy of Science and Engineering (CASE) to identify a strategy to achieve a vision of a pathway to minimize the carbon footprint for CTDOT-contracted bus operations in Connecticut (bus systems owned by CTDOT and branded as *CTtransit*), including resulting benefits and challenges. The economic value of investments necessary to achieve strategy goals in terms of initial capital costs, ongoing operating costs including life-cycle costs, and overall benefits/savings were considered and utilized to estimate the efficiency of the identified strategies. The carbon footprint was calculated/estimated for all CTDOT-contracted bus operations. Additionally, this analysis looked at the carbon footprint associated with day-to-day operations of bus facilities and equipment. The study did not address carbon emissions associated with the supply chain or rail operations.

OVERVIEW

Study research methods included the following:

- a literature review, supported by other information-gathering methods, to identify strategies developed by other transit agencies, as well as other industries, as appropriate, to reduce greenhouse gas emissions
- review methods for applicability for use by CTDOT to measure progress for the reduction of carbon footprint
- conduct a calculation/estimation of the carbon footprint for all CTDOT-contracted bus operations. The analysis included an inventory of the carbon footprint associated with day-to-day operations of facilities and equipment
- review the findings and recommendations from the 2014 CASE study on *Energy Efficiency and Reliability Solutions for Rail Operations and Facilities* for applicability
- interviews, surveys, and guest presentations to the CASE Study Committee to inform the study findings and recommendations

The study report includes the following sections: Background, Literature Synthesis, Public Transportation in Connecticut, Economic Cost Analysis Overview, Scenario Development and Analysis, Recommendations, and References. Appendices include a Bibliography by Topic for References Reviewed (Not Cited), Models for Estimating Transportation Emissions, Examples of Transit System Sustainability Plans, Performance Metrics Examples, Sample Battery Electric Bus Procurement Guidelines, Battery Electric Bus Deployment Examples, APTA's Energy Saving Strategies for Transit Facilities, Output from Baseline Scenarios, and Study Committee Meetings and Guest Speakers.

BRIEF STATEMENT OF PRIMARY CONCLUSION

The most effective strategy for minimizing the carbon footprint of CTDOT-contracted bus operations is to reduce greenhouse gas (GHG) emissions through the replacement of the

existing fleet with battery electric buses over the next 12 years. Battery electric buses outperform existing and alternative fuel technologies with respect to the reduction of GHG emissions and provide the additional benefit of having the second lowest expected life-cycle cost of alternative fuel technologies. Additionally, CTDOT can effect further reductions by adopting recommendations and standards for retrofitting existing bus facilities and constructing new bus facilities that are designed to reduce GHG emissions and energy consumption. In adopting these strategies, CTDOT should consider the resilience of the fleet and its operations, and institute a practice of monitoring, and modifying as needed, the assumptions of this analysis and updating these strategies accordingly.

RECOMMENDATIONS

The eight transit divisions under the *CTtransit* brand operate a fleet of 549 buses on behalf of CTDOT (CTDOT-contracted bus operations). CTDOT owns the rolling stock and facilities in three of the *CTtransit* divisions (Hartford, New Haven, and Stamford), and only the rolling stock in the remaining divisions (Bristol, Meriden, New Britain, Wallingford, and Waterbury). For the *CTtransit* bus fleet and the three operating and maintenance facilities CTDOT owns, the annual greenhouse gas (GHG) emissions are estimated to be 0.07 MMTCO_{2e}, a small fraction of the roughly 15 MMTCO_{2e} (million metric tons carbon dioxide equivalent) emitted by the transportation sector in Connecticut or the 8 MMTCO_{2e} from light-duty vehicles statewide.

Of the *CTtransit* emissions, 0.05 MMTCO_{2e} is from bus fleet (mobile) emissions, with the remainder split between purchased gases at facilities at 0.015 MMTCO_{2e} and 0.0025 MMTCO_{2e} each for both electricity consumption and refrigeration. This study concludes that the most important strategies that *CTtransit* can deploy to control GHG emission reduction in Connecticut are associated with the rolling stock, though other strategies were considered. The recommendations are consolidated into four categories: rolling stock, facilities, resilience, and monitoring.

Additionally, the source(s) of electricity as fuel for the battery electric buses must be considered, in order to attain maximum GHG emission reduction and to justify the initial capital investments for a battery electric bus fleet. The maximum GHG emission reduction will be achieved only if the state meets its Class I renewable energy source goals for generating electricity.

RECOMMENDATION #1: ROLLING STOCK

Reducing GHG emissions from the *CTtransit* rolling stock was found to be the most impactful strategy. Nine baseline scenarios, the year 2050 GHG profile, and sensitivity analyses were conducted and confirm that battery electric buses are the best fleet option to reduce public transit's GHG emissions and contribute to Connecticut's GHG emission reduction targets. The scenarios presented and analyses conducted were based on assumptions presented in Chapter 5. Battery electric buses were shown to have the second lowest life-cycle cost of the alternative fuel technologies, with hybrid diesel-electric buses comparatively having a slightly lower life-cycle cost of between 0.2% - 6%. This result holds true under all assumptions in the baseline and sensitivity analyses.

Supporting this recommendation further, the local pollutant reduction from eliminating diesel buses from the CTtransit fleet has a combined health benefit estimated at \$2 million - \$9 million in the year 2030, not including intermediate years. These benefits are in addition to the social cost of carbon benefits associated with GHG reduction.

RECOMMENDATION #2: FACILITIES

As reported, CTtransit facilities produce the least significant proportion of CTtransit GHG emissions, though there are several strategies that can help to reduce this further.

- High Performance Building Standards: CTDOT advised that public transit's operating and maintenance facilities are exempt from the state's high-performance building standards as defined in CGS Chapter 298 §16a-38k(a), with additional guidance from the Connecticut Department of Administrative Services: Capital Projects High Performance Buildings Guidelines, as follows:

... to adopt state building construction standards that are consistent with or exceed the silver building rating of the Leadership in Energy and Environmental Design's rating system for new commercial construction and major renovation projects, as established by the United States Green Building Council, including energy standards that exceed those set forth in the 2004 edition of the American Society of Heating, Ventilating and Air Conditioning Engineers (ASHRAE) Standard 90.1 by not less than twenty per cent, or an equivalent standard, including, but not limited to, a two-globe rating in the Green Globes USA design program, and thereafter update such regulations as the Commissioner of Energy and Environmental Protection deems necessary.

CTDOT further advised that energy efficient options would be used whenever possible in the construction of public transit facilities.

Therefore, it is suggested that the state's high performance buildings guidelines, including LEED or Green Globes USA design program specifications, be used as a best practice whenever possible for the construction of public transit facilities, including the new CTtransit Hartford Division Facility. Additionally, internationally recognized standards for achieving near-zero energy consumption and measurable carbon reduction in facilities, such as Passive House, should be considered to further reduce GHG emissions.

- Virtual Net Metering: CTDOT should research the potential and possibility of deploying behind-the-meter installations of renewable energy and the advantages of virtual net metering, and if benefits are determined, include these as part of facilities planning, maintenance and the rehabilitation of existing facilities. According to DEEP, virtual net metering allows state and municipal customers with United Illuminating and/or Eversource who "...operate behind-the-meter generation (Customer Host) to assign surplus production from their generator to other metered accounts (Beneficial Accounts) that are not physically connected to the Customer Host's generator." (DEEP website) Energize Connecticut, an initiative to help homeowners and businesses optimize energy

efficiency and clean energy improvements, provides additional guidance for state customers to encourage the installation of Class I and Class III distributed generation (Energize CT website).

- Other Options: CTDOT should explore other ways to reduce the GHG emissions, including the recommendations in a 2014 CASE study conducted for CTDOT, *Energy Efficiency and Reliability Solutions for Rail Operations and Facilities* (CASE website), as applicable to bus operating and maintenance facilities. These recommendations included conducting an energy audit, transitioning to LED lighting, utilizing radiant floor heating (potentially reducing methane usage, which is purchased by CTtransit primarily for heating), and use of solar PV systems in conjunction with virtual net metering.

RECOMMENDATION #3: RESILIENCE

System resilience is a potential negative consequence from converting to an entirely battery electric bus fleet. If there is an extended power outage, CTtransit might not be able to maintain basic operations or assist in an emergency response for areas that lack electricity. While specific recommendations to address this challenge are beyond the scope of this study, CTDOT should review the 2017 TCRP report, *Improving the Resilience of Transit Systems Threatened by Natural Disasters Volumes 1, 2, and 3: A Guide*. Additionally, the following are important considerations that must be included as part of the GHG reduction strategy:

- Emergency Scenarios: What emergency scenarios and duty cycle should the CTtransit fleet be able to withstand and/or assist with? This decision will frame the minimum amount of operations and rolling stock diversity that need to be maintained for an emergency during which no electrical recharge is available.
- Leveraging Existing Resources: What existing energy resources can CTDOT leverage in an emergency, and for what duration and capacity (# of diesel or hybrid diesel-electric buses)? Such resources may include the state's reserve diesel fuel that currently provides several days' worth of operations. This fuel could be used to power a mixed fleet of diesel/hybrid diesel-electric buses or generators in an emergency to charge the battery electric bus fleet. Emergency operations could also incorporate use of existing facility power plants such as combined cycle fuel cell or micro turbines.
- Other Benefits: Consider the potential benefits of battery electric buses and hybrid diesel-electric buses, such as use of the buses to power emergency shelters, medical facilities or other critical response infrastructure during power outages.

RECOMMENDATION #4: MONITORING

Given the uncertain nature of predictions through 2030 and 2050, it is almost certain that the assumptions underlying this analysis will need to be modified to provide an accurate portrayal of future conditions. To mitigate this situation, CTDOT should adopt a strategy of revisiting this study's analysis on a periodic basis to update the assumptions and/or perform additional sensitivity analyses.

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The following supports this recommendation:

- Conservative assumptions for electricity production (percent of Class I renewables), light-duty vehicle fleet electrification, and battery electric bus price reductions were used whenever possible. If actual numbers are more favorable than the conservative assumptions used for this study's analysis and/or the price of battery electric buses declines more significantly than assumed in the analysis, the results would further support the recommendation to convert to a battery electric bus fleet.
- The baseline scenario analysis assumed a bus fleet turnover cycle that follows the practice used by CTDOT over the past 12 years. CTDOT should evaluate whether an optimized fleet replacement schedule could reduce life-cycle costs and result in even greater GHG reductions.
- To facilitate CTDOT's periodic review and update of strategies to reduce GHG emissions, the methodology used for this study's analysis is available as a tool for the department's use. The Greenhouse Gas Inventory and Life-cycle Cost Tool will be accessible by March 1, 2018, to CTDOT staff via the University of Connecticut's t-HUB: The Public Transportation Data Hub of Connecticut.

The Greenhouse Gas Inventory and Life-cycle Tool should be used to update assumptions and/or perform additional sensitivity analyses. However, the tool was not designed to optimize a bus fleet turnover strategy. Alternative turnover strategies could be evaluated and updated from a set of feasible alternatives, such as a delayed transition to battery electric buses, a mixed fuel technology fleet, or a more uniform turnover of vehicles than the existing fleet turnover cycle.

The Greenhouse Gas Inventory and Life-cycle Tool can also be utilized to input data based on future operating practices and policy developments. CTDOT should use the tool to inform transit-supportive legislation and policies, such as transit-oriented development and complete streets. The input data for this analysis can then be updated based on actual ridership, interest rates and discount rates, to provide an improved estimate of GHG emission reductions and expected life-cycle cost.

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EXECUTIVE SUMMARY

1.0 INTRODUCTION

This study was conducted for the Connecticut Department of Transportation (CTDOT) by the Connecticut Academy of Science and Engineering (CASE) to identify a strategy to achieve a vision of a pathway to minimize the carbon footprint for CTDOT-contracted bus operations in Connecticut (bus systems owned by CTDOT and branded as *CTtransit*), including resulting benefits and challenges. The economic value of investments necessary to achieve strategy goals in terms of initial capital costs, ongoing operating costs including life-cycle costs, and overall benefits/savings were considered and utilized to estimate the efficiency of the identified strategies. The carbon footprint was calculated/estimated for all CTDOT-contracted bus operations. Additionally, this analysis looked at the carbon footprint associated with day-to-day operations of bus facilities and equipment. The study did not address carbon emissions associated with the supply chain or rail operations.

1.1 BACKGROUND

The Connecticut Department of Transportation has observed a demographic change in the makeup of public transportation customers in Connecticut, from principally commuters and transit-dependent people to millennials and others using transit for all travel needs as indicated by growth in off-peak usage and frequency of trips.¹ This change in the makeup of transit customers is linked to increased interest in a return to urban living. This trend has been accelerating both nationally and in Connecticut in recent years — expanding from the historically commuter suburbs of Fairfield County to New Haven, Hartford and beyond.

This change encompasses all aspects of travel and time-of-day usage, including evenings and mid-day travel. It is considered neither cyclical nor temporary, but rather, seems to be based on lifestyle preferences for urban living and interest in sustainability, including increased customer awareness of lifestyle choices with respect to the environment. CTDOT has taken actions recently to reduce its environmental footprint for public transportation through improved facility design and greater vehicle efficiency. However, CTDOT does not have a unifying sustainability strategy to optimize carbon reductions for public transportation operations. Development of a comprehensive strategy to reduce greenhouse gas (GHG) emissions will provide CTDOT with an opportunity to align its public transit services and future investment decisions with emerging customer preferences and to achieve broader statewide goals related to the state's climate change initiatives.

As stated on the Federal Transit Administration's website (FTA website):

Greenhouse gases such as carbon dioxide trap heat in the Earth's atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC), Greenhouse gas emissions from human activities, primarily the burning of fossil fuels, are causing global warming.

1 For demographic changes in public transportation ridership, see: Sakaria, Neela and Stehfest, Natalie. *Millennials and Mobility: Understanding the Millennial Mindset*. Latitude Research: (TCRP) Project J-11, American Public Transportation Association, Washington, DC, 2013; and Dutzik, Tony and Baxandall, Phineas. U.S. PIRG Education Fund. *A New Direction: Our Changing Relationship with Driving and the Implications for America's Future*. Frontier Group and the U.S. PIRG Education Fund, Spring 2013.

The IPCC's latest report lists several projected impacts of climate change, including sea level rise, more intense storms and droughts, biodiversity loss, reduced agricultural yields, and water supply stress. The report represents the consensus of world's leading climate scientists and was approved by member governments, including the United States. The report concludes that greenhouse gas emissions must be reduced by 50 to 85% by 2050 in order to limit global warming to 4 [3.6] degrees Fahrenheit, avoiding many of the worst impacts of climate change (IPCC 2007).

Transportation accounts for 29 percent of U.S. GHG emissions. (USDOT website) [Note: In Connecticut, the transportation sector in 2014 accounted for 32% of the state's total energy consumption (EIA [b] website) and in the process produced about 42% of the state's GHG emissions in 2013 (EIA[c] website)].

Strategies for reducing transportation emissions fall into four categories: 1) increasing vehicle efficiency, 2) lowering the carbon content of fuels, 3) reducing vehicle miles traveled (VMT), and 4) improving system efficiency. Public transportation can reduce GHG emissions by providing a low emissions alternative to driving and facilitating compact development (thus reducing VMT [for all vehicles]), as well as by minimizing the carbon footprint of its operations.

1.2 PUBLIC TRANSPORTATION AND CLIMATE CHANGE INITIATIVES

Figure 1.1 provides a timeline of major milestones for international, national, regional and state actions related to public transportation and climate change discussed in this report.

Considered by many the most successful environmental global action, The Montreal Protocol on Substances that Deplete the Ozone Layer is designed to reduce the production and consumption of ozone-depleting substances in order to reduce their abundance in the atmosphere, and thereby protect the Earth's fragile ozone layer. The original Montreal Protocol was agreed upon on September 16, 1987, and became effective January 1, 1989 (UN Ozone Secretariat website). The Montreal Protocol was signed by 197 countries – the first treaty in the history of the United Nations to achieve universal ratification. The United States signed the Montreal Protocol in 1987 and, according to the US Environmental Protection Agency (EPA), has been a leader in guiding the successes of the treaty (EPA [b] website).

The IPCC was established in 1988 by the World Meteorological Organization and the United Nations Environment Program to prepare assessments on all aspects of climate change and its impacts, with a goal of formulating realistic response strategies (IPCC [b] website). The IPCC estimates that in the absence of additional climate policies to reduce GHG emissions, baseline global GHG emissions from human sources will increase between 25% and 90% between 2000 and 2030, with carbon dioxide (CO₂) emissions from energy use growing between 40% and 110% over the same period. The IPCC projects that global temperatures will rise between 2°F and 11.5°F by the year 2100, and global sea levels will rise between 7 and 23 inches (Cambridge Systematics [c] 2010, p. ES2).

The United Nations Framework Convention on Climate Change was created at the Earth Summit in Rio de Janeiro, Brazil, in 1992 to stabilize atmospheric GHG concentrations at a level

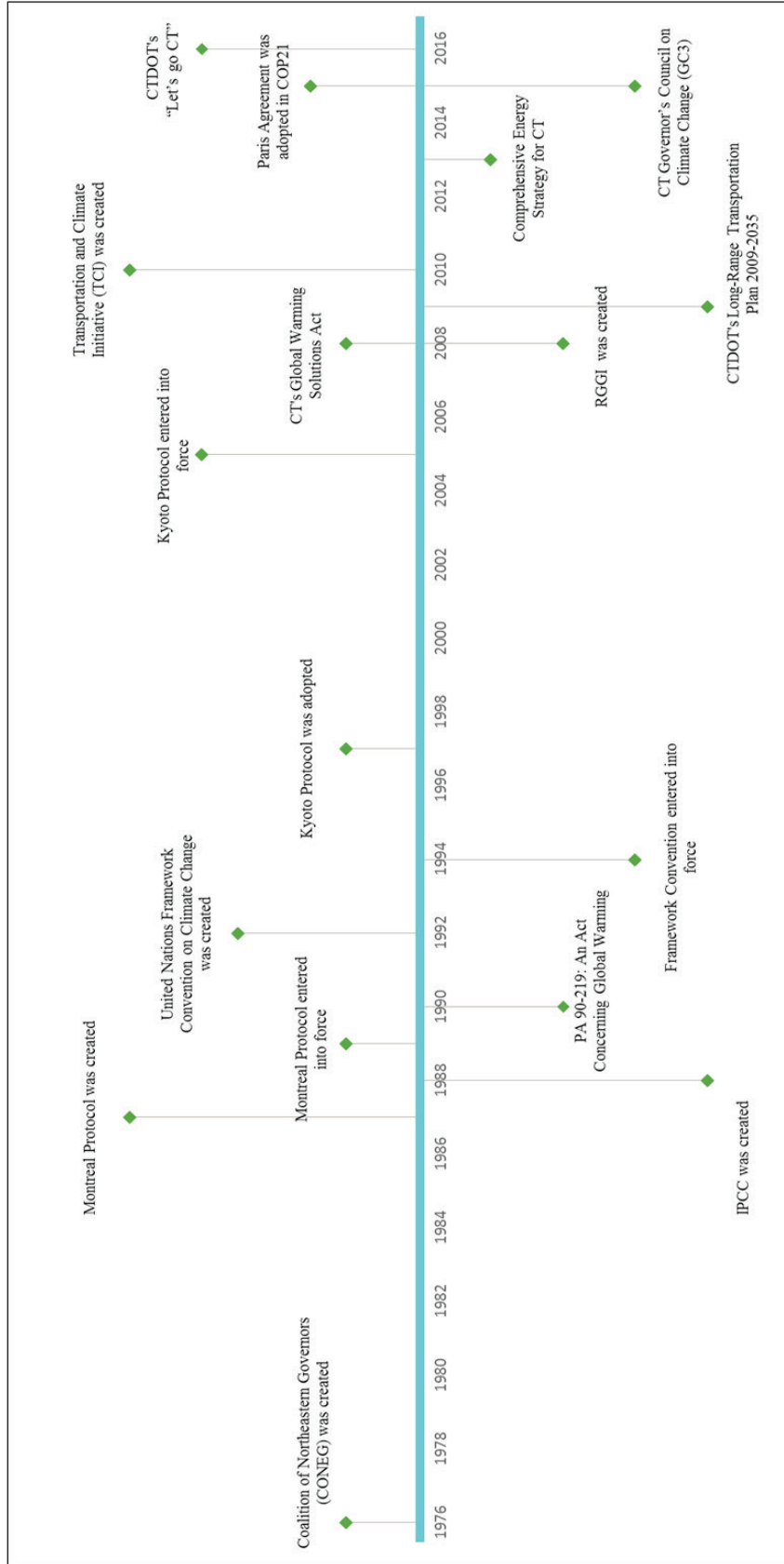
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that would prevent any dangerous human interference with the climate system. The Framework Convention entered into force on March 21, 1994, and has been ratified by 195 countries, including the United States. The parties to this convention convene annually at the Conference of the Parties (COP) to evaluate its implementation and negotiate new commitments. The COP21 convention closed on December 12, 2015, with the adoption of the first international climate agreement (also widely called the “Paris Agreement”). According to COP21, on October 5, 2016, the threshold for entry into force of the Paris Agreement was achieved. The Paris Agreement entered into force on November 4, 2016. The first session of the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement took place in Marrakech, Morocco, from November 15-18, 2016. The Paris Agreement’s central goal is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further, to 1.5°C (COP21 website).

The Kyoto Protocol was adopted in 1997 and took effect in 2005. The protocol established, for the first time, quantified GHG reduction commitments for developed countries for the period between 2008 and 2012. The Kyoto Protocol is a legally binding international instrument and has been extended until 2020 (COP21 website). However, the United States has signed, but not ratified the protocol. The US response to GHG emissions and climate change continues to be impacted by the Kyoto Protocol, along with the other international protocols and conventions to which the United States is a party. Furthermore, international and national efforts have led to a variety of regional and state initiatives designed to address the issues of climate change and GHG reduction.

In a press release dated June 2, 2017, Connecticut Governor Dannel P. Malloy announced that, “... he has committed the State of Connecticut to join the United States Climate Alliance – a coalition of US states committed to upholding the Paris Climate Agreement and taking aggressive action on climate change.” (CT.gov website)

FIGURE 1.1: TIMELINE OF MAJOR INTERNATIONAL, NATIONAL, REGIONAL AND STATE CLIMATE INITIATIVES AND RELATED EVENTS



1.2.1 *Climate Change (Regional)*

The Regional Greenhouse Gas Initiative (RGGI) is a cooperative effort among nine states – Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont – to reduce GHG. Their primary mission is to, “... *provide administrative and technical services to support the development and implementation of each RGGI State’s CO₂ Budget Trading Program*” (RGGI website). RGGI has no regulatory or enforcement authority, with all such sovereign authority reserved within each state.

Seven states, including Connecticut, have established goals in legislation or through executive action required by legislation. Additionally, the New England Governors and Eastern Canadian Premiers have collectively established a regional GHG reduction goal (Pacyniak et al. 2015, p. 12).

Connecticut is a party to the Coalition of Northeastern Governors, a nonpartisan association of the seven governors of Northeast states: Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island and Vermont. The coalition encourages intergovernmental cooperation on issues affecting the economic, social and environmental well-being of the Northeast (CONEG website). Connecticut also participates in the Transportation and Climate Initiative (TCI), a regional forum of 11 Northeast and Mid-Atlantic States and the District of Columbia. Priority policy areas include energy efficiency, clean energy, changing regional energy markets, and comprehensive strategies to address climate change and its impacts. TCI seeks to develop the clean energy economy and reduce oil dependence and GHG emissions from the transportation sector (TCI website).

As early as 1990, the Connecticut General Assembly began to address climate change through legislation. Public Act 90-219, titled, *An Act Concerning Global Warming*, is a multi-faceted Act that addressed several issues related to energy conservation and GHG emissions. Some of the areas addressed by the Act, with subsequent amendments to the Connecticut General Statutes, include

- goals to reduce energy use in state buildings from 1990 levels by 15% in 1995 and 50% by 2010;
- reducing dependency on fossil fuels via energy conservation, and use of solar and alternative energy sources for all new state building designs;
- prescribed average state vehicle fuel efficiency goals for fleet vehicle purchases;
- planting of trees and turf grass to offset emitted CO₂;
- regulations on electric resistance space heating; and
- regulations that direct CTDOT to
 - analyze public transportation, paratransit or traffic management options for all new expressway alternatives
 - create a Public Transportation Commission
 - set specific statewide goals for increasing passenger vehicle occupancy levels, such as increasing the use of public transportation and ridesharing, so that

by the year 2000 at least 10% of all trips between home and work would occur in vehicles occupied by more than one person.

More recent climate goals and plans for Connecticut are summarized as follows:

- Connecticut Global Warming Solutions Act (Public Act 08-98): Set mandatory economy-wide GHG emission reduction targets of at least 10% below 1990 levels by 2020 and at least 80% below 2001 levels by 2050 (CT Gen. §22a-200 a(a)(2010).²
- Governor’s Council on Climate Change (GC3): On April 22, 2015, Connecticut Governor Dannel P. Malloy issued Connecticut Executive Order No. 46 creating the GC3. The Council is charged with developing interim statewide GHG reduction targets for the years between 2020 and 2050 and identifying short- and long-term statewide strategies to achieve the necessary reductions (DEEP website).
- Comprehensive Energy Strategy (CES) for Connecticut: Issued by the Connecticut Department of Energy and Environmental Protection (DEEP) in February 2013, the CES outlines strategies to reduce energy use in the transportation sector, as well as the electricity, natural gas, energy efficiency, and industrial sectors. The transportation strategy envisions that by 2050, 53% of vehicles in the state will be high efficiency/alternate fuel vehicles. This goal places a high priority on VMT reduction strategies (DEEP 2013, p. 182). The report estimates that the state’s transportation-sector strategies could result in a 37% reduction below a “no-policy” baseline in transportation-sector GHG emissions by 2050 (DEEP 2013, p. 189).³

Of note is the use of target years – Connecticut is using the years 2020 and 2050 – for identifying strategic elements and performance measurements (Cambridge Systematics [b] 2015).

1.2.2 Greenhouse Gas Emissions (United States)

The EPA defines GHG as gases in the atmosphere that trap heat. The basis of the EPA’s list of GHGs reflects the six Kyoto Protocol GHGs: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆). The EPA also includes a seventh GHG, nitrogen trifluoride (NF₃). These GHGs are directly related to carbon footprint; the Climate Registry⁴ defines the carbon footprint as the total amount of GHG emitted into the atmosphere each year by an organization or company, either directly or indirectly (Cassutt et al. 2016).

Carbon dioxide is the primary GHG emitted through human activities. As shown in Figure 1.2, in 2015, CO₂ accounted for about 82% of all US GHG emissions from human activities, with transportation accounting for 27% of total US GHG by economic sector.⁵ According to TCRP

2 The Department of Energy and Environmental Protection tracks progress toward achieving these targets through regular reports. Reports are available at: <http://www.ct.gov/deep/cwp/view.asp?a=4423&q=537014>

3 DEEP has prepared a draft 2017 CES update. For more information: http://www.ct.gov/deep/cwp/view.asp?a=4405&q=500752&deepNav_GID=2121%20http://www.ct.gov/deep/cwp/view.asp?a=4405&q=500752&deepNav_GID=2121%20

4 See Chapter 2 for more detail on the Climate Registry

5 The data presented in Figure 1.2 is from the EPA’s Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015. In the Executive Summary, EPA states that the inventory, “...adheres to both (1) a comprehensive and detailed set of methodologies for estimating sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent mechanism that enables Parties to the United Nation as Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission sources and greenhouse gases to climate change.”

Synthesis #84, CO₂ accounts for 95% of transportation GHG emissions (Gallivan and Grant 2010, p. 34), which consequently accounts for 27% of CO₂ emissions in the United States, as shown in the second graphic of Figure 1.2. Most transportation studies focus only on CO₂, CH₄ and N₂O, as they account for approximately 97% of GHG emissions, with the most significant source of transportation emissions from the combustion of fossil fuels.

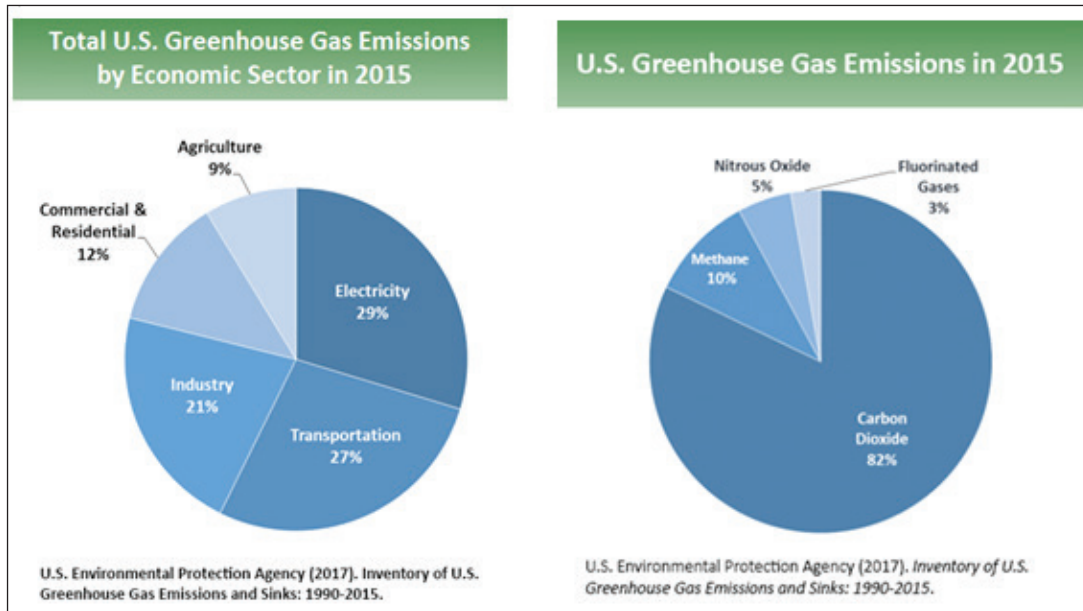


FIGURE 1.2: US GHG EMISSION COMPOSITION AND CO₂ SOURCE (SOURCE: EPA [A] WEBSITE, WWW.EPA.GOV/GHGEMISSIONS/SOURCES-GREENHOUSE-GAS-EMISSIONS)

1.2.3 Connecticut GHG Emissions

Connecticut is one of at least eighteen states by 2009 that had legislated mandatory reporting of GHG emissions (ICF International [a] 2011, p. 65).⁶ As of 2010, Connecticut had over three million registered motor vehicles, which accounted for over 50% of all man-made air pollution emitted in the state. Transportation emissions of GHG are estimated to make up 39% of the state's GHG inventory as the leading source of GHG emissions in Connecticut, with passenger cars and light duty trucks responsible for 61% of those GHG emissions (CTDOT and CCAT 2011, p. 31).

6 See Chapter 2 for specific Connecticut legislative initiatives

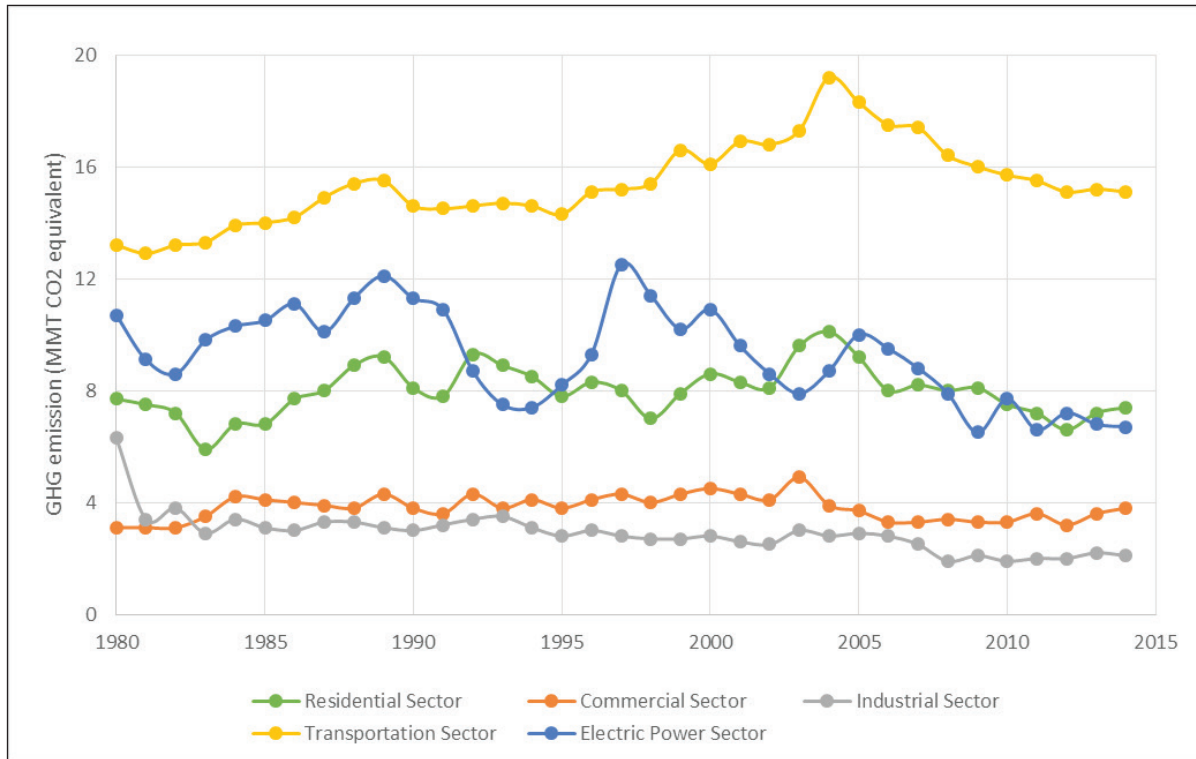


FIGURE 1.3: CONNECTICUT GHG EMISSIONS BY SECTOR (SOURCE: GRAPH DEVELOPED FROM DATA POSTED BY THE US ENERGY INFORMATION ADMINISTRATION, 2014: BY STATE/BY SECTOR, [HTTPS://WWW.EIA.GOV/ENVIRONMENT/EMISSIONS/STATE/](https://www.eia.gov/environment/missions/state/))

CTDOT’s long-range plan, *Connecticut on the Move, Strategic Long-Range Transportation Plan, 2009-2035*, identifies strategies and actions to meet the state’s GHG goals (Cambridge Systematics [a] 2015). Of note is that although state-owned public transportation operations account for a small portion of the overall carbon footprint of the state, CTDOT does have an important role in direct emissions reduction and the promotion of residential location choice and travel decisions that promote fewer GHG emissions.

According to the Cambridge Systematics report to Congress, expansion of urban transit (not just buses) has the potential to generate modest to moderate reductions in GHG emissions. Under the scenario of investing in transit sufficiently to nearly double the average annual ridership growth rate (from the current 2.4% to 4.6%), expanded urban transit could reduce GHG emissions from 0.2% to 0.9% of transportation GHG by 2030, or 0.4% to 1.5% in 2050 (Cambridge Systematics [c] 2010, pp. 3-18). Between 2011 and 2016 (the last quarter for which data is available), CTtransit growth in passenger trips has been approximately 4.2% (CTDOT Performance Measures website).

1.3 SUMMARY OF STRATEGIES

Public transportation system owners and operators have three primary ways to directly and strategically reduce GHG emissions: through operational improvements, purchase of low or no emission rolling stock, and the inclusion of emission-reducing technology and practices

at fixed transit facilities, such as maintenance facilities. Indirect strategies are also important, including collaboration with local, regional and statewide authorities to coordinate transit system planning and transit-supportive development and land use policies. These strategies can lead to travel and residence location choices that are more compatible with GHG reduction than suburban, single family dwelling practices. A state can also choose suppliers of electricity that use a larger share of renewable power generation technologies, thereby addressing upstream carbon footprint contributions. Each of these strategies is discussed in further detail in Chapter 2. This report focuses on the direct strategic elements, though their compatibility with the indirect elements and their combined possible impacts were also considered.

As noted earlier, the economic value of investments necessary to achieve strategy goals in terms of initial capital costs, ongoing operating costs including life-cycle costs, and overall benefits/savings were considered and utilized to estimate the efficiency of the identified strategies for this study.

1.4 ORGANIZATION OF REPORT

The following is an overview of the remaining chapters of this report:

- Chapter 2 presents a comprehensive literature synthesis of relevant topics.
- Chapter 3 details the existing GHG conditions in Connecticut and provides an estimate of the GHG inventory associated with Connecticut bus operations used as the baseline value against which strategies for GHG reductions will be compared.
- Chapter 4 reviews several cost analysis approaches and identifies life-cycle cost analysis as the preferred approach in the context of GHGs. This chapter considers issues related to the life-cycle cost analysis approach and offers an approach to consider health costs.
- Chapter 5 provides detailed results from the GHG Inventory and life-cycle cost analysis.
- Chapter 6 includes a discussion of the specific recommendations based on the results obtained through the GHG Inventory and life-cycle cost analysis.
- Chapter 7 includes the references cited, followed by Appendices A through I.

2.0 LITERATURE SYNTHESIS

This chapter introduces several important topics that directly impact the goals of this study, providing a background for the analysis and discussion. First and foremost, the tools necessary to estimate carbon footprints and strategies to reduce them are described in detail. Technologies associated with those strategies are described in further detail, with particular emphasis on alternative fuel technologies. The means of evaluating the costs and benefits of these strategies (e.g., their efficiency) are summarized, with detailed information provided in later chapters.

Nearly 225 references were reviewed for the literature synthesis. Of note is that aside from a Center for Neighborhood Technology report prepared for the Transit Cooperative Research Program (McGraw, Shull and Miknaitis 2010), a report for New York City Transit (Aber 2016), and a report for King County Department of Transportation, Washington State (King County Metro Transit 2017) – which evaluates the feasibility of achieving a carbon-neutral or zero-emission fleet – few literature sources were found that specifically discuss minimizing the carbon footprint of transit agency operations. This can be explained in part by the fact that good business practices for transit operations already provide reasons for making operations and buildings energy efficient, as both have been proven to be cost effective actions in the past. Additionally, many transit agency carbon reduction studies might be internally generated, and not necessarily easily accessible by the public.

2.1 CARBON FOOTPRINT ESTIMATION

Transportation's contribution to GHG emissions are primarily (97%) associated with three GHGs: CO₂, N₂O, and CH₄. Approximately 95% of the transportation GHG emissions are associated with CO₂. The other GHGs can be converted to CO₂ equivalents (CO_{2e}) using Global Warming Potential (GWP) factors developed by the IPCC for a 100-year time horizon (APTA [a] 2009). Carbon dioxide is the baseline unit, and therefore assigned a GWP value of 1. Some typically-used ranges of GWP values for the other GHGs are listed in Table 2.1, limited to the three principal pollutants associated with transportation emissions.

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TABLE 2.1. GLOBAL WARMING POTENTIALS: 100-YEAR TIME HORIZON
(SOURCES: EPA [A] 2016, P. ES-3 AND APTA 2009, P. 17)

Greenhouse Gas	100 Year Global Warming Potential	Typical Sources of Gases for Transit Agencies
Carbon Dioxide (CO₂)	1*	<ul style="list-style-type: none"> • Gasoline and diesel combustion • Combustion at stationary sources, e.g., maintenance yards • Electricity purchases
Methane (CH₄)	21 - 25*	<ul style="list-style-type: none"> • Gasoline and diesel combustion • Fugitive emissions of natural gas
Nitrous Oxide (N₂O)	298* - 310	<ul style="list-style-type: none"> • Gasoline and diesel combustion
*Values in bold italicized text are used by EPA, from the IPCC Fourth Assessment Report (2007)		

NCHRP Study Project 20-24 shows that GHGs are different from other air pollutants in several ways:

1. *The environmental impact of most GHG emissions is the same regardless of where or when they are released.*
2. *GHGs encompass at least six different gases that generally have the same effect on climate, though some are more potent than others.*
3. *There are no means of using air quality monitoring data to designate nonattainment areas that exceed safe levels.*
4. *GHGs persist in the atmosphere for decades; thus cumulative emissions are important.*
5. *Due to the global nature of GHGs, there is not a clear health basis for setting limits of GHG emissions for specific regions or states. (Grant et al. 2010, p. vi)*

Transportation GHG emissions have been growing steadily. From 1990 to 2006, transportation GHG emissions increased 27%, accounting for almost one-half of the increase in total US GHG emissions for the period (Cambridge Systematics[c] 2010, p. ES3). The EPA reported that CO₂ emissions in the United States increased by about 9% between 1990 and 2014. Transportation emissions remain a significant factor, due primarily to an increase in VMT (EPA[a] website).

A study conducted by the USDOT's Center for Climate Change and Forecasting for Congress evaluates, but does not provide recommendations for, four groups of strategies for reduction of transportation GHG emissions:

1. Introduce low-carbon fuels: alternative fuels that have lower carbon content and generate fewer transportation GHG emissions. The alternative fuels evaluated are ethanol, biodiesel, natural gas, liquefied petroleum gas, synthetic fuels, hydrogen, and electricity.
2. Increase vehicle fuel economy: strategies include developing and bringing to market advanced engine and transmission designs, lighter-weight materials, improved vehicle aerodynamics, and reduced rolling resistance.
3. Improve transportation system efficiency: optimizing the design, construction, operation, and use of transportation networks.

4. Reduce carbon-intensive travel activity: reduce on-road VMT by reducing the need for travel, increasing vehicle occupancies, and shifting travel to more energy-efficient options that generate fewer GHG emissions (Cambridge Systematics[c] 2010, p. ES3-ES5).

Since fossil fuel combustion is the overwhelming source of transportation GHGs, it is important to understand the production of GHGs from various fuel sources. Table 2.2 includes the carbon content by weight per unit for use of selected fuels.

TABLE 2.2: SELECTED CONVERSION FACTORS USED IN CALCULATING ENERGY AND GHG EMISSIONS
 (SOURCE: EUDY, CATON, POST 2016, P. 30)

Fuel or Energy Type	Units	BTU/Unit	lb CO ₂ /Unit
B10 Biodiesel	gal	127,560	22.0385
Compressed Natural Gas	gge ^a	114,717	14.7272
Diesel Fuel	gal	128,450	22.1447
E10 Ethanol	gal	112,114	16.9935
Electricity	kWh	3,414	N/A
Gasoline	gal	116,090	19.6658
Hydrogen	kg	113,724	0.0000
Liquid Petroleum Gas/Propane	gal	84,950	12.7467
^a gge = gasoline gallon equivalent and is defined as the amount of alternative fuel required to equal the energy content of one liquid gallon of gasoline			

Public transportation plays an important role in reducing the nation’s energy use and GHG emissions (Neff and Dickens 2015, p. 21). Public transit is an avenue to address Strategy 4 – reduce carbon-intensive travel activity – included in the referenced USDOT report to Congress by offering an alternative that is not only more efficient but also able to reduce on-road VMT. The Federal Highway Administration (FHWA) states in their *Reference Sourcebook for Reducing Greenhouse Gas Emissions from Transportation Sources* that “transit systems (which include bus, light rail, heavy rail, commuter rail, and paratransit) can generally transport people more efficiently, with fewer GHG emissions than cars, particularly in comparison to single-occupancy vehicle trips.” (FHWA Reference Sourcebook 2016, p. 5) It should be noted that these assertions hold when bus occupancy exceeds ridership thresholds – in the case of a diesel bus operating at a fuel efficiency of four miles per gallon versus a single-occupant gasoline-powered vehicle operating at 25 miles per gallon, the CO₂ emissions per passenger are equivalent if there are seven passengers on the bus⁷. Fewer passengers result in higher per passenger emissions from the bus, with more than seven passengers resulting in lower emissions per passenger. For high ridership corridors, the carbon savings can be substantial. American Public Transportation Association (APTA) reinforces this idea with their suggestion that even the greenest transit system will not be an effective means of mitigating environmental impacts and GHG emissions if it is not used (APTA[d] 2011).

⁷ For the bus example, 25/4 gallons of fuel will be required to travel an equivalent distance to the example passenger vehicle. For a 100-mile trip, this would require 25 gallons of diesel fuel generating 22.1 lb CO₂ per gallon, or 552.5 lb CO₂. The single occupant passenger car would consume 4 gallons of fuel at 19.7 lb CO₂ per gallon over the same distance, or 78.8 lb CO₂. This implies that the bus would need 552.5/78.8 = 7.0 passengers on board during the trip to have an equivalent amount of emissions on a per-passenger basis.

It is important to recognize that public transportation’s carbon footprint has an inverse relationship to the global carbon footprint – the world’s GHG emissions will decrease relative to public transport’s footprint increase. (International Association of Public Transport 2014, p. 6). Figure 2.1 demonstrates this relationship through two scenarios. The circles on the left represent a scenario similar to today in which transit (yellow circle) accounts for a small proportion of the total GHG emissions of the transportation sector (blue circle). On the right, the circles depict a scenario in which public transit has a much larger proportion of shrinking total transportation GHG emissions.

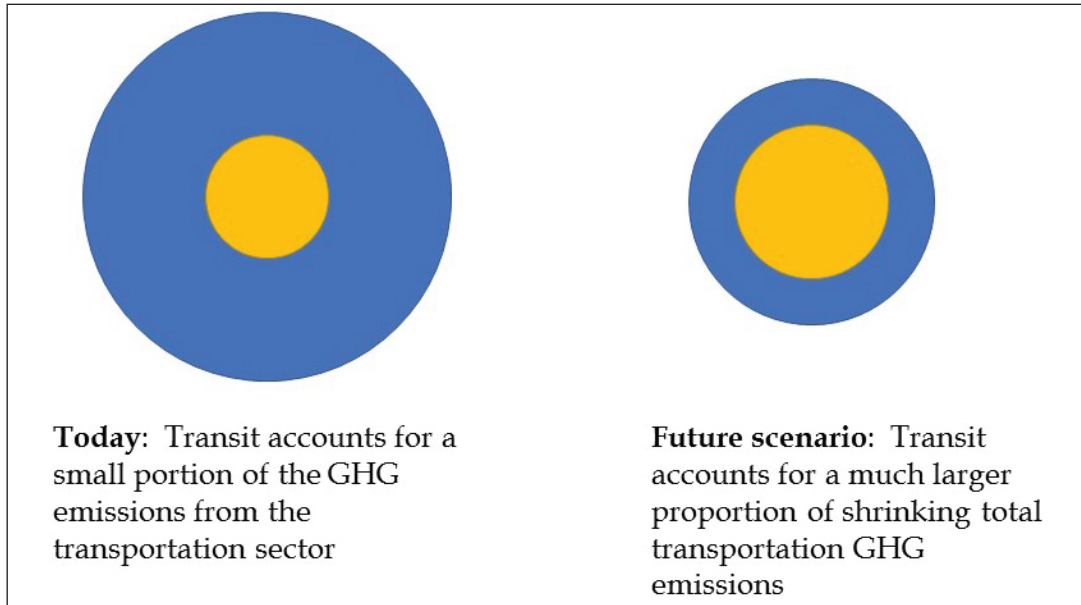


FIGURE 2.1: THE INVERSE RELATIONSHIP BETWEEN TRANSIT AND TOTAL GHG EMISSIONS

As seen in Table 2.3, public transportation accounts for a very small proportion of the total GHG emissions in the transportation sector for Connecticut at 0.44%. In a situation similar to Figure 2.1, there would be a reduction in total transportation emissions over time as more of the light-duty vehicle fleet is electric and the proportion of Connecticut’s energy from renewable sources rise. This reduction would be compounded by a VMT reduction through policies and investments geared towards encouraging transit usage.

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TABLE 2.3: U.S. AND CONNECTICUT GHG EMISSIONS

SOURCE	Total GHG (MMTCO ₂ e)	% of National Total GHG	% of CT Total GHG	% of CT Transportation GHG
US (All sectors) ¹	6,587			
US (Transportation) ¹	1,810	27.4%		
CT (All sectors) ²	43	0.65%		
CT (Transportation) ²	15.5	0.24%	36.05%	
CT (Public Transportation) ³	0.0708	0.001%	0.17%	0.44%

¹National GHG Contribution from the Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2015, for year 2015 (p. ES-25), https://www.epa.gov/sites/production/files/2017-02/documents/2017_complete_report.pdf
² CT All Sectors and CT Transportation from the 2013 CT GHG Inventory http://www.ct.gov/deep/lib/deep/climatechange/2012_ghg_inventory_2015/ct_2013_ghg_inventory.pdf
³Based on a CT Public Transportation GHG Inventory conducted for this Connecticut Academy of Science and Engineering Study Report using calendar year 2017 data. The inventory is discussed in more detail in Chapter 3.

However, there is not a 1:1 relationship between transit patronage and passenger car VMT reduction. As shown in Figure 2.2, while transit ridership in the United States has grown 20% and passenger miles increased 50% over 1980 levels, VMT has more than doubled during that same period. Elasticities – the change in one variable due to a change in another variable – for VMT as a function of transit service are difficult to identify. However, Dong et al. (2012) suggest an elasticity value of -0.0445, which can be interpreted as a 100% increase in transit service coverage results in a 4.45% reduction in household VMT (Dong et al. 2012).

Behavioral shifts, such as switching to transit, illustrate one of the ways that transit can positively impact total GHG emissions. Public transport’s GHG emissions can be categorized as:

1. DEBITS: GHGs emitted directly or indirectly by public transport operations
2. CREDITS: GHG emissions avoided as a result of its operations in a given region. The net carbon avoided is the result of mode shift, land use changes, and congestion relief.

A comprehensive strategy to reduce GHG should include both categories. Strategic elements to reduce debits – such as alternative fuels – are a direct way to reduce total GHGs. Increasing credits through increased transit patronage is less direct and more difficult, but can have long-term benefits in terms of the sustainability of a transportation system and the communities it serves. Public transportation agencies – particularly in larger metropolitan areas – with current services alone, are assisting in reducing GHGs. As an example, the New York Metropolitan Transportation Authority (NYMTA) prevents about 17 million metric tons of carbon from being emitted throughout the course of a year, while only emitting two million metric tons. (International Association of Public Transport 2014, pp. 6-7) However, according to FHWA (FHWA Reference Sourcebook 2016, p.5], at the national level transit use constitutes only 1.6% of all trips (even fewer than walking) and 1.2% of all miles traveled. According to the Frontier Group, “The United States currently lags behind much of the world in transit use – the result of historical investment policies that prioritized highway construction, ongoing subsidies and incentives for vehicle use, and inadequate transit in many cities.” (Gallivan and Grant 2010, p. 34)

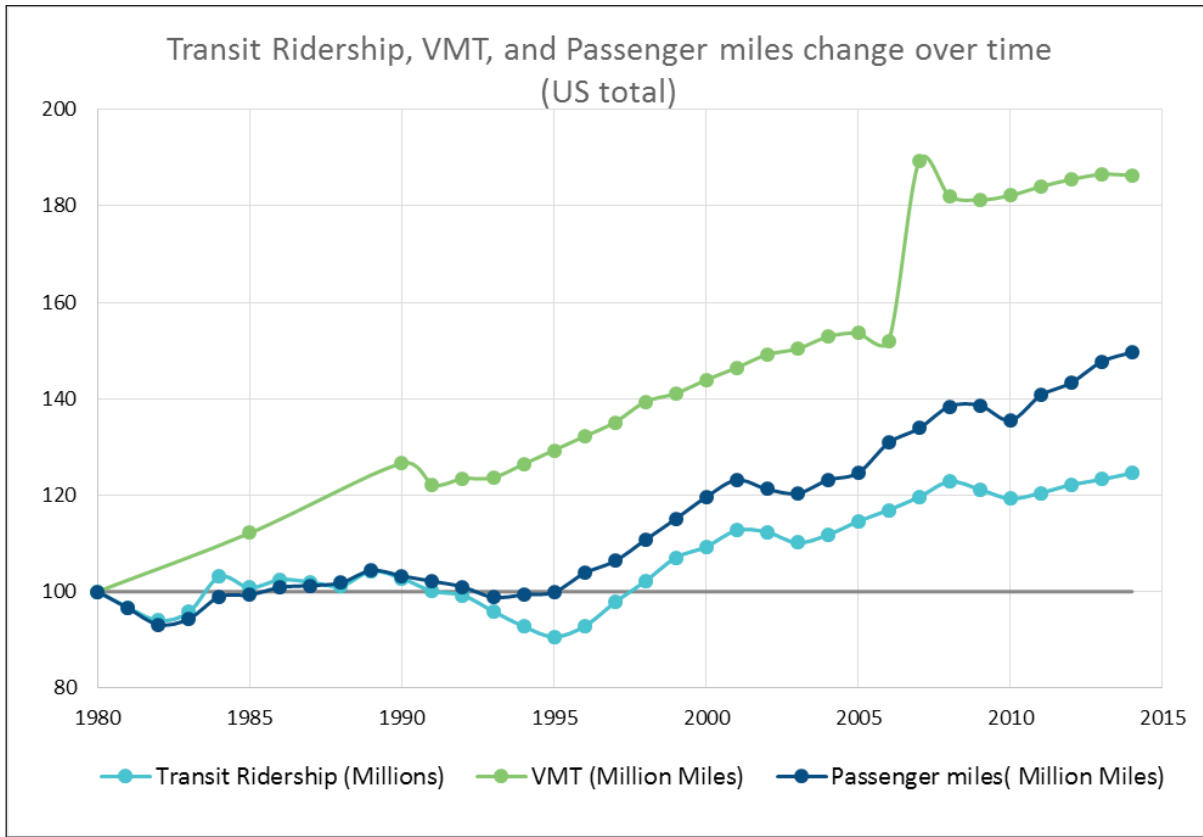


FIGURE 2.2: US TRANSIT RIDERSHIP, PASSENGER MILES AND PASSENGER CAR VMT GROWTH (1980 = 100). (SOURCE: USDOT BUREAU OF TRANSPORTATION STATISTICS, TRANSIT RIDERSHIP FACTBOOK 2015 [TABLE 116]; PASSENGER MILES FACTBOOK 2015 [TABLE 116]; AND VMT - NATIONAL TRANSPORTATION STATISTICS⁸ [TABLE 4-11])

The FHWA reports that the use of transit varies significantly by region and density; in 2009 about 40% of all transit trips in the United States were in the New York region (FHWA Reference Sourcebook 2016). According to a Pew Research Center survey conducted in November/December 2015, 11% of Americans take public transportation on a daily or weekly basis. Additionally, according to the Pew Research Center via *FacTank News in the Numbers*,

...the Northeast, home to several of the most traveled transit systems in the country, has the largest share of adults by region (25%) who use public transportation on a regular basis (daily or weekly). City dwellers are also more frequent users of mass transit. Some 21% of urban residents use public transit on a regular basis, compared with 6% of suburban residents and just 3% of rural residents. (Pew Research Center, FACTank, 2016)

Public transportation plays an important role in reducing GHG emissions. Benefits include: reduction in private passenger vehicle miles; reduced automobile congestion; reduced travel

⁸ Data for 2007-13 were calculated using a new methodology for light-duty vehicles (formerly passenger cars) and motorcycles developed by FHWA. Data for these years are based on new categories and are not comparable to previous years. The new category for LDV includes passenger cars, light trucks, vans and sport utility vehicles with a wheelbase equal to or less than 121 inches.

distances due to the land use impact of public transportation; savings of more than billions of gallons of gasoline; and avoidance of tens of millions of metric tons of CO₂ emissions (Neff and Dickens, APTA, 2015, p. 21). These benefits are aligned with FHWA's comments that

...transit improvements can apply to a variety of modes and include increases to the frequency of service on existing routes, system-wide route optimizations, the addition of new routes, and improvements to transit information and comfort. The effects of a particular type of transit improvement additionally depend on the state of the existing transit system, demographic and economic trends, and land use patterns. (Kalra et al. 2012, p. 12)

The case for public transportation as a key strategic element in total GHG reduction is strong. The next section discusses GHG sources associated with bus public transportation operations and importantly, methods available to estimate total GHG emissions.

2.1.1 GHG Emissions from Transit Buses

The USDOT Federal Transit Administration (FTA) reported that, in 2007, there were 834,000 buses in the United States, with 20 powered by hydrogen fuel cells. In Connecticut, FTA reports that for the same year "there were approximately 1000 buses and 480 vans in revenue service being operated by a public agency, or authority, a private transportation provider or private transportation broker." (CTDOT and CCAT 2011, p. 18)

According to the Cambridge Systematics report to Congress, buses have the lowest emissions per passenger mile traveled for heavy-duty vehicles, including passenger rail travel and domestic aircraft, due to their relatively high occupancy rate. However, transit buses have a lower occupancy rate compared to the average of all buses – about 9 to 10 people per bus averaged across the United States. Transit buses only account for 15% of all bus passenger miles traveled (Cambridge Systematics [c] 2010, pp. 2-19). Not surprisingly, buses – as a source of GHG emissions relative to the contribution of GHGs from the entire transportation sector – are not a very significant source. According to an EPA report on GHGs in the transportation sector during 2003, buses produced approximately 0.5% of transportation GHGs, and transit buses were responsible for only 46% of the total bus emissions, which would be equivalent to less than 0.25% of GHG emissions in the United States for that year (EPA [b] 2006). However, in the greater New York City area, where buses are much more prevalent due to high population density, the bus GHG emissions represent about 3% of the total GHG emissions for the transportation sector.

Bus transit GHG are produced in several ways and there are several tools for the estimation of carbon footprints and GHG inventories. For an agency, GHG inventories are detailed accounts of emissions attributable to that agency, subdivided by source category (Gallivan and Grant 2010, p. 42). Standard reporting schemes have emerged including The Climate Registry, a nonprofit emissions reporting agency governed by US states and Canadian provinces and territories. The Registry uses conventions developed by the World Resources Institute to divide emissions into the following three scopes, as further defined for transit agencies:

1. Scope 1: Direct Emissions: anything combusted or emitted on the agency's premises or in the agency's vehicles

2. Scope 2: Indirect Emissions: emissions from purchased electricity, heating, cooling, and steam. (Note: electricity, heat, steam or cooling generated within a facility under an organization's control are categorized as Scope 1 emissions.)
3. Scope 3: Optional:
 - displaced emissions from mode shift to transit, congestion relief, and the land use multiplier
 - emissions from transit access trips (e.g., to rail stations or park-and-ride facilities)
 - emissions from employee commuting and business travel
 - life-cycle emissions from vehicle manufacture and disposal
 - upstream (well-to-tank) emissions from fuel extraction, refining, and transportation
 - emissions from waste disposal (including contracted solid waste). (Climate Registry website; Gallivan and Grant 2010, p. 42)

GHG Calculators are the tools used to provide the GHG estimates found in GHG inventories. There are also various methodologies available to perform GHG life-cycle analyses. Inventories generally only consider direct combustion emissions and/or fugitive emissions due to released refrigerants, whereas life-cycle calculations usually include upstream and downstream emissions. This type of GHG life-cycle assessment is sometimes known as a “well to wheels” (WTW) assessment (Gallivan and Grant 2010, p. 26).

Upstream and downstream emissions are described as follows:

- Upstream emissions: mining or harvesting materials; emissions from building the infrastructure (highway, busway, track, buildings, etc.); manufacturing (construction materials, transit and other vehicles); maintaining infrastructure, buildings and vehicles; and producing (refining), delivering and sometimes even combustion of the fuel in the vehicles (Gallivan and Grant 2010, p. 38).
- Downstream emissions: usually associated with end of life, disposal or recycling of vehicles and their parts (e.g., tires); used oils and other spent lubricants; and with discarded building contents (e.g., old furniture, used light bulbs) and construction materials.

If fuel combustion is not included, upstream and downstream emissions are sometimes combined and called indirect emissions (Southworth 2011, p. 16).

Not all inventories present GHG life-cycle calculations in the same manner. For example, Cambridge Systematics in its report to Congress defines “well-to-wheel” (WTW) emissions as including three stages of the life-cycle of a transportation fuel (first, feedstock extraction and distribution; second, fuel production and distribution – collectively known as “upstream” or “well-to-pump” emissions; and third, vehicle operation (called “downstream” emissions in some other studies). (Cambridge Systematics [c] 2010, pp. A-6)

According to studies by Chester et al. and Chester, any comprehensive environmental inventory that evaluates energy use and/or emissions should include:

The energy and emissions associated with raw materials extraction and processing, supply chain transport, vehicle manufacturing, vehicle maintenance, infrastructure construction, infrastructure operation, fuel production, as well as many others....” They note that, “the inclusion of life-cycle processes necessary for any transportation mode results in significant increases for the region. For example, emissions of CO₂ from cement production used in concrete throughout infrastructure, and SO₂ from electricity generation in non-operational components (vehicle manufacturing, electricity for infrastructure materials, and fuel refining), result in significant additional inventory.” (Chester et al. 2010, p. 1071; Chester 2008)

As another example, Cambridge Systematics (Cambridge Systematics [c] 2010, pp. 2-25) indicates that the inclusion of upstream emissions such as vehicle manufacturing and maintenance, infrastructure construction, and fuel production for urban buses would give emissions that are 45% higher than for on-road operations alone. Chester reports that when upstream production is included for buses, life-cycle energy consumption is 38% higher, and life-cycle GHG emissions are 43% higher (Cambridge Systematics[c] 2010, pp. 2-25; Chester 2008, p. 2).

As noted in this study’s scope, the GHG inventory will be established based on Scope 1 and 2 emissions, which is also consistent with Climate Registry requirements for transit systems. GHG emissions are rarely measured directly. Emissions are estimated using the product of activity data, emission factors and GWPs. GWPs were previously discussed and referenced in Table 2.1. Recommended GWPs for particular gases may change over time as the state of the science advances. Emission factors are ratios of the GHGs emitted per unit of activity data, for example, metric tons of CO₂ emitted per kWh of generated electricity (ICF International [a] 2011, p. 18).

The USDOT (USDOT website) has a comprehensive website with links to models and analysis tools for transportation emissions, with some of these models included in Appendix B. Since measurement of emissions for air quality has been ongoing for over 40 years, several of the models in the appendix have been in existence since the 1980s, and as such are not as pertinent to GHG emissions as other models. The models referenced in the appendix that should be of greatest interest for bus transit emissions calculations include GREET (USDOE), MOVES (EPA), VISION (USDOE), IBIS (TCRP), GreenDOT (NCHRP), the GHG Calculator (APTA) and the Simplified GHG Emissions Calculator (SGEC), which was selected as the analysis tool for this study. These tools provide a means of establishing a GHG baseline and measuring an organization’s performance in reducing GHG emissions.

2.2 CARBON REDUCTION STRATEGIES

This section broadly describes overarching carbon reduction strategies, elements specifically of importance to transit operators, performance measures, and GHG estimates that can be used to track progress toward the goal of carbon footprint and GHG reduction.

At the United Nations Climate Summit held September 23, 2014, the International Association of Public Transport (UITP)⁹ indicated that the public transport sector can provide “... *enormous economic, environmental and social benefits,*” for the 21st century. In a Declaration of Climate Leadership, over 110 public transport organizations in cities around the world pledged 350

⁹ The International Association of Public Transport is the international network for public transport authorities and operators, policy decision-makers, scientific institutes and the public transport supply and service industry. It brings together 1,300 public transport members from 92 countries.

actions to reduce carbon emissions and consequently, the carbon footprint, of public transport (UITP 2014). For buses, UITP identified 106 initiatives in eight categories that can lead to significant CO₂ emission reductions. The eight categories include

1. hydrogen buses
2. increase routes/efficiency
3. clean fuels
4. fuel-efficient driving
5. hybrid buses
6. new bus lines/bus rapid transit
7. electric buses
8. technological enhancements (UITP 2014, p. 8)

A detailed evaluation of bus transit GHG emissions was performed as part of a study conducted for TCRP by the Center for Neighborhood Technology titled, *The Route to Carbon and Energy Savings* (McGraw et al. 2010). Most of the 17 areas that were evaluated are of direct interest for Connecticut bus operations:

Vehicles and Fuels

1. Hybrid Vehicles: Vehicles that operate on two or more fuels
2. Biofuel: Fuel derived from plants or algae
3. Electric Buses: Vehicles that run on stored or grid-supplied electricity
4. Fuel Cell Buses: Vehicles that use hydrogen fuel cells for propulsion
5. Weight Reduction and Right-Size Vehicles: Lighter weight buses and trains, as well as vehicles of all types sized to meet demand
6. Regenerative Braking: Capture and use of energy usually lost as heat during braking
7. Auxiliary Systems Efficiency: Reducing the demand of non-propulsion energy uses, such as air conditioning
8. Personal Rapid Transit: Fixed guideway transit with two- or four-person cars
9. Renewable Power: Low-carbon electricity for transit vehicles or facilities

Operations and Maintenance

10. Operational Efficiency: Changes in the ways vehicles are operated, such as routing or acceleration
11. High Global Warming Potential Gases: Chemicals used in systems, such as air conditioners, that have a global warming impact significantly greater than that of CO₂
12. Maintenance: Upkeep of vehicles and systems to ensure maximum possible efficiency

Other

13. Construction and Life-Cycle Impacts: Transit system construction projects and the upstream emissions associated with transit activity
14. Non-Revenue Vehicles, Employee Commute, and Employee Travel: Vehicles that are not part of the transit revenue service fleet
15. Facilities: Transit system buildings including stations, offices, and maintenance facilities
16. Land Use: Community location efficiency to increase transit ridership and reduce vehicle use
17. Ridership and Occupancy: Improving transit emissions per passenger mile by increasing transit vehicle occupancy (McGraw et al. 2010, pp. 7-8)

The study concluded that compared with a base year of 2010, it is anticipated that it is possible to reduce the carbon footprint of bus transit fleet operations 51% by 2030 and 61% by 2050. This could be accomplished with diesel hybrid buses and increased fuel efficiency, as well as increased operating and maintenance efficiencies, facility retrofits, and increased vehicle occupancy (the 2010 average bus occupancy is reported as 28%). Conclusions from the study are illustrated in Figure 2.3.

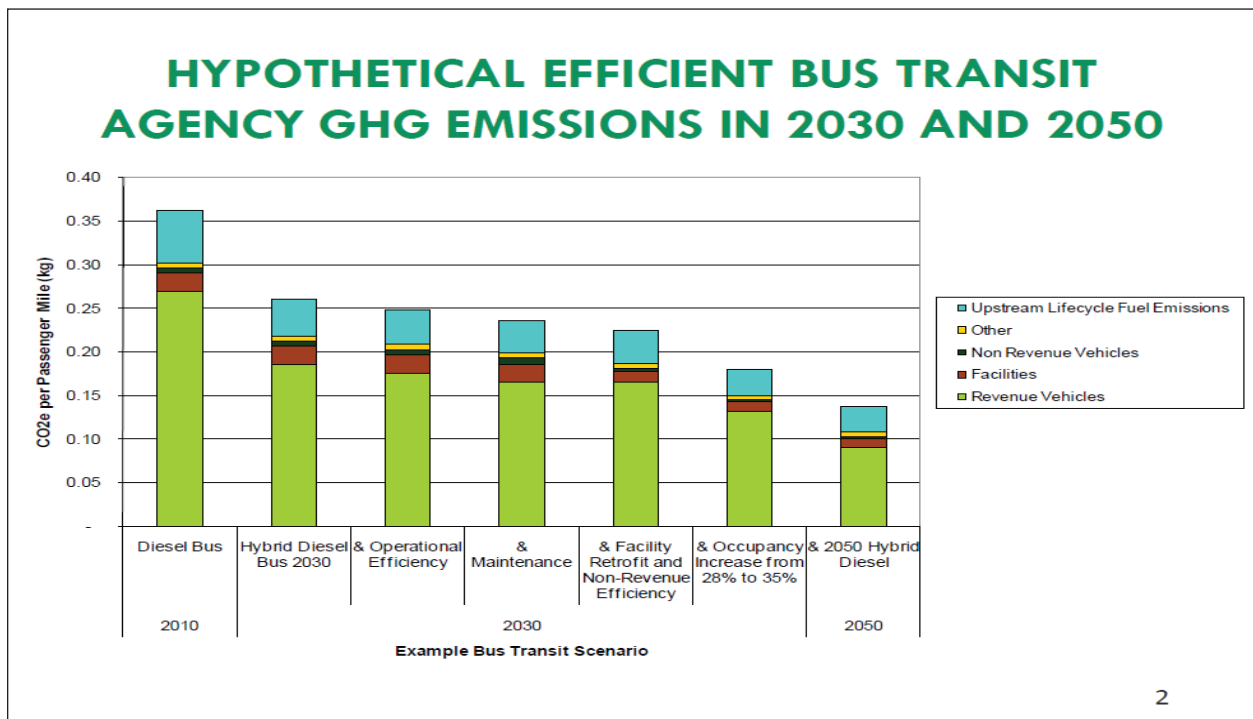


FIGURE 2.3: HYPOTHETICAL EFFICIENT BUS TRANSIT AGENCY GHG EMISSIONS IN 2030 AND 2050
 (SOURCE: MCGRAW ET AL. 2010)

The potential areas of focus to reduce GHGs have been identified in several previous studies. Gallivan et al. provides a concise list of the areas in which transit can have a positive influence on GHG reductions, including

- reduction in automobile VMT;
- reduction in road congestion with an associated savings in idling fuel and air pollution;
- facilitation of compact development patterns (transit-oriented development¹⁰); and
- reduction in emissions from the transit vehicles and their facilities (Gallivan et al. 2011, p. 19).

Increased transit availability and utilization, more efficient operations, and use of renewable fuel transit vehicles are necessary to achieve GHG reductions from these areas of focus. Strategies that increase ridership and/or improve operating efficiencies and energy reductions in facilities will contribute to additional GHG emission reductions.

This study's analysis will focus on rolling stock and mobile emissions, as those contribute the majority of GHG emissions for the Connecticut public transportation system. Additionally, a discussion of facility strategies is presented in the analysis. Plausible policy scenarios that impact transit ridership will be used to frame the analysis.

Carbon reduction strategies should be viewed within the context of an overarching sustainability plan, as the goals and efforts of both can be mutually reinforcing if properly designed and implemented. Sustainability¹¹ is a method of harvesting or using a resource so that the resource is not depleted or permanently damaged. There are many definitions of sustainability depending upon the context of use. APTA defines sustainability for transit as, "... practices that make good business sense and good environmental sense, balancing economic, social and environmental needs" (Bergener et al. 2011). A slight variation on this definition is provided in another APTA report on sustainability practice guidelines. It defines sustainable transit business practices as "...about respect for the environment, sensitivity to community needs, and optimizing available resources within transit agency business." (APTA [d] 2011)

A sustainable transportation system "...allows the basic access needs of individuals to be met safely in a manner consistent with human and ecosystem health, and with equity within and between generations. ... is affordable, efficient, offers choice transport mode, and supports a vibrant economy. ...limits emissions, pollution, and wastes; minimizes consumption of resources and land." (Atkinson-Palombo 2016 website)

According to APTA, "*Sustainability practices by the transit industry should aim at having broad impact through the following:*

- *Improving mobility via enjoyable transit services.*
- *Creating livable communities through facilitating more environmentally friendly forms of mobility, such as walking, biking, and public transit, and increasing the number of routine destinations that are safely and comfortably accessible through these modes.*

10 Transit-oriented development (TOD) is a type of community development that includes housing, office, retail and/or other amenities. TOD is usually characterized by above-average density, orientation to pedestrian activity, and easy walking access to a major public transit station or stop (Gallivan and Grant, 2010).

11 The UN's 1987 Brundtland Commission Report gave the original definition of sustainability as "...meets the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland Commission [1987], "Report of the World Commission on Environment and Development".

- *Reducing per capita automobile vehicle miles traveled (VMT).*
- *Reducing stress, loss of productivity, traffic deaths and injuries, and related health-care costs caused by automobile travel.*
- *Reducing passenger transportation-generated CO₂ and other greenhouse gases.*
- *Reducing passenger transportation-caused ambient hazards such as noise, pollution, and vibration. (APTA[d] 2011, p. 1)*

The City of Seattle, in its report, “*Getting to Zero: A Pathway to a Carbon Neutral Seattle*,” states that transit improvements will need to include “*investments in broader geographic coverage, increasing frequency and reliability, reducing travel times to make transit fast, reliable, comfortable, and affordable, and thus dramatically increase ridership*” (Lazarus et al. 2011, p. 22). Seattle’s goal is to increase the percentage of passenger miles traveled by transit from current levels of 8% to 25% by 2050.

Another example is a goal set by the city of Copenhagen, Denmark, to become the world’s first carbon neutral capital city, with the following strategies related to transit:

By 2025, the city wants 75 percent of trips to be made by foot, bike, or public transit. The city will also invest in alternative fuels. Jørgen Abildgaard, Executive Climate Project Director for the city of Copenhagen, said Copenhagen is looking to convert its bus fleet to models powered by hybrid drives running on biogas. The city projects that 20 percent to 30 percent of all cars and small trucks, and 30 percent to 40 percent of all heavy vehicles, will run on electricity, hydrogen, biogas, or bioethanol by 2025. By 2015, 85 percent of the city’s fleet of 1,000 small vehicles will run on electricity, hydrogen, or biofuels ... (Gerdes 2013)

In 2011, APTA prepared and published a report titled “*Guidelines for Climate Action Planning*,” listing the following benefits for transit agency climate action plans:

- Demonstrating the environmental benefits of transit
- Improving cost-effectiveness
- Supporting internal sustainability efforts
- Demonstrating leadership
- Preparing for the effects of climate change (APTA[b] 2011)

Transit agency climate action plans to reduce costs and GHG emissions have additional benefits, such as air quality improvements, improvements in public image, and/or energy savings for the agency.

Some climate change plans, such as British Columbia’s Climate Action Charter (Union of British Columbia Municipalities 2007) and Ontario’s Five Year Climate Action Plan, 2016-2020, include transit as a subcategory within the overall plan. For example, the Province of Ontario’s Climate Action Plan includes the following transit-related actions:

- Increase the availability and use of lower-carbon fuel
- Increase the use of electric vehicles

- Support cycling and walking
- Increase the use of low-carbon trucks and buses
- Support the accelerated construction of regional express rail (Ontario Ministry 2016 website)

Several agencies have prepared sustainability plans that also include GHG reductions, as the two areas are complementary. Appendix C includes a brief description of selected agencies with sustainability plans.

It is noteworthy that FTA states that while there is

a wide range of actions that transit agencies have been using to reduce their GHG emissions, and in the process often lowering their energy bills, a consistent approach to selecting the best mix of these activities for a given situation and type of transit agency has yet to be developed. Still largely absent from the available empirical evidence is a comprehensive and standardized accounting of the costs associated with many GHG emissions reduction actions now available. (Southworth et al. 2011)

2.2.1 Performance Metrics

While the near-term goal of carbon reduction strategies may be to reduce or eliminate GHG emissions, this cannot be the only metric. Given the complementary relationship with sustainability and sector-wide carbon reduction strategies, it is important to monitor and measure more than GHG emissions with appropriately chosen performance metrics. Performance metrics are strongly encouraged at the federal level to provide a measurement of accountability and transparency for transit agencies. The EPA's *Guide to Sustainable Transportation Performance Measures* includes the following performance measures that may be directly or indirectly applicable for bus transit:

1. Transit accessibility: measures the ability of people to reach destinations using public transportation
 - a. Distance to transit stops
 - b. Destinations accessible by transit
 - c. Share of population and employment within walking distance (1/2 mile) of transit
 - d. Percent of non-work related trips accessible within 15 minutes by transit
2. VMT: measures the amount of vehicle activity normalized by population
 - a. VMT per capita
 - b. Light-duty VMT per capita
 - c. VMT per employee
3. Carbon intensity: measures the amount of CO₂ emitted from transportation per person
 - a. Total transportation CO₂ emissions per capita

- b. Passenger transportation CO₂ emissions per capita
- c. Heavy-duty vehicle CO₂ emissions per capita
- 4. Transportation affordability: measures the cost of transportation relative to income
 - a. Public transportation fares
 - b. Private vehicle ownership and operating costs
- 5. Average vehicle occupancy: measures the ratio of passengers to vehicles on the roadway (the average number of people in each vehicle; also called average vehicle ridership or vehicle occupancy rate)
 - a. Average number of occupants
- 6. Transit productivity: measures the average number of riders on transit vehicles
 - a. Average weekday transit boardings per vehicle revenue hour
 - b. Average transit boardings per vehicle revenue mile
 - c. Average annual transit boardings per route mile
 - d. Passenger miles traveled per vehicle revenue mile (ICF International[b] 2011, pp. 10-38)

Appendix D provides examples of performance metrics from transit agencies and others, and APTA's guidance on the development of indicators and sample targets.

2.3 TRANSIT ROLLING STOCK

As of 2010, there were less than 100 battery electric, ethanol, hydrogen fuel cell, or dimethyl ether buses operating in transit agencies in the United States. As of the same year there were more than 1000 diesel, biodiesel, compressed natural gas (CNG), liquefied natural gas and hybrid diesel-electric transit buses in operation. There has been a significant increase in alternative fuel buses during the past six years. For example, Figure 2.4 shows growth in the battery electric bus fleet in the United States from 2010 - 2017.

The following subsections describe the various alternative fuel technologies that offer GHG reduction possibilities for transit system owners and operators.

2.3.1 *Battery Electric Buses*

The Connecticut Green Bank reported that electric drive vehicles powered by rechargeable batteries or hydrogen offer the greatest potential to reduce emissions for passenger vehicles in Connecticut (Nigro and Morrison 2016). Similarly, the following statement was included in the Connecticut Department of Energy and Environmental Protection's (DEEP) 2013 *Comprehensive Energy Strategy*:

...electric vehicles represent an insignificant amount of total vehicle miles traveled, and as such, a very small portion of transportation energy consumed. But given the very clean

sources of power in Connecticut (about 92% of generation is either nuclear or natural gas), the expanded use of electric vehicles in the state would yield substantial environmental benefits. (DEEP 2013)

To gather and disseminate the latest information about battery electric buses, the Transit Cooperative Research Program (TCRP) is currently preparing a synthesis study and report on the state-of-the-practice for battery electric buses. The goal of the TCRP study is to provide an overview of the current state of practice for the deployment of battery electric buses (i.e., planning, service, operations and maintenance, costs and benefits).

A 2014 Massachusetts Bay Transit Authority (MBTA) study (Dimino et al. 2014) reported that battery electric buses are 63% more expensive than clean diesel buses, including infrastructure upgrades for recharging batteries. It is noted that upfront capital costs have declined in the three years subsequent to the MBTA study. However, the GHG emissions for battery electric buses are 68% lower than for clean diesel buses, with the potential for greater reductions – even to zero emissions – depending upon the source of the electricity. As electricity production becomes cleaner, with more renewable and lower carbon fuel sources, any use of electricity becomes less carbon intensive.

MassDOT reported that in 2014 the Worcester Regional Transit Authority (WRTA) in Massachusetts added six Proterra Plug-in all-electric buses to their transit fleet. The governor at the time, Deval Patrick, noted that *“The WRTA’s new fleet is an example of how we are accelerating the adoption of cleaner vehicles throughout Massachusetts to reduce harmful pollutants and promote a more sustainable environment for future generations.”* (MassDOT Blog website)

The Pioneer Valley Transit Authority in Massachusetts introduced four Proterra electric buses into their fleet in December 2016 (MassLiVE.com website). The authority purchased three 40-foot Catalyst Fast Charge battery electric buses, two fast chargers and one depot charger for their Holyoke to Springfield route.

A US Department of Energy, National Renewable Energy Laboratory (NREL) paper titled, *Fast Charge Battery Electric Transit Bus In-Use Fleet Evaluation*, presented at the Institute of Electrical and Electronics Engineers (IEEE) Transportation Electrification Conference, reported on a successful fleet of 12 Proterra battery electric buses purchased in 2013 and operated by Foothill Transit in San Gabriel and Pomona Valley near Los Angeles, California. Eudy et al. emphasized the importance of understanding how a vehicle’s drive cycle and operating environment influence its overall duty cycle, and how that duty cycle impacts the overall performance of advanced vehicle technologies. While the battery electric buses demonstrated an energy efficiency of 1.34 kWh/km in Foothill Transit operations, road grade and non-tractive energy demands such as HVAC can have a significant effect on overall energy efficiency and must be taken into account when determining the feasibility of deploying battery electric bus technologies. While the data showed seasonal variation in energy efficiency, additional analysis is required to accurately define the thermal load characteristics of these B battery electric buses to isolate the HVAC system power requirements specific to this operational duty cycle (Eudy, Prohaska et al. 2016).

Battery electric bus technology appears to be reaching a point that may be cost-effective for implementation. NREL developed a 1 to 9 scale for the commercialization process, with

technology readiness level (TRL) 1 defined as the basic research/concept and TRL 9 as commercial deployment. As of 2015, Eudy et al. reported battery electric buses to be at TRL 7 (Eudy, Caton & Post 2016, p. vi; Eudy, Post et al. 2015, p. vi). It is noted for this literature search that battery electric bus orders in the United States and China have advanced far past those of hydrogen fuel cell buses during the past two years (USDOT, U.S.-China Race to Zero Emissions website; Shahan 2017 website).

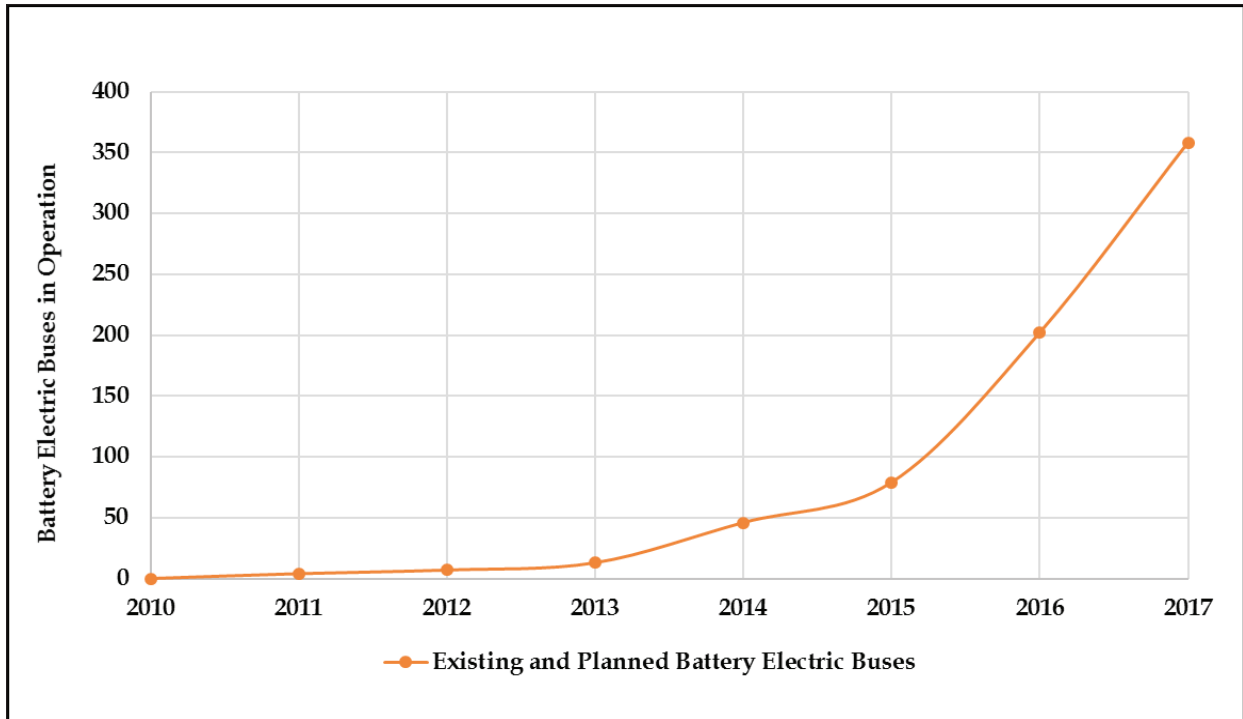


FIGURE 2.4: BATTERY ELECTRIC BUS GROWTH IN THE US 2010 – 2017¹²

Appendix F provides additional examples of battery electric bus deployment in the United States. Figure 2.4 depicts the growth of battery electric buses in the United States from 2010 to 2017. Figure 2.5 projects US battery electric bus growth from 2010 to 2030. The exponential growth scenario is in line with CALSTART projections of low- and no-emission vehicle deployment in 2030 (CALSTART website 2017).

12 (Sources: <https://www.transportation.gov/r2ze>; <https://www.transit.dot.gov/funding/grants/lowno>; <https://ww2.arb.ca.gov/>; Technology Assessment: Medium and Heavy Duty Battery Electric Trucks and Buses, October 2015; <http://www.nrel.gov/transportation/>; <http://foothilltransit.org/>; https://en.wikipedia.org/wiki/List_of_electric_bus_makers_and_models; https://en.wikipedia.org/wiki/Battery_electric_bus; <https://www.proterra.com/products/>; <http://www.byd.com/la/auto/ebus.html>; <http://www.vta.org/>; <https://www.ridetarc.org/>; <http://www.transitchicago.com/electricbus/>; <https://www.cabq.gov/transit>; <https://frederickcountymd.gov/>; <http://www.miamidade.gov/>; <http://energy.utah.gov/>; <http://kingcounty.gov/depts/transportation/metro.aspx>; and <https://energy.gov/eere/vehicles/vehicle-technologies-office>)

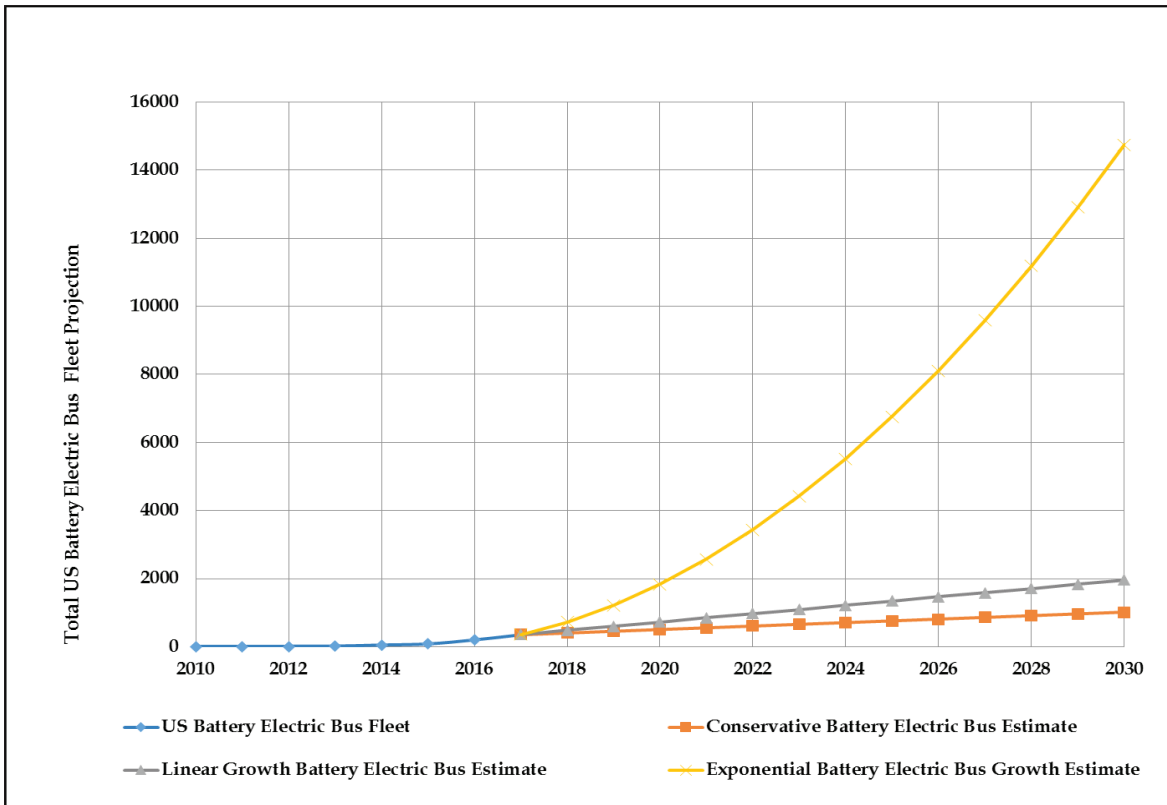


FIGURE 2.5: PROJECTED BATTERY ELECTRIC BUS GROWTH TO 2030

Additionally, technical specifications for the procurement of battery electric buses, including appropriate equipment and services, were researched via the literature and through interviews and presentations by APTA and selected transit agencies. Appendix E provides examples for use in the development of technical specifications for the purchase of battery electric buses.

2.3.2 Hydrogen Fuel Cell Buses

Companies in Connecticut have been world leaders in the research, design, and manufacture of fuel cell-related technology (CTDOT and CCAT 2011). From 2007 until 2011, CTtransit operated the second largest fleet of hydrogen fuel cell buses (also termed Fuel Cell Electric Buses [FCEB]) in the United States as part of the Connecticut Transit Nutmeg Project. Alameda-Contra Costa Transit District (AC Transit website) in Oakland, California, had the largest fleet as part of the Zero Emission Bay Area Demonstration Group. Both the Connecticut and California fuel cell bus fleets participated in a federal evaluation study by NREL.

According to a report by CTDOT and the Connecticut Center for Advanced technology (CCAT) in 2011, "...the operation of the 2011 CTtransit fleet of six hydrogen-fueled cell buses [was projected] to use approximately 37,000 kg of hydrogen each year and displace approximately 49,000 gallons of diesel fuel annually. This displaced fuel [was] expected to result in the reduction of over one million pounds of CO₂ annually." (CTDOT and CCAT 2011)

In 2009, the Connecticut General Assembly passed Public Act 09-186, which led to the publication of the "Connecticut Hydrogen and Fuel Cell Deployment Transportation Strategy, 2011-

2050.” (CTDOT and CCAT 2011) This legislation also resulted in changes to the Connecticut General Statutes §13b-38dd (a), which stated, “*The Department of Transportation shall consult with the Connecticut Center for Advanced Technology, Inc., to develop a plan to implement zero-emissions buses state-wide.*” However, in 2013 United Technologies sold UTC Power, its fuel cell division, to ClearEdge Power to whom CTtransit returned the leased fuel cell buses used during the Nutmeg evaluation. Some of these buses ultimately were transferred to AC Transit District in California.

The following three sites are examples of where hydrogen fuel cell buses are currently in use and/or continue to be evaluated:

- 1. AC Transit Fuel Cell Bus Fleet Extended Operations, Oakland, California:** AC Transit hydrogen fuel cell bus fleet entered operation in 2006 and as of 2016 has since accumulated 249,338 fuel cell hours of operation over 2,064,892 miles. The fuel cell buses have provided an 83% increase in fuel economy as compared with the control diesel fleet. With funding provided through the FTA National Fuel Cell Bus Program, operation of AC Transit’s 12 fuel cell bus fleet continued through 2016, and by the end of 2018, the AC Transit fuel cell fleet will have expanded to 24 vehicles.

The grant [FTA National Fuel Cell Bus Program] provides extended support for warranties that began expiring in August of 2013. This grant will allow these buses to continue to operate for a total of six years of continuous demonstration, providing critical operational and maintenance cost data on performance over time, and fuel cell, battery and drive system durability. (CTE website; CTE Presentation 07/14/17 website; AC Transit website)

- 2. Capital Metro Zero Emission Hydrogen Fuel Cell Bus (Capital Metro), Austin, Texas:** Capital Metro recently took delivery of a zero-emission Proterra fuel cell bus. This bus will be used for daily transit service.

This Proterra fuel cell bus is based on Proterra’s 35-foot battery electric bus design with the addition of two roof mounted hydrogen fuel cell Auxiliary Power Units (APU). Each APU converts hydrogen directly to electricity, supplying enough clean electric power to support most transit routes with only a single APU operating. The Proterra bus contains two 33 kW Hydrogenics HD30 fuel cell units and the same high power lithium titanate batteries as Proterra’s fast charge electric buses.” (CTE website)

- 3. Massachusetts Bay Transportation Authority (MBTA), Boston, Massachusetts:** A 2014 publication by the MBTA titled, *Alternative Propulsion Systems – Boston’s Next Generation Bus Fleet*, makes transit bus recommendations for the city of Boston. The propulsion technologies reviewed in this paper, diesel, hybrid diesel-electric, and CNG, were the current propulsion systems used at that time by the MBTA, as well as battery electric and hydrogen fuel cell systems. The fuel cell buses – shown to emit zero CO₂ – proved to be the most expensive option in 2014 (Dimino et al. 2014).

Hydrogen fuel cell buses have the potential to supply zero-emission transportation. However, based on the literature cited, it appears that the cost of the buses, as well as the cost and state of hydrogen fuel dispensing infrastructure, has not progressed to the point that hydrogen fuel cell buses would be a cost-effective or viable alternative for Connecticut, for the short term. NREL has stated that producers of fuel cell buses predict the cost of buses could decline to under \$1

million per bus with orders of greater than 40 buses (Eudy, Post and Jeffers 2016). Lastly, NREL also reported that similar to battery electric buses, hydrogen fuel cell buses reached TRL-7 on a scale of 1 to 9 (Eudy, Prohaska et al. 2016, p. vi; Eudy, Post et al. 2015, p. vi).

2.3.3 Hybrid Diesel-Electric Buses

Hybrid diesel-electric buses offer the potential for fuel savings and reduced exhaust emissions when compared to diesel engines. Other advantages include, “...the ability to recover and reuse energy lost during braking, engine downsizing, reduced engine transient operation, idle engine-stop, and flexible engine control.” The disadvantages may include “...higher capital costs, battery system replacement costs, additional maintenance costs, and mechanic and training costs.” (Wayne 2013) The greatest fuel efficiency advantage occurs during low-speed stop and go during city operations.

CTtransit has approximately 15 years of experience operating hybrid diesel-electric buses. Although these buses have operated effectively, CTDOT reports expensive mid-life overhaul repairs that impact cost effectiveness.

2.3.4 Natural Gas Buses

Natural gas buses commonly are used in non-attainment air quality areas. For example, the state of California does not allow new transit diesel buses in certain areas of the state. Natural gas also offers limited GHG emissions benefits from the lower carbon content of the fuel. Alternatively, it is noted that the natural gas option can include “...high refueling and maintenance infrastructure installation costs, increased vehicle weight resulting from onboard CNG storage tanks, and throttling losses that reduce engine efficiency.” (Wayne 2013)

In a report conducted for USDOT, Smith and Gonzales reported that infrastructure installation costs for CNG can vary widely from one project to another. Relative to other types of fleets, transit stations require special considerations because they must fuel large numbers of vehicles with high volumes of fuel during short fill-time windows. Instead of the traditional CNG fast-fill design used at public filling stations, these stations are typically designed to fuel vehicles directly from multiple large compressors and have lower station storage capacity. It may be desirable to fuel transit buses indoors while being cleaned. Indoor fueling adds significant costs due to its specialized construction and high-specification heating and electrical equipment, and these transit bus stations require significantly more engineering and are typically costlier than stations serving other types of fleets (Smith and Gonzales 2014).

Despite the noted costs, the previously referenced MBTA report found that CNG is the most cost-effective option as determined from life-cycle cost analyses (LCCA) that compared diesel, hybrid diesel-electric, battery electric and hydrogen fuel cell technologies. However, it is noteworthy that MBTA reports that GHG emissions from CNG for CO₂ are 94% as high as for clean diesel and 18% higher than hybrid diesel-electric.

2.4 TRANSIT BUILDINGS AND FACILITIES

For a typical transit agency, transit vehicles account for the majority of energy use and GHG emissions. However, buildings and facilities can be significant users of energy and emitters of GHGs, as well. Specifically, transit maintenance yards, offices and stations contribute

substantially toward energy use by bus transit operations, and thus contribute to an agency's carbon footprint. Transit administration and maintenance buildings are similar to buildings used for similar purposes by other industries and businesses, and energy conservation measures that apply to those facilities also can be used by transit agencies. A FTA report on *Transit Greenhouse Gas Emissions Management Compendium* noted, "During 2007, eighteen percent of GHG emissions from the New York MTA were attributable to electricity and heating in the agencies' facilities, stations and maintenance yards." The Metropolitan Atlanta Regional Transit Authority reported, "30% of emissions are attributable in 2008 to facilities, electricity generation and consumption." (Southworth et al. 2011, p. 4)

Green building practices demonstrated by transit agencies to significantly reduce GHG emissions can be grouped into the following areas:

- Green building codes and standards
- Integrated design
- Building envelopes
- Energy consuming equipment
- Renewable energy systems
- Building retrofits (Southworth et al. 2011, p. 77)

An agency should first conduct an energy audit to identify and prioritize improvements for any facility efficiency project. Energy audits¹³ can be conducted by consultants, utility companies, and government entities in the energy sector, as well as through use of software packages and web tools (Eudy, Caton, and Post 2014).

The USDOE's Office of Energy Efficiency and Renewable Energy has resources available on its website that provide useful information about retrofits and energy reduction measures for a variety of building types.¹⁴

Retrofitting buildings with more energy-efficient options includes periodic upgrades to incorporate the latest lighting, heating and cooling system components. Renewable energy installations (e.g., solar and wind) can further increase the net efficiency of a building, and be a source of offsetting revenue (Southworth et al. 2011, p. 5).

Leadership in Energy and Environmental Design (LEEDTM) certification, which was developed by the United States Green Building Council (USGBC), refers to a national rating system for developing high performance energy efficient buildings.

The LEED® rating system is a multi-tiered system that includes Certification, Silver, Gold, and Platinum rating, with Platinum being the highest rating. The LEED® standard has been applied to transit facilities such as the Corona Maintenance Facility in Queens, New York among others throughout the country. (Southworth et al. 2011, p. 78)

13 Energy Audits became common practice during the 1979 energy crisis.

14 USDOE Office of Energy Efficiency and Renewable Energy website: <https://energy.gov/eere/buildings/building-technologies-office>

According to USGBC, “LEED-certified buildings are resource efficient. They use less water and energy and reduce greenhouse gas emissions. As an added bonus, they save money. Projects pursuing LEED certification earn points across several areas that address sustainability issues.” Based on the number of points achieved, a project receives one of the four LEED rating levels: Certified, Silver, Gold or Platinum. (USGBC website)

Examples of transit agencies with experience in LEED certified buildings include:

- King County Metro Transit, Seattle, Washington State
- Los Angeles County Metropolitan Transportation Authority, Los Angeles, CA (NYMTA Blue Ribbon, undated)

Chapter 4 of the TCRP Synthesis report #106, titled *Energy Saving Strategies for Transit Agencies* (Gallivan 2013), contains many examples of energy efficiency efforts performed at various transit agencies around the United States, including

- lighting (LED) upgrades
- use of natural sunlight
- automatic timers and sensors for lights
- LEED certified “green” building construction
- recycling construction waste
- replacing 40% of cement with fly ash
- light colored surfaces to reflect sunlight
- passive heating and cooling
- solar installations
- enhanced insulation
- efficient appliances and computers
- more efficient heating and cooling systems
- escalators with sleep mode
- station entrance and exit routes where inclines are designed to take advantage of regenerative braking and gravity starts
- energy miser devices in vending machines

APTA also details some of the energy efficiency methods referenced in the TCRP report and notes that methods should be considered for applicability and feasibility at the design phase of all new construction and rehabilitation projects (See Appendix G for APTA’s full list; APTA[d] 2011).

Energy management systems (EMS) are tools that allow agency staff to monitor building functions remotely. An EMS consists of sophisticated software that communicates with and

controls key building functions, including lighting and climate control. According to TCRP Synthesis Report 106, *“An EMS can reduce energy use and costs in facilities automatically by*

- *Turning lighting systems on or off depending on the time of day, available natural light, or occupancy.*
- *Switching on or off noncritical building systems to take advantage of variable rate structures at different times of day.*
- *Switching air handlers in HVAC systems on or off depending on the time of day.*
- *Adjusting building temperatures based on the time of day or on data from outside weather sensors.*
- *Reducing heating of hot water for public lavatories during off-peak hours.”* (Gallivan 2013, p. 34)

2.5 ECONOMIC ANALYSIS

In addition to the ability to calculate the GHG emissions over the life of a transit system, a more traditional formal LCCA is typically performed for comparison of transportation infrastructure or vehicle purchasing options, such as highways versus fixed transit, buses versus rail, and diesel buses versus electric buses.

Ercan et al. (2016) identified several studies on life-cycle costing specifically for alternative transit energy, including

- Alternative fuel use level scenarios for future years under various scenarios related to the adoption of alternative fuels for transit buses are investigated (Ou et al. 2010).
- A hybrid-LCCA approach is used to evaluate the environmental emission impacts of battery electric and diesel transit buses, taking the different state-based electricity grid mixes into account (Cooney et al. 2013).
- The environmental emission performance of various alternative fuel options for transit buses in different US cities under different operational conditions is investigated (Zu et al. 2015).
- The lifetime energy consumption rates and cost-benefit analysis results of battery electric and hybrid diesel-electric transit buses are presented (Lajunen 2014).
- Hybrid diesel-electric and battery electric passenger vehicles are analyzed for their LCA impacts for environmental, social, and economic concerns (Onat et al. 2014).

A Blue Ribbon Commission study on transit agency life-cycle costing was conducted by the nation’s largest transit authority, the New York Metropolitan Transit Authority (NYMTA). The report recommends:

... instituting a systemwide green Lifecycle Analysis (LCA) System to manage materials from procurements through disposal.” “Lifecycle Analysis (LCA) assesses products all the way from raw materials through manufacturing, transportation, and disposal to determine the total environmental and CO₂ effects. (NYMTA Blue Ribbon undated)

The FTA published a report prepared by West Virginia University that included the development of online tools, collectively termed the IBIS, or Integrated Bus Information System, for assisting transit agencies in evaluating alternative fuel and propulsion system options when making vehicle procurement decisions. These tools include a searchable database of transit bus emissions data, a transit bus fleet emissions inventory modeling tool, and a transit bus LCCA model (Wayne 2013, p. 3; See Center for Alternative Fuels (website), Engines and Transmissions for a user accessible LCCA).

TCRP Report # 132 (Clark et al. 2009), includes a LCCA model developed to compare conventional diesel, hybrid diesel-electric and CNG buses using Excel spreadsheets. Long Beach Transit was used as an example for this model; CNG was found as the most cost effective option (Wayne, 2013, pp. 89-90). It should be noted that neither GHG costs nor the negative costs of emissions are considered in this traditional LCCA (see later discussion on GHG costs).

A later TCRP Report, #146 (SAIC 2011), presents methods to assist transit agencies in selecting a fuel option for new buses – FuelCost2 – using Excel spreadsheets. Extending decisions beyond fuel costs to account for GHG costs requires the use of other tools designed for that purpose. The Transportation and Climate Initiative recommends viewing GHG reduction strategies through the lens of “GHG reduction per dollar of capital investment.” (Cambridge Systematics [a] 2015)

TCRP Synthesis report #84 (Gallivan and Grant 2010), identifies and discusses two general types of cost analysis. The first approach, cost effectiveness, measures the impact of a strategy on GHG emissions in dollars per ton reduced (\$/ton). Cost-effectiveness analysis is a simpler methodology, which is appropriate when analyzing GHG emissions in isolation. When considering multiple objectives, the second general type of cost analysis, cost-benefit analysis (CBA), is a better choice. CBA compares impacts of strategies by converting each impact to dollar terms, including environmental impacts of transit. For CBA analyses,

...assigning a cost to GHG emissions allows GHG impacts to be included in a CBA of strategies, in which all impacts of a given strategy are monetized. A CBA analysis including GHG emissions was conducted for conventional diesel, hybrid diesel-electric, and CNG buses used by the New York City Transportation Authority. For each bus technology, the analysis included capital expenditures, operations and maintenance expenditures, and environmental impacts, as well as several smaller categories of costs and benefits. The study used a value of \$149/ton of GHG. While New York's study used a price of \$149/ton, any price assigned to GHG emissions currently is largely speculative. (Gallivan and Grant 2010, p. 44)

Other agencies contacted in this TCRP study used values ranging from \$4 to \$50/ton of GHG. Energy saving strategies, similar to GHG evaluations, often use a cost-effectiveness analysis to compare the net cost of an investment with the impact of the investment on energy savings, or other goals. For agencies with specific goals to reduce energy consumption, a cost-effectiveness metric can help to prioritize investments to meet those goals (Gallivan 2013).

The NYMTA Blue Ribbon Study recommended a Sustainable Return on Investment (SROI)-based analysis to select green initiatives. SROI is based on a standard economic return on investment calculation, but also includes the estimated amount of carbon averted as a result of a particular green initiative, valued at the real opportunity cost of carbon (NYMTA Blue Ribbon undated).

An August 2016 EPA update on the Social Cost of Carbon provides estimates for CO₂ costs for use in regulatory impact analysis (EPA [c] website). Table 2.5 includes an excerpt from this report. It is noted that the reporting of carbon costs can be sometimes misconstrued. A report, *“Weighing the Options on Global Warming Policies”* (Nordhaus 2008), noted that the weight and therefore the price of carbon differs from the weight and price of CO₂ emissions. Carbon dioxide is reported to be 3.67 times the weight of carbon. This is explained by the addition of two oxygen atoms to each carbon atom when CO₂ is formed (oxygen has an atomic weight of 44 – roughly 3.6667 times the atomic weight of the carbon, which is 12). To demonstrate this further, an assigned price of \$30 per ton for CO₂ equals a price of \$110 per ton of carbon.

TABLE 2.5: SOCIAL COST OF CO₂, 2010 – 2050 (IN 2007 DOLLARS PER METRIC TON OF CO₂)
 (SOURCE: INTERAGENCY WORKING GROUP ON SOCIAL COST OF GHG AUGUST 2016)

Year	Column 1	Column 2	Column 3	Column 4
	5% Average	3% Average	2.5% Average	High Impact (95th Percentile at 3%)
2010	\$10	\$31	\$50	\$86
2015	\$11	\$36	\$56	\$105
2020	\$12	\$42	\$62	\$123
2025	\$14	\$46	\$68	\$138
2030	\$16	\$50	\$73	\$152
2035	\$18	\$55	\$78	\$168
2040	\$21	\$60	\$84	\$183
2045	\$23	\$64	\$89	\$197
2050	\$26	\$69	\$95	\$212

The first three columns in Table 2.5 represent three values based on the average social cost of CO₂ from three integrated assessment models, at discount rates of 5%, 3%, and 2.5%. The fourth column shows the 95th percentile of the frequency distribution of the social cost of CO₂ estimates based on a 3% discount rate and a model with a low-probability, high-impact scenario (Interagency Working Group 2016). Table 2.5 is only representative of the costs for CO₂. Similar tables have been developed for N₂O and CH₄.

Robert Johnston (Johnston 2015) suggests that a CBA for transit include social welfare and tradeoffs, not merely economic activity, and that it is common for some issues to be underrepresented or ignored, such as: unpriced benefits or costs, spatial dimensions, temporal dimensions, and uncertainty and sensitivity analyses. Benefits due to reduced GHG emissions and other pollutants include the

- social cost of carbon; approximates net benefit of reduced climate effects
- reduced mortality and morbidity
- benefits of increased aesthetics

These benefits can be due to reduced fleet emissions or reduced use of substitute transportation, such as cars and trucks.

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A recent Victoria Transport Policy Institute (VTPI) publication regarding the use of CBA for transit provides a generalized list of items to consider in such an analysis as shown in Table 2.6.

TABLE 2.6. PUBLIC TRANSPORT BENEFITS AND COSTS (SOURCE: EVALUATING PUBLIC TRANSIT BENEFITS AND COSTS – BEST PRACTICES GUIDEBOOK, TODD LITMAN, VTPI, NOVEMBER 2016, P. 2)

Category Indicators	Improved Transit Service	Increased Transit Travel	Reduced Automobile Travel	Transit-Oriented Development (TOD)
CATEGORY DESCRIPTORS	<i>Service Quality (speed, reliability, comfort, safety, etc.)</i>	<i>Transit Ridership (passenger miles or mode share)</i>	<i>Mode Shifts or Automobile Travel Reductions</i>	<i>Portion of Development With TOD Design Features</i>
BENEFITS	Improved convenience and comfort for existing users	Increased user security, as more users ride transit and wait at stops and stations	Reduced traffic congestion	Additional vehicle travel reductions (“leverage effects”)
	Equity benefits (since existing users tend to be disadvantaged)	Mobility benefits to new users	Road and parking facility cost savings	Improved accessibility, particularly for non-drivers
	Option value (the value of having an option for possible future use)	Increased fare revenue	Consumer savings	Reduced crime risk
	Improved operating efficiency (if service speed increases)	Increased public fitness and health (by stimulating more walking or cycling trips)	Reduced chauffeuring burdens	More efficient development (reduced infrastructure costs)
	Improved security (reduced crime risk)		Increased traffic safety Energy conservation Air and noise pollution reductions	Farmland and habitat preservation
COSTS	Increased capital and operating costs, and therefore subsidies	Transit vehicle crowding	Reduced automobile business activity	Various problems associated with more compact development
	Land and road space			
	Traffic congestion and accident risk imposed by transit vehicles			

Current transportation evaluation practices tend to overlook and undervalue many transit benefit categories. Ignoring benefits and undervaluing those associated with transit investments understates the benefits they provide (Litman 2016, p. 4). Not surprisingly, many of these benefits are difficult to capture in a traditional analysis. However, although the operation of transit vehicles is not in and of itself a benefit, the travel habits and sustainable development patterns that are associated with many transit investments are an important aspect and substantial benefit of transit investments.

In support of a thorough analysis, the following framework from VTPI identifies elements that should be decided upon prior to beginning an economic analysis (Litman 2016, p. 9):

- Evaluation method, such as cost-effectiveness, benefit-cost, LCCA, etc.
- Evaluation criteria, which are the impacts to be considered in analysis. Impacts can be defined in terms of problems, or their opposite, objectives (for example, if congestion is a problem then congestion reduction is an objective), and in terms of costs and benefits (for example, congestion reduction benefits are measured based on congestion costs reduced).
- Modeling techniques, which predict how a policy change or program will affect travel behavior and land use patterns.
- Base case, meaning what would happen without the policy or program.
- Comparison units, such as net present value, benefit/cost ratio, or cost per lane mile, vehicle mile, passenger mile, incremental peak-period trip, etc.
- Base year and discount rate, which indicates how costs are adjusted to reflect the time value of money.
- Perspective and scope, such as the geographic range of impacts to consider.
- Dealing with uncertainty, such as use of sensitivity analysis or other statistical tests.
- How results are presented, so that the results of different evaluations can be compared (Litman 2016, p. 9).

Broadly, (Litman 2016, pp. 13-14) suggests three types of benefits associated with transit:

- User benefits: result from improved convenience, speed, comfort or financial savings to travelers who would use transit even without those improvements.
- Mobility benefits: result from the additional mobility provided by a transportation service, particularly to people who are physically, economically or socially disadvantaged; these benefits include access to medical services, shopping, education or employment
- Efficiency benefits: result when transit reduces the costs of traffic congestion, road and parking facilities, accidents and pollution emissions.

The authors further suggest that the benefits summarized in Table 2.7 are not often fully considered when evaluating transit investments.

TABLE 2.7: UNDERREPRESENTED BENEFITS OF TRANSIT INVESTMENTS (SOURCE: EVALUATING PUBLIC TRANSIT BENEFITS AND COSTS – BEST PRACTICES GUIDEBOOK, TODD LITMAN, VTPI, NOVEMBER 2016, P. 72)

Benefits	Description
User Benefits	Increased convenience, speed and comfort to users from transit service improvements
Congestion Reduction	Reduced traffic congestion
Facility Cost Savings	Reduced road and parking facility costs
Consumer Savings	Reduced consumer transportation costs, including reduced vehicle operating and ownership costs
Transport Diversity	Improved transport options, particularly for non-drivers
Road Safety	Reduced per capita traffic crash rates
Environmental Quality	Reduced pollution emissions and habitat degradation
Efficient Land Use	More compact development, reduced sprawl
Economic Development	Increased productivity and agglomeration efficiencies
Community Cohesion	Positive interactions among people in a community
Public Health	Increased physical activity (particularly walking)

2.5.1 Emissions Trading and Offsets

Transit agencies could benefit from GHG emissions trading schemes at national or state levels. Emissions trading allows parties to buy and sell emissions credits. As net reducers of GHG emissions (e.g., through passenger ridership), transit agencies may be able to generate and sell emissions credits and could therefore be a source of funding for a transit agency (Gallivan and Grant 2010).

According to the American Association of State Highway and Transportation Officials GHG emission inventory guidelines,

If a state DOT finds that installing and operating a renewable energy system is impractical at a given location, another option is to use Renewable Energy Certificates (RECs). RECs provide a useful way for state DOTs to reduce GHG emissions by purchasing credit for off-site renewable energy when the location, ownership, or operation of a renewable energy-creating asset is impractical. For electricity (the most common application), a REC [Recognizable Environmental Condition] is a tradable certificate created when one MWh of electricity is produced by an individual renewable energy source. By purchasing a REC, a state DOT can claim the production of the corresponding amount of renewable electricity and thereby reducing scope 2 GHG emissions. (ICF International [a] 2011)

3.0 PUBLIC TRANSPORTATION IN CONNECTICUT

Of the nearly 45 million Connecticut passenger trips in 2015 that included public transportation services, approximately 42 million occurred on Connecticut’s bus transit systems (USDOT BTS 2015 website). Nearly 80%, or approximately 32 million, of those 42 million trips were on CTDOT-contracted bus operations – systems owned by CTDOT and branded as *CTtransit*. *CTtransit* includes fixed route local bus services in eight urban areas: Bristol, Hartford, Meriden, New Britain, New Haven, Stamford, Wallingford, and Waterbury. These systems form the geographic basis of this study. The unlinked passenger trips¹⁵ reported in Table 3.1 are from the National Transit Database agency profiles – data for Bristol, Meriden, and Wallingford were not available. In Hartford, Stamford and New Haven, CTDOT owns both the rolling stock and the facilities associated with bus operations. For Bristol, Meriden, New Britain, Wallingford, and Waterbury, CTDOT owns only the rolling stock.¹⁶

CTDOT also has contracts with other private providers for services in Bristol, Meriden, New Britain, Wallingford, and Waterbury. In these service areas, the state is fully responsible for all operating deficits and capital costs. Additionally, CTDOT contracts with *CTtransit* and four private companies for the operation of express bus services to Hartford.

TABLE 3.1: CTTRANSIT ROUTE DISTRIBUTION
 (SOURCE: CTTRANSIT DATA SUBMITTED TO THE NATIONAL TRANSIT DATABASE FOR 2015,
WWW.TRANSIT.DOT.GOV/NTD)

Urban Area	Total Routes	Annual Unlinked Passenger Trips (thousands)
Hartford Local	80	14,621
New Britain	15	1,232
New Haven	21	9,527
Stamford	19	3,537
Waterbury	32	2,870
Total	161	31,790
NOTE: Hartford Local includes <i>CTfastrak</i> , Hartford Express and Meriden routes; New Britain includes Bristol routes, and Waterbury includes Wallingford routes		

Figure 3.1 is an image showing routes serviced by *CTtransit* Divisions and *CTfastrak*.

15 According to APTA, “Unlinked passenger trips is the number of times passengers board public transportation vehicles. Passengers are counted each time they board vehicles no matter how many vehicles they use to travel from their origin to their destination and regardless of whether they pay a fare, use a pass or transfer, ride for free, or pay in some other way.” APTA, 2017, Definitions of Terms and Abbreviations, <http://www.apta.com/resources/statistics/Pages/ridershipreport.aspx>

16 Companies operating CTDOT’s rolling stock in these urban areas include DATTCO, New Britain Transportation Company, and Northeast Transportation Company. <http://www.ct.gov/dot/cwp/view.asp?a=1386&q=305318>

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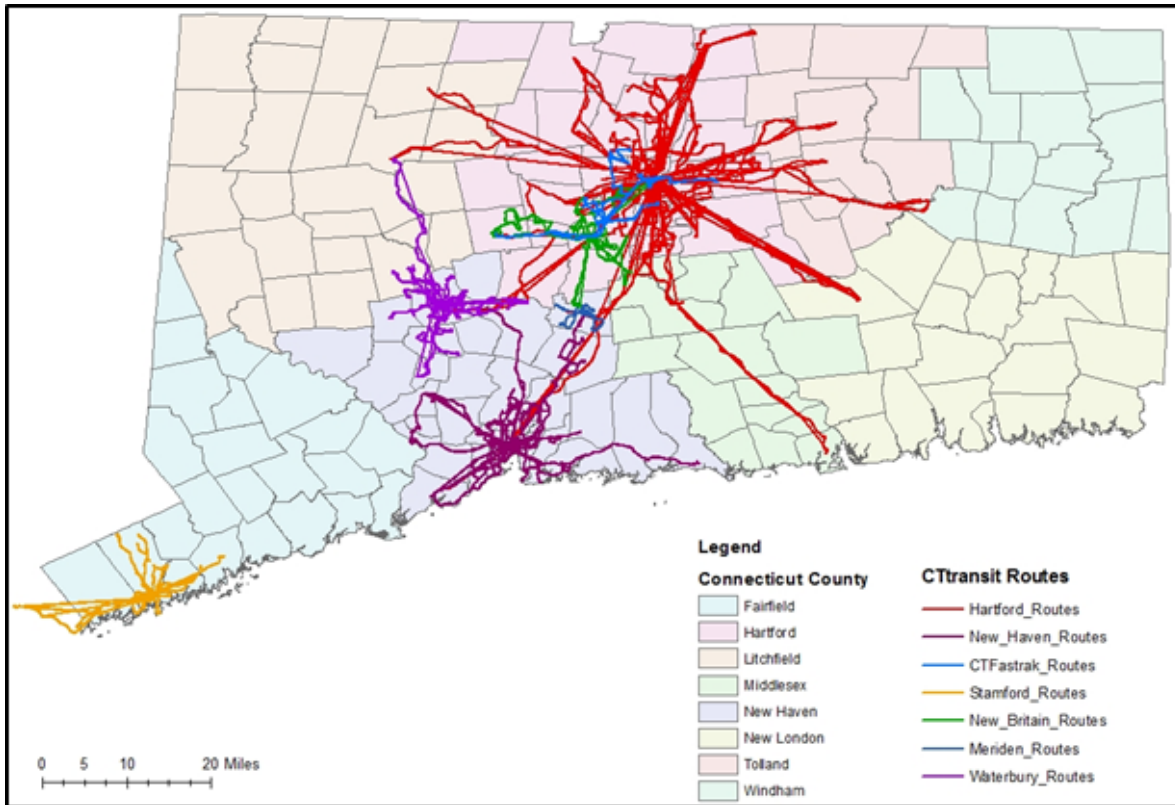


FIGURE 3.1: ALL ROUTES IN THE CTTRANSIT SERVICE AREA
(SOURCE: GENERATED USING GENERAL TRANSIT FEED SPECIFICATION)

CTfastrak is Connecticut's first bus rapid transit system and has been operating between downtown Hartford and downtown New Britain since March 2015. The system has both 40 foot and 60 foot articulated buses operating on a 9.4 mile dedicated busway. The service area for CTfastrak is shown in Figure 3.2.

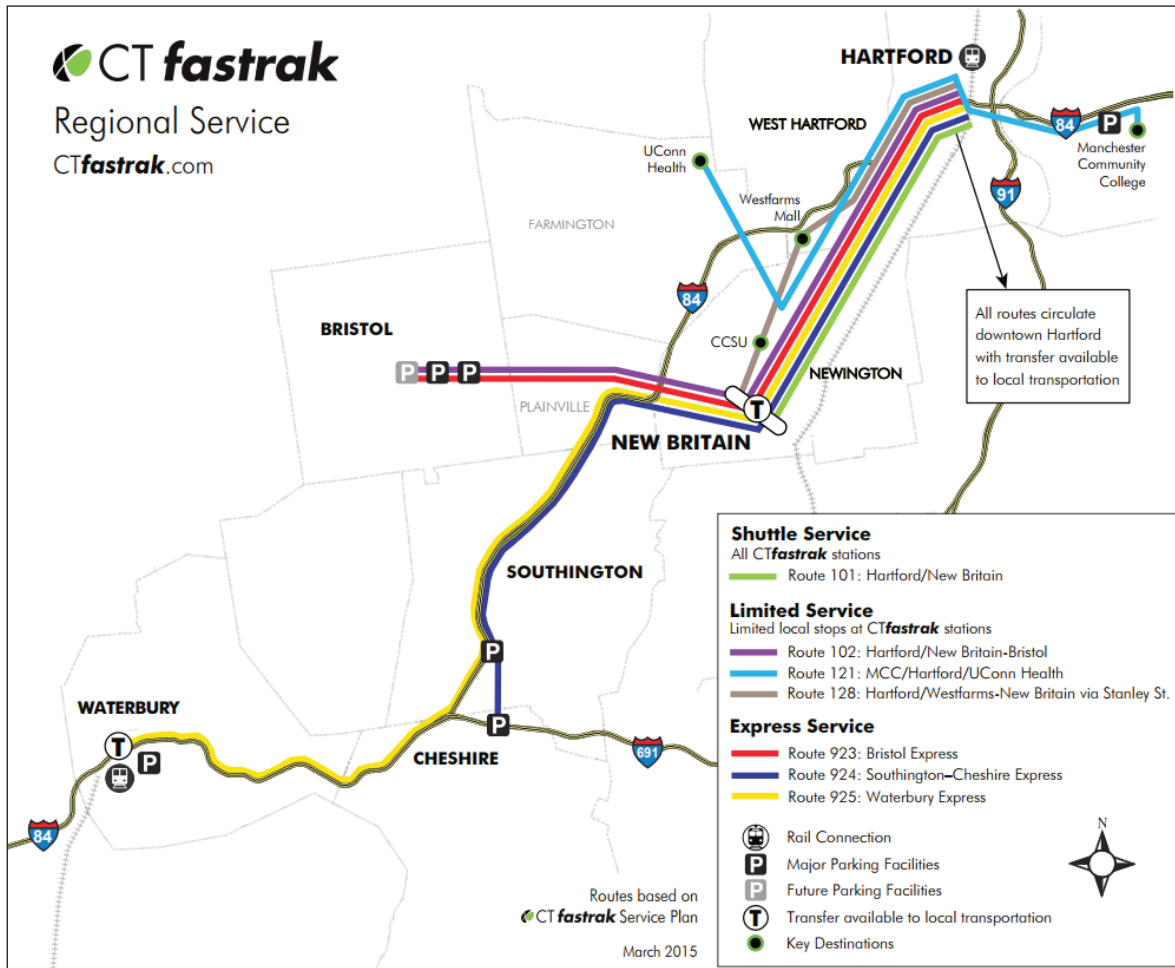


FIGURE 3.2: CTFASTRAK SERVICE AREA MAP (SOURCE: CTTRANSIT WEBSITE, [HTTP://CTFASTRAK.COM/FILES/2015-03-17_CTFASTRAK_REGIONAL_MAP.PDF](http://ctfastrak.com/files/2015-03-17_CTFASTRAK_REGIONAL_MAP.PDF))

3.1 CTDOT PUBLIC TRANSPORTATION

3.1.1 Fleet

There were 549 buses in operation and owned by CTDOT in Calendar Year 2016 based on the Greenhouse Gas (GHG) inventory conducted for this study. Details of the inventory are described in the next section. Table 3.2 provides a breakdown of the CTDOT fleet, along with their total annual vehicle miles traveled (VMT) and diesel fuel consumption. The combustion of diesel fuel is the primary contributor to the CTDOT public transportation GHG emissions inventory. Table 3.3 presents additional detail on the Hartford, New Haven, and Stamford fleets, which account for 88% of the total fleet and 85% of the diesel consumption.

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TABLE 3.2: FLEET SIZE, VEHICLE MILES TRAVELED AND DIESEL FUEL USAGE OF
FLEET MANAGED BY CTTRANSIT FOR CALENDAR YEAR 2016

CTtransit Division	Fleet Size	VMT	Diesel Fuel Usage (Gallons)
Hartford	289	10,342,365	2,581,485
New Haven	129	4,167,289	1,168,637
Stamford	59	1,604,373	370,797
Other	72	3,719,109	766,909
TOTAL	549	19,833,136	4,887,828

Detail for the CTtransit Division buses in operation is shown in Table 3.3.

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TABLE 3.3: CTTRANSIT DIVISIONS BUS INVENTORY AS OF CALENDAR YEAR 2016

CTtransit Division	Bus Identification #	# of Buses	# of Seats	Model #	Year
Hartford	101, 114-117, 120-122, 135	9	36	NF DL 40	2001
	201-240	40	38	NF DL 40	2002
	H302**	10	38	NF HDL 40	2003
	303-309*	7	57	MCI D4500	2003
	312-322	11	38	NF DL 40	2003
	401-442	42	38	NF DL 40	2004
	501-548	48	38	NF DL 40	2005
	711-714, 716-753	42	38	NF DL 40	2007
	761-782*	22	38	NF DL 40	2007
	801-802	2	38	NF DL 40	2008
	1011-1018*	8	57	MCI D4500	2010
	1101-1110**	10	57	Nova Artic	2011
	1201-1203**	3	30	NF XDE 35	2012
	1430-1438**	9	26	Gilling 30	2014
	1501-1503**	3	26	Gilling 30	2015
	1211-1212**	2	38	NF XDE 40	2012
	1441-1458**	18	35	NF XDE 40	2014
1462-1473**	12	55	Nova Artic	2014	
Hartford Total		298			
New Haven	106-112	7	36	NF DL 40	2001
	310, 311, 323, 330-336, 338-371	44	38	NF DL 40	2003
	451-492	42	38	NF DL 40	2004
	1023-1036**	14	38	NF XDE 40	2010
	1041-1052	12	57	Nova Artic	2010
	1204**	1	30	NF XDE 40	2012
	1426-1429**	4	57	Nova Artic	2014
	1489-1493**	5	40	NF XDE 40	2014
New Haven Total		129			
Stamford	1225	1	36	NF DL 40	2001
	127-132*	6	36	NF DL 40	2001
	1019-1022*	4	57	MCI D4500	2010
	1061-1073	13	57	Nova Artic	2010
	1213-1014**	2	38	NF XDE 40	2012
	1401-1425**	25	40	NF XDE 40	2014
	1481-1488**	8	40	NF XDE 40	2014
Stamford Total		59			
*High back commuter seat bus configuration **Hybrid Buses					

3.1.2 Facilities

The CTDOT operations, maintenance and storage facilities in the CTtransit Divisions for Hartford, New Haven and Stamford also contribute to the GHG emissions inventory for CTDOT public transportation. The CTtransit Hartford maintenance facility is designed for a capacity of 250 buses; it is currently housing approximately 300 buses. Plans for a new maintenance facility to be operational by 2023 are in preliminary stages of planning and design. The impact of this facility is discussed in Chapter 5. The CTtransit New Haven facility has a capacity of 140 buses, with 129 currently in operation and the CTtransit Stamford facility has a capacity of 75 with 59 buses in operation. The facilities use electricity, purchased gases, fire suppression equipment, heating and cooling systems, and refrigeration equipment, all of which contribute to the GHG inventory.

3.1.3 Other CTDOT Fleet Operators

Beyond CTtransit, five other private agencies operate under CTDOT. A breakdown of their fleet size, along with their total annual VMT and diesel fuel consumption, for Calendar Year 2016 is detailed in Table 3.4. CTDOT does not own or maintain the facilities associated with these operations.

TABLE 3.4: FLEET SIZE, VEHICLE MILES TRAVELED, AND DIESEL FUEL USAGE OF FLEET MANAGED BY OTHER FLEET OPERATORS UNDER CTDOT FOR CALENDAR YEAR 2016

Fleet Operator	Fleet Size	Annual VMT	Annual Diesel Fuel Usage (Gallons)
Collin Bus	6	224,595	46,000
Dattco Inc.	26	1,284,190	291,000
Nason Partners LLC	4	79,360	20,000
Peter Pan	21	737,176	189,000
The New Britain Transportation Co.	16	867,649	220,000
TOTALS	73	3,192,970	766,000
NOTE: The New Britain Transportation Company operates 10 bus routes in Berlin, New Britain, Cromwell, Newington, Plainville, Bristol and Meriden.			

3.2 CTDOT PUBLIC TRANSPORTATION GHG INVENTORY

A comprehensive GHG inventory was conducted for CTDOT bus transit operations to establish a firm baseline of the GHG profile. This baseline will be used as the starting point for analyses to evaluate the strategies for carbon footprint reduction included in this study report. A GHG emission calculator tool was developed for calculating CTDOT's GHG profile, using a modified version of the EPA's Simplified GHG Emissions Calculator. Modifications were made to simplify data entry and remove sections not relevant to CTDOT public transportation. The sections were removed after detailed discussions with CTtransit administrators responsible for the items in the inventory. Sections removed included: stationary combustion, waste gases, steam, business travel, and fire suppression. Fire suppression was not considered as all CTtransit facilities and buses use ABC dry chemical fire extinguishers, which do not contribute to GHG emissions. Additional modifications included more specific input parameters from the

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American Public Transportation Association GHG Calculator for Transit, particularly emission factors tailored to transit buses.

The inventory was conducted for Calendar Year 2016 and focuses on three items: diesel fuel combustion, electricity usage, and gas purchases. Only the major three gases were considered in this analysis, including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). For calculating total emissions, multipliers were applied on the total usage for diesel fuel combustion, electricity usage, refrigeration and air conditioning, and purchased gases. All emissions factors used are from EPA's Emission Factors Hub as of November 2015 (US EPA[e] 2015).

3.2.1 Diesel Fuel (Mobile Emissions)

Diesel fuel combustion is the largest share of GHG emissions for CTDOT public transportation and accounts for all of its mobile emissions. Nearly 4.9 million gallons of diesel fuel were used in Calendar Year 2016 based on the fuel usage records. This results in the emission of 50,191 metric tons of CO₂ equivalent (CO_{2e}). This value incorporates the higher global warming potential (GWP) associated with CH₄ and N₂O. Table 3.5 demonstrates the calculation of GHG for diesel fuel.

TABLE 3.5: CTDOT PUBLIC TRANSPORTATION GHG CONTRIBUTION FROM DIESEL FUEL COMBUSTION FOR CALENDAR YEAR 2016 (MOBILE SOURCES)

CTtransit Division/ Fleet Operators	Emissions Multipliers			GWP Multipliers		
	CO ₂ (kg/gal)	CH ₄ (g/mile)	N ₂ O (g/mile)	CH ₄	N ₂ O	
	10.21	0.0051	0.0048	25	298	
	Diesel Fuel Usage (gal)	Total VMT (miles)	CO ₂ emitted (kg)	CH ₄ emitted (kg)	N ₂ O emitted (kg)	CO _{2e} (kg)
Hartford	2,581,485	10,342,365	26,356,962	53	50	26,373,074
New Haven	1,168,637	4,167,289	11,931,784	21	20	11,938,276
Stamford	370,797	1,604,373	3,785,837	8	8	3,788,337
Other CTDOT Fleet Operators	766,910	3,719,109	7,830,151	19	18	7,835,945
TOTALS	4,887,829	19,833,136	49,904,734	101	95	49,935,632

Table 3.5 takes into account two multipliers, the total production of GHG and their associated GWP. CO₂ is a function of diesel fuel consumption, and CH₄ and N₂O a function of VMT, which their associated multipliers reflect. Totals for diesel fuel consumption and VMT are given in the first two columns. The subsequent three columns show the total kg of each GHG produced by the respective CTtransit division and other fleets. The final column applies the GWP multipliers to each GHG (CO₂ having a multiplier of 1) to produce a total CO_{2e} for each division. The total GHG for mobile emissions is then calculated at 49,936 metric tons (MT) of CO_{2e}.

3.2.2 Electricity Usage

There are currently no electric vehicles in the CTDOT public transportation fleet, meaning that all electricity consumption is associated with the administrative, operational and maintenance facilities owned by CTDOT in Hartford, New Haven and Stamford. Electricity consumption and associated GHG for the three CTtransit facilities is shown in Table 3.6.

TABLE 3.6: CTTRANSIT GHG CONTRIBUTION FROM ELECTRICITY CONSUMPTION FOR CALENDAR YEAR 2016

CTtransit Division	Emissions Multipliers			GWP Multipliers	
	CO ₂ (lb/MWh)	CH ₄ (lb/MWh)	N ₂ O (lb/MWh)	CH ₄	N ₂ O
	637.9	0.07284	0.01071	25	298
	Electricity Usage (MWh)	CO ₂ (lb)	CH ₄ (lb)	N ₂ O (lb)	CO _{2e} (MT)
Hartford	3,694	2,356,695	269	40	1,077
New Haven	3,762	2,399,598	274	40	1,097
Stamford	1,257	801,611	92	13	367
TOTALS	8,713	5,557,904	635	93	2,541

A total of 8,713 Megawatt Hours (MWh) was consumed in Calendar Year 2016. Using the emissions and GWP multipliers in a fashion similar to diesel fuel results in a total of 2,541 MT of CO_{2e}.

3.2.3 Refrigeration and Air Conditioning

The contribution to GHG from refrigeration and air conditioning equipment stems from the usage of refrigerants in their operation. The recharging of refrigerants in Calendar Year 2016 was used to estimate the GHG emissions. The GWP of refrigerants varies, with Table 3.7 providing the GWP of those refrigerants recharged in CTtransit facilities and the associated calculations.

Each refrigerant is multiplied by its GWP to calculate a total CO_{2e} in lbs. The 5.4 million lbs. CO_{2e} is equivalent to 2,446 MT CO_{2e}.

TABLE 3.7: CTTRANSIT GHG CONTRIBUTION FROM REFRIGERANT RECHARGING FOR CALENDAR YEAR 2016

CTtransit Division	Gas	GWP Multiplier	Recharge (lb)	CO _{2e} (lb)
Hartford	CO2	1	65	65
	R-22	1,810	400	724,000
	R-134a	1,430	3,250	4,647,500
	R-290	3	175	525
	R-1270	2	7,458	14,916
New Haven	R-1270	2	2,739	5,478
	CO2	1	5	5
Stamford	R-1270	2	165	330
TOTALS		3,251	14,257	5,392,819

3.2.4 Purchased Gases

CTtransit purchased only CH₄ in Calendar Year 2016. Primarily used for heating, 1.4 million lbs. of CH₄ was purchased in Calendar Year 2016, with a GWP of 25. This resulted in roughly 35 million lbs. of CO_{2e}, or 15,875 MT CO_{2e}.

3.2.5 GHG Inventory Summary

The total Calendar Year 2016 GHG emissions for CTDOT public transportation is shown in Table 3.8. Mobile sources comprise the largest portion, followed by purchased gases used primarily for heating. Figure 3.3 depicts the GHG emissions graphically. CTDOT public transportation contributes a total of 0.0708 MMTCO_{2e}.

TABLE 3.8: CTDOT PUBLIC TRANSPORTATION GHG INVENTORY FOR CALENDAR YEAR 2016

Source	CO _{2e} (MMT)
Mobile Sources (Diesel)	0.04994
Electricity	0.00254
Refrigerants	0.00245
Purchased Gas	0.01588
TOTALS	0.07080

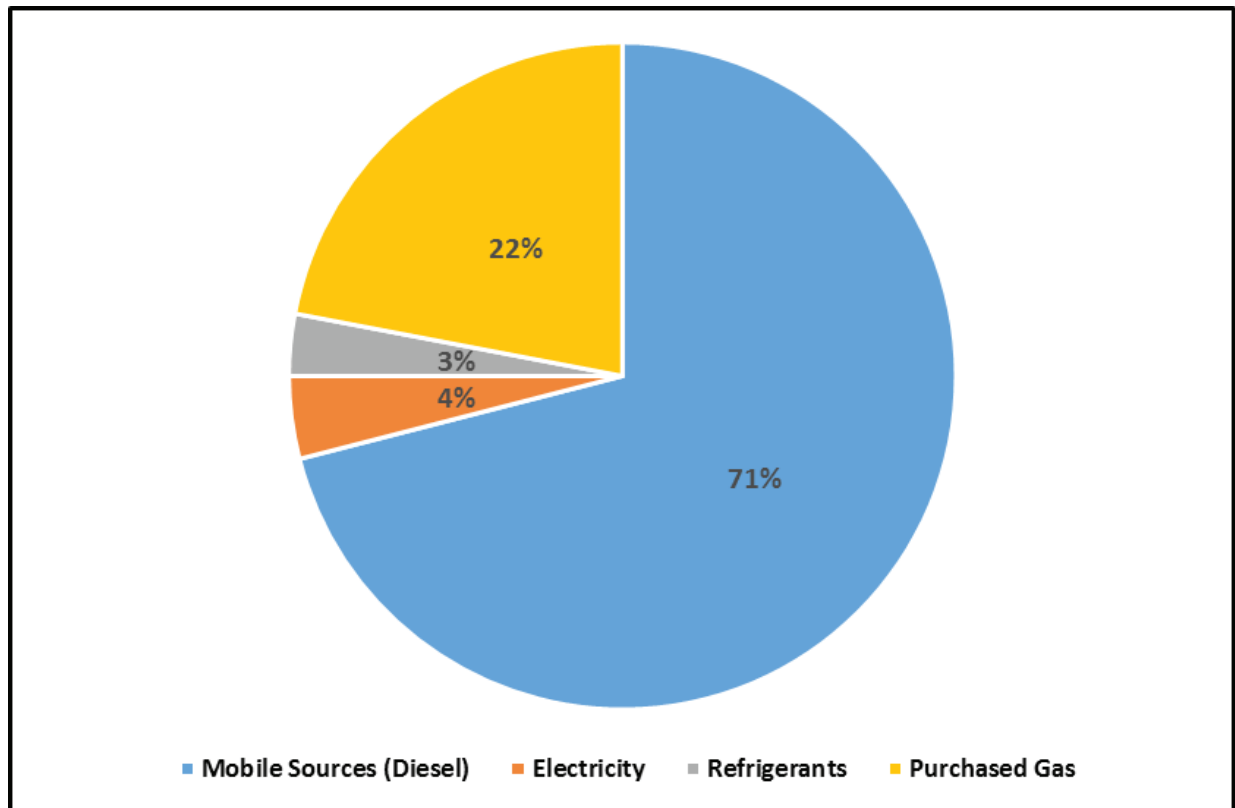


FIGURE 3.3: CTDOT PUBLIC TRANSPORTATION GHG INVENTORY BY SOURCE FOR CALENDAR YEAR 2016

This chapter introduced the CTDOT public transportation fleet and facilities and presented the details of establishing a GHG baseline through the comprehensive GHG inventory conducted for Calendar Year 2016. The following chapters will present two methods of analysis applied to evaluate strategies for reducing the carbon footprint of CTDOT public transportation. One method focuses on GHG reduction and rolling stock fuel technology. The second method focuses on an economic analysis of the strategies, as cost efficiency is a significant factor in the selection of any strategy.

Both of these methods rely on the development of scenarios that estimate the state of the system in 2030 and 2050. These dates are in line with analysis conducted by DEEP and the goals established by the Governor's Council on Climate Change. Multiple scenarios are presented, as there is a great deal of uncertainty in trying to predict conditions so far in the future. The next chapter discusses the development of these scenarios and their inherent assumptions in detail.

4.0 ECONOMIC COST ANALYSIS OVERVIEW

Several cost analyses alternatives are considered in this chapter: benefit-cost analysis (BCA), cost-effectiveness analysis, and life-cycle cost analysis (LCCA). LCCA is identified as the preferred approach in the context of GHGs. The chapter includes a limited exposition on the issues related to the LCCA conducted for replacing Connecticut's existing diesel and diesel hybrid electric bus fleet with lower carbon footprint buses, a description of the approach taken to consider health costs, and concludes with other issues considered.

4.1 APPROACHES

As discussed in Chapter 2, a specific type of analysis that is often utilized to address the task of choosing investment alternatives is a benefit-cost analysis (BCA), alternatively commonly denoted as a cost-benefit analysis. The Transportation Research Board's Transportation Economics Committee's website¹⁷ defines benefit-cost analysis as "... a systematic process for calculating and comparing benefits and costs of a project for two purposes:

- *to determine if it is a sound investment (justification/feasibility)*
- *to see how it compares with alternate projects (ranking/priority assignment)"*
(Transportationeconomics.org website 2017)

Additionally, Transit Cooperative Research report # 78, *Estimating the Benefits and Costs of Public Transit Projects: A Guidebook for Practitioners*, provides a benefit-cost analysis guide for transit. (ECONorthwest et al. 2002)

According to Gallivan and Grant, the cost of strategies that reduce GHG emissions is a key factor for agencies when deciding which strategies to pursue. There are several general types of cost analysis, including

- *Cost-Effectiveness Analysis (CEA): measures the impact of a strategy on GHG emissions in dollars per ton reduced (\$/ton) (i.e., cost spent per ton reduction of carbon). A highly cost-effective strategy has a low \$/ton value; for example, a strategy that costs \$50/ton can reduce twice the GHG emissions for the same dollar amount as a strategy that costs \$100/ton.*

To analyze the cost-effectiveness of a strategy, agencies must calculate both the cost and the emissions impact of the strategy.

- *Benefit-Cost Analysis (BCA): compares multiple impacts of strategies by converting each impact to terms of dollars [and can therefore] account for other environmental impacts of transit beyond GHGs. These other environmental impacts include reduced emissions of criteria pollutants, and societal impacts such as time saved and improved safety.*

For CBA [BCA] analyses, assigning a cost to GHG emissions (e.g., \$50/ton) allows GHG impacts to be included in a CBA of strategies, in which all impacts of a given strategy are monetized. (Gallivan and Grant, 2010, pp. 43-44)

17 Website: <http://bca.transportationeconomics.org/>

Similarly, the social cost of carbon, which differs from the costs of strategies that reduce GHG emissions discussed above, is defined as the present discount value of the economic cost caused by an additional ton of CO₂ emissions, or its equivalent in non-CO₂ GHG emissions. The social cost of carbon concept is commonly used to implement climate change policies. Social costs include such items as agricultural productivity (crop yields), value of the loss of species and habitats, and risks to human health. Nordhaus estimates that the social cost of carbon can be expected to grow at 3% per year (in real dollars) over the period through 2050 (Nordhaus 2017). However, there is significant variability in social cost of carbon estimates due to differing assumptions about the future path of emissions, how climate will respond, the impacts this will cause, and the way we value future damages (Evans website 2017).

According to Gallivan and Grant, CBA [BCA] is more appropriate for evaluating transit strategies across multiple objectives, whereas cost effectiveness is a simpler and more common framework for evaluating just the impact of strategies on GHG emissions, relative to cost (Gallivan and Grant, 2010, p. 43). Also, CBA generally includes more intangibles such as health benefits/costs and therefore, policy makers should decide whether or not to include them in an analysis.

In the current context, CEA relies on cost savings per unit of carbon emissions reduction. But there can be serious ramifications of using estimates based on averages when there are large outlier observations. LCCA is a reasonable, middle ground alternative to these two other cost approaches; therefore, the remainder of this chapter focuses on the LCCA approach.

4.2 LIFE-CYCLE COST ANALYSIS

4.2.1 Background

LCCAs are typically performed for the comparison of transportation infrastructure or vehicle purchasing options. This cost approach was determined to be the most appropriate for the economic component of the analysis conducted for this study. An innovative variation of LCCA was utilized, specifically analyzing 1) total costs between 2018 and 2030 for the entire bus fleet, and 2) separately, for a specific type of bus.

Hunkeler et al. (2008) defines and contrasts the following three types of LCCA:

- *Conventional or Traditional: ...the assessment of all costs associated with the life cycle of a product that are directly covered by the main producer or user in the product life cycle. The perspective is mostly that of one actor, the manufacturer, user or consumer.*
- *Environmental: ...the assessment of all costs associated with the life cycle of a product that are directly covered by 1 or more of the actors in the product life cycle (supplier, manufacturer, user or consumer, and or end of life actor) with the inclusion of externalities that are anticipated to be internalized in the decision relevant future.*
- *Societal: ...the assessment of all costs associated with the life cycle of a product that are covered by anyone in the society, whether today or in the long-term future. The perspective is from society overall, nationally and internationally, including governments. (Hunkeler, 2008, p.4)*

The life-cycle costs that result from conducting a LCCA will increase respectively based on the type of LCCA conducted from conventional to environmental to societal.

According to Hunkeler, a societal LCCA includes a larger set of costs and directly concerns a larger set of stakeholders, including governments and other public bodies not directly concerned with the product being evaluated (Hunkeler, 2008, p. xxviii). A weakness of this approach is the lack of agreement from the scientific community on definitions used for conducting a societal LCCA and there can be high uncertainty in the evaluation of societal effects. It is noted that a benefit-cost analysis may be considered as a source of ideas for how to take a social cost perspective into account for the development of societal LCCA. An approach taken by the European Commission is a 3-pillar concept for policy impact assessments that considers separately the social, environmental and economic dimensions. Hunkeler suggests that an environmental LCCA is more suitable for sustainability (Hunkeler, 2008, pp. 6-9).

4.2.2 *Life-Cycle Cost Calculations*

For this study's LCCA, an analysis tool was developed that includes a calculation to determine the life-cycle cost for several strategies including battery electric buses, as well as various mixes of bus fuel type combinations, including a given percentage of the fleet with battery electric buses with the remainder as diesel buses¹⁸. The primary purpose of the calculation is not to consider the life-cycle cost of particular capital equipment (i.e., bus), as is typically the case with LCCA; rather, this cost is a consideration of the LCCA conducted for the carbon reduction strategies associated with each identified scenario between 2018 and 2030.

The Python™ programming language¹⁹ was used to develop the analysis tool to perform the calculation. This customized tool allows a user conducting an analysis to change a number of parameters, including level of ridership and VMT options, the fleet mix (i.e., percentage of battery electric and types of diesel buses, such as diesel and hybrid diesel-electric), the discount rate and rate of general price increases, the decline in capital costs due to technological and production improvements, as well as other options.

In the expression that follows, a set of strategies for achieving carbon reductions can be defined as $s \in S$. A set of scenarios defining assumptions about a transportation system context can be defined as $n \in N$. The set of strategies for achieving carbon reduction can be found in Chapter 5 of this report.

Specifically, the life-cycle cost for each carbon reduction strategy within each scenario context can be calculated using the following expression:

18 Various strategies, including hydrogen fuel cell buses, are discussed in more detail in Chapter 5)

19 Python™ is a widely used, open source scripting language that is relatively straightforward, allowing modifications/updates by experienced users.

$$LCC_{s,n} = \sum_{t \in T} \left[\frac{C_{t,s,n}(1 - d_{t,s,n})(1 + p_{t,n})}{(1 + i_{t,n})} + \frac{O_{t,s,n}(1 + p_{t,n})}{(1 + i_{t,n})} \right]$$

where,

- $t \in T$ the set of time periods in the analysis (years, year 0 = 2018)
- $s \in S$ the set of strategies for achieving carbon reduction
- $n \in N$ the set of scenarios defining assumptions about transportation system context
- $LCC_{s,n}$ life-cycle cost for strategy s in scenario n
- $C_{t,s,n}$ Capital costs for strategy s in year t within scenario n
- $d_{t,s,n}$ the decline in capital costs relative to the base year for s , in t , within n
- $i_{t,n}$ long-run discount rate in year t under scenario n relative to base year
- $O_{t,s,n}$ operating and maintenance expenses for strategy s in year t within scenario n
- $p_{t,n}$ rate of increase in general prices in year t under scenario n relative to base year (Note: To include the rate of change in general prices into the discount rate, $i_{t,n}$, set $p_{t,n}$ equal to zero)

For this expression, capital costs ($C_{t,s,n}$) include warranty, facility conversion and financing costs, and operating and maintenance costs ($O_{t,s,n}$) include vehicle maintenance, facility maintenance, fuel cost and overhaul cost.^{20, 21}

The life-cycle cost is calculated as the present discounted value of capital costs plus operating and maintenance expenses for a given strategy. In addition to being discounted due to the fact that these costs will be incurred in the future, the possible increase in general prices that can lead to higher costs over time is embedded in the equation.

For capital costs, $(1 - d_{t,s,n})$ is a term²² that allows for the possibility that these costs may decrease over time, e.g., the capital cost for battery electric buses due to technological and production improvements and increased production and demand. This assumption is based on the fact that the average battery pack price per kWh decreased by approximately 77% between 2010 and 2016 (McKinsey and Company, 2017); therefore, a further downward trend in these prices is anticipated.

The long-run discount rate can be selected. This rate reflects long-run interest rates, and in the current context, focus on equities for the capital discount rate.²³

20 These values have been estimated using methods associated with the TCRP FuelCost 2 calculator assembled by TCRP. (SAIC, 2011)

21 The remaining inputs are the details for the set of strategies – the other combinations of bus type alternatives – and are described in Chapter 5.

22 Term in this case refers to $d_{(t,s,n)}$; which, when multiplied by $C_{(t,s,n)}$, essentially yields the net capital costs (after factoring the fall in capital costs over time) relative to the base year strategy “ s ”, in year “ t ”, within scenario “ n ”.

23 Additional background on long-run interest rates can be found at: <https://obamawhitehouse.archives.gov/blog/2015/07/14/decline-long-term-interest-rates>

The interest rate and general price level increase rate can be adjusted. There are options to choose between these two parameters (see Chapter 5 for more detail). However, projected trends in the New York Metropolitan Area Consumer Price Index (an estimate often used by CTDOT for price level increases), the Connecticut Department of Labor wage index, information obtained from Engineering News Report, and/or the urban Consumer Price Index from the US Bureau of Labor Statistics can be considered.

Also, it is possible to adjust the discount for risk. For example, if there is a greater risk that a battery electric bus manufacturer may exit the industry, this risk could be considered by changing the discount rate for risk-adjustments.

The following assumptions about the various parameters are included in the analysis tool, in addition to the various scenarios for level of ridership and VMT, as described in more detail in Chapter 5:

- a. Year 0 is 2018, Year 1 is 2019, ..., Year 12 is 2030.
- b. Estimated capital costs for buses and infrastructure upgrades, the decline in capital costs from 2018 to 2030 (where applicable), fuel economy, fuel costs, and operating and maintenance expenses used in the calculations are shown in Table 4.1.
- c. Two NREL reports (M. Lekaina & M. Penev, 2013; L. Eudy, R. Prohaska, K. Kelly, & M. Post, 2016) were used for fueling infrastructure capital cost baseline values. These costs are a function of the type of alternative fuel technology buses in the fleet and the capacity of the fueling infrastructure. For example, for every 28 hydrogen fuel cell buses a capital cost of \$2.8 million per charging infrastructure is required. Assumptions from California's Advanced Clean Transit program (ACT 2016) were used for annual fueling infrastructure operating and maintenance costs.

The cost of new infrastructure for general operations/maintenance, such as the new CTtransit Hartford Division maintenance facility is not included in this analysis. This is further detailed in Chapter 5, Section 5.2.1.4.

- d. Learning cost is the cost for introducing a newer technology, regardless of the technology – so it is applied equally for battery electric buses and hydrogen fuel cell buses. This cost is considered for only the first two years according to Fuelcost2. This assumes that after two years, staff will be familiar with the new technology and there will be no need to provide additional training. Fuelcost2 also notes the difference in learning cost between year 1 and 2.
- e. The hydrogen fuel cell bus cost assumption for 2018 is from the Eudy & Post, 2017 NREL report.
- f. Other general assumptions and values used for this analysis are listed in Table 4.2.

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TABLE 4.1. COST ASSUMPTIONS FOR LIFE-CYCLE COST ANALYSES

Input Data		Conventional Diesel	Hybrid Diesel-Electric	Battery Electric	Hydrogen Fuel Cell
Estimated Capital Bus Cost	2018	\$450K(a)	\$600K(a)	\$800K(a)	\$1.356M(b)
	2030	\$450K	\$600K	\$700K(c)	\$1.356M
Fuel Economy		3.67 mi/gal(d)	5.13 mi/gal(d)	0.47 mi/kWh(e)	7.01 mi/DGE(b)
Fuel Price		\$2.50/gal(a)	\$2.50/gal(a)	\$0.12/kWh(g)	\$7.81/DGE(a)
Fuel Cost (\$/mile) (calculated)		\$0.68	\$0.49	\$0.25	\$1.12
Bus Maintenance Cost (\$/mile)		\$0.45(a)	\$0.47(a)	\$0.16(e)	\$0.21(a)
Fueling Infrastructure Capital Cost				\$50K/bus(e)	\$100K/bus(f)
Annual Fueling Infrastructure Operating and Maintenance Cost (g)		\$189/bus	\$163/bus	\$38/bus	\$140K/unit
Learning Cost Multiplier (a)	Year 1			1.1	1.1
	Year 2			1.2	1.2
(a): SAIC (2011); (b): L. Eudy & M. Post, 2017, p. 31 (https://www.nrel.gov/docs/fy18osti/70075.pdf); (c): See report section 5.2.1.5, p. 64; (d): CTDOT data; (e): L. Eudy, R. Prohaska, K. Kelly & M. Post, 2016, p. vii, Table ES-1 (https://www.nrel.gov/docs/fy16osti/65274.pdf); (f): M. Melaina & M. Penev, 2013, p. v, Table ES-1 (https://www.nrel.gov/docs/fy13osti/56412.pdf); (g) Advanced Clean Transit (ACT) Cost Assumptions, 2016, Table 11 (https://www.arb.ca.gov/msprog/bus/tco_assumptions.xlsx)					

TABLE 4.2. OTHER COST ASSUMPTIONS AND VALUES

Cost Categories	Assumptions/Values	Sources
Labor Rate	\$50/hour	FuelCost2, SAIC, 2011
Discount Rate	3%	Assumptions Detailed in Chapter 5
Rate of Price Increase	3%	Assumptions Detailed in Chapter 5
Annual Mileage of Bus	36,000	CTDOT
% Renewable Electricity in 2018	17%	Connecticut Renewable Portfolio Standard: Required Renewable Energy Percentages for Class I Renewables for 2018 http://www.ct.gov/pura/cwp/view.asp?a=3354&q=415186
% Renewable Electricity in 2030	30%	2017 Comprehensive Energy Strategy (in draft, 07-26-17), p. 65
% Renewable Electricity in 2050	85%	Governor's Council on Climate Change. http://www.ct.gov/deep/cwp/view.asp?a=4423&Q=568878&deepNav_GID=2121 . This assumption is consistent with those made by the GC3 in its analysis to meet the state's Global Warming Solution Act
Social Cost of Carbon	\$36/metric ton CO ₂	Amount used for 2017, with average discount rate of 3% (EPA, 2016)
Note: Predictions more than five years into the future should be interpreted with caution.		

4.3 HEALTH COSTS

Health costs for each strategy were considered for the various LCCA scenarios conducted in this study. Also, the analysis tool provides the option to consider health costs for other strategies. Exposure to air pollution from fossil fuel-based energy can exacerbate respiratory diseases, like bronchitis and asthma, and cause heart attacks and premature death. Beyond the physical health effects, pollution-related illnesses impose other costs on people, such as lost wages, productivity for work, school absences, cost of medical treatments, and outdoor activity restrictions when air quality is poor (EPA, 2015). There is some debate regarding the exact value of a human life and therefore the value of improved health is somewhat difficult to quantify (Viscusi, 2011). Nevertheless, a second tier of LCCA estimates are presented so that the health benefits from air pollution reduction can be considered.

The EPA's Co-Benefits Risk Assessment (COBRA; EPA [d] website) Screening Model is a tool typically used by DEEP and many others to estimate the health and economic benefits of air quality policies.²⁴ The advantage of using the COBRA model is that many features can be specified, including examining a specific state or the entire United States, as well as counties within a state. It allows for the selection of the type of vehicle(s), pollutant (i.e., ammonia, sulfur dioxide, nitrous oxides, and volatile organic compounds), particulate matter, the estimated pollution reduction in percentage terms, and the discount rate. It provides a detailed set of estimates for the overall health cost savings based on both high and low scenarios, as well as the cost savings for many specific types of illnesses.

The following are several advantages of breaking out the health costs into a second tier of analysis using COBRA, rather than incorporating them into a cost analysis, such as in a BCA:

- COBRA cannot exclusively estimate the effects of GHGs; rather it considers the health cost effects of a broad array of pollutants.
- COBRA can be used to compare health costs by bus fuel-types.
- Policy makers may opt not to include health costs, or may use health costs to assist in strengthening a proposal for a particular fleet mix.
- Breaking out health costs can provide a clear picture of the portion of costs that are due to health cost savings, as well as other costs such as capital and operating and maintenance costs.

COBRA was used to estimate the health benefits from air pollution reduction for this study. The emission factors shown in Table 4.3 were used to calculate the reduction in pollutants to determine health cost savings, with an assumed discount rate of 3%. Diesel type bus VMT were used to calculate pollutant emissions. Total highway diesel type vehicle pollutant data was collected from the EPA's Emission Inventory (2014). Then the percentage decrease in pollutants was calculated and used as an input for the scenarios. Both high and low scenarios were run using COBRA.²⁵

²⁴ For more information on EPA's COBRA Model see: https://19january2017snapshot.epa.gov/statelocalclimate/co-benefits-risk-assessment-cobra-screening-model_.html

²⁵ The COBRA user manual states: Note that the health effects table includes low and high estimates for the changes in the number of cases and the corresponding economic values for adult mortality, nonfatal heart attacks, and total health effects. The low and high estimates are derived using two sets of assumptions about the sensitivity of adult mortality and non-fatal heart attacks to changes in ambient PM2.5 levels. The high estimates are based on studies that estimated a larger effect of changes in ambient PM2.5 levels on the incidence of these health effects (EPA[g] website)

TABLE 4.3. POLLUTANT FACTORS USED IN THE EPA’S COBRA MODEL
 (SOURCE: CALIFORNIA AIR RESOURCES BOARD, 2013)

Pollutant	Emission Factors (g/mile)
Nitrogen oxides (NO _x)	14.793
Sulfur dioxide (SO ₂)	0.453
Particulate matter (PM-2.5)	0.604
Volatile organic compounds (VOC)	0.642

A range of health cost savings scenarios is presented in Chapter 5 based on the estimated amount of statewide pollutant reduction anticipated with the various ridership levels and VMT scenarios.

While there are many other societal cost savings that could be considered separately, many are more difficult to quantify than the health cost savings. Therefore, the analyses were restricted to including health cost savings only as a separate tier of cost savings.

4.4 OTHER CONSIDERATIONS

Another potential issue to consider in a LCCA is the impact of system fare revenues. Subsidies are needed to offset the difference between operating costs and farebox recovery for all public transit systems in the United States (NTD 2017). These subsidies will be required regardless of fuel technology and the farebox recovery rate will not likely change depending on fuel technology. Therefore, fare revenues and subsidies were not included in the analyses.

Additionally, the number of battery electric buses being produced now is relatively low compared with the number of battery electric buses anticipated to be placed in service in the coming years. Due to economies of scale, production costs will be expected to fall as production rises, therefore there may be some additional cost savings from larger scale production. There may also be other indirect cost savings, such as from greater energy security as a result of less need to rely on diesel in the future.

5.0 SCENARIO DEVELOPMENT AND ANALYSIS

Prior chapters described the methods that will be used to evaluate the conversion of the *CTtransit* fleet to an alternative fuel technology through the target years 2030 and 2050. The life-cycle cost analysis (LCCA) approach provides the basis for an economic analysis, and a GHG Inventory using published emissions factors generates the respective GHG profiles for alternative fuel technology strategies. Detailed GHG and LCCA results are presented for years 2018 through 2030. This period represents the approximate timeline necessary to replace completely the *CTtransit* fleet.²⁶ The target year 2050 focuses only on total GHG reduction for the following reasons:

- projecting the parameters associated with this analysis over three decades into the future is conjecture, and for the purposes of this study, not of value; and
- the strategies should be fully executed with a complete fleet replacement by 2030 – meaning that there will not be future differences in technology price or performance to consider, which is the core of the analysis conducted.

A substantial number of parameters were considered for each of the GHG and LCCA approaches. Accordingly, the best available information was used to determine values for these parameters. Values used were based on reputable, published documentation – and whenever possible these values were verified as consistent across several reliable documented sources. However, notwithstanding this effort, there may be values used in this analysis that are associated with significant uncertainty or disagreement with alternative sources. Therefore, analysis results are presented through use of scenarios designed to capture the uncertainty associated with several primary parameters, with one of the scenarios selected for a detailed sensitivity analysis. For this analysis, secondary parameters were examined in greater detail to develop a range of possible outcomes for comparison and analysis.

The chapter includes

- Scenario parameters considered and discussion of the assumptions used in setting baseline values for these parameters
- Primary scenario matrix and assumptions
- Baseline scenario results and discussion of the results individually and in aggregate
- Sensitivity analysis results
- Summary

5.1 SCENARIO PARAMETERS AND ASSUMPTIONS

The two primary parameters that frame the scenarios are: 1) future public transit ridership, and 2) growth in light-duty vehicle miles traveled (VMT). Public transit in Connecticut currently accounts for roughly 3% - 5% mode share depending on the source of the estimate and type of

²⁶ CTDOT reported that a complete bus fleet turnover may require 14-15 years

trip. This mode share is typically presented as the percentage of workers using public transit for a particular type of trip.²⁷ Three possible public transit ridership scenarios were considered in this baseline analysis: 3%, 7% and 10% of total population by 2030. These percentages roughly represent flat ridership, a doubling and a tripling of ridership respectively – or from another perspective, from a pessimistic to an optimistic estimate of future ridership. The percentages used are reasonable given the current public transit mode share and consistent with goals reported by CTDOT. Public transit ridership will play an important role in the GHG Inventory and LCCA, and will determine the fleet size needed to serve the respective public transit ridership base. Public transit ridership also will impact public transit’s GHG footprint in Connecticut. As more people shift to public transit, it is possible that public transit will account for a much larger proportion of shrinking total transportation GHG emissions – an example of the inverse relationship discussed in Chapter 2.

The relationship between ridership and fleet size is not 1:1, as demand for transit may not be spread evenly across a system and smaller capacity buses can be substituted for larger capacity buses that are used on high-ridership routes. A detailed analysis of fleet size growth as a function of ridership was beyond the scope of this study. However, the following section describes a method for quantifying fleet size as a function of ridership at the system level (not accounting for differences in vehicle capacities).

The first step for estimating fleet size requires an estimate of the number of persons that will be using public transit based on the given percentages. Over the next three decades, Connecticut’s population is expected to grow from 3.6 to nearly 3.8 million persons (Figure 5.1). Estimates that are more recent have placed Connecticut’s estimated population for 2030 at 3.63 million as opposed to the 3.7 million used in this study. However, the assumptions regarding population are consistent across all scenarios and analyses, meaning that the relative comparisons between fuel technologies will not be impacted by assumed population. The precise GHG reductions and life-cycle cost estimates would change slightly, but the relative difference between battery electric and hybrid diesel-electric buses would remain intact.

27 CTDOT Connecticut ... on the move, Transportation Fast Facts, p. 11. Commuting modes include: Drove Alone, Carpooled, Public Transportation, Worked at Home, Walked, and Other Means (including bicycle). http://www.ct.gov/dot/lib/dot/documents/dcommunications/2015_ct_fastfacts_final.pdf

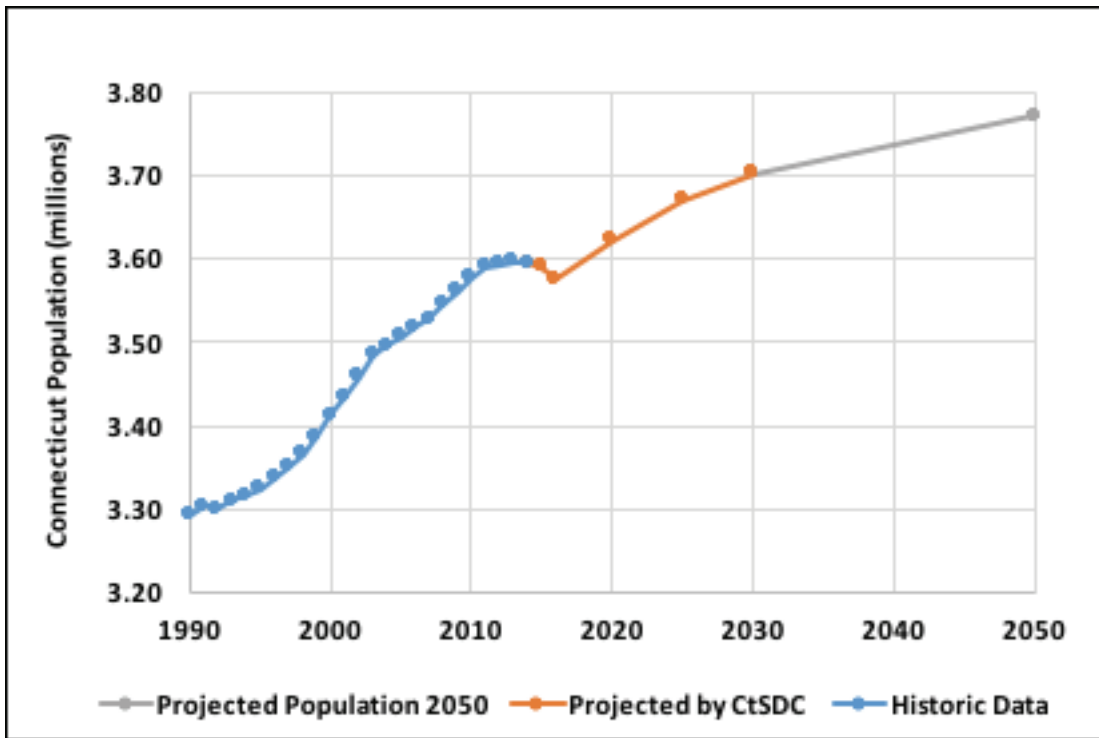


FIGURE 5.1. CONNECTICUT POPULATION: HISTORIC AND PROJECTED
(SOURCE: FOR 2015 THROUGH 2030 THE CT STATE DATA CENTER,
[HTTP://CTSDC.UCONN.EDU/2015-TO-2030-POPULATION-PROJECTIONS-STATE-LEVEL/2016](http://ctsdc.uconn.edu/2015-to-2030-population-projections-state-level/2016);
FOR 2031 THROUGH 2050, EXTRAPOLATED BASED ON TREND)

The proportion of population mostly strongly associated with the number of public transit trips taken, and therefore capacity consumed, are those taking public transit to work. Figure 5.2 depicts the linear relationship between unlinked passenger trips and the number of people using transit to commute to work. This graphic is based on the latest data from all 50 states in the National Transit Database (NTD website), and while an approximation, it reasonably represents the relationship between unlinked passenger trips and persons using public transit to commute to work. It is important to note that unlinked trips and fleet size data are at a statewide level.

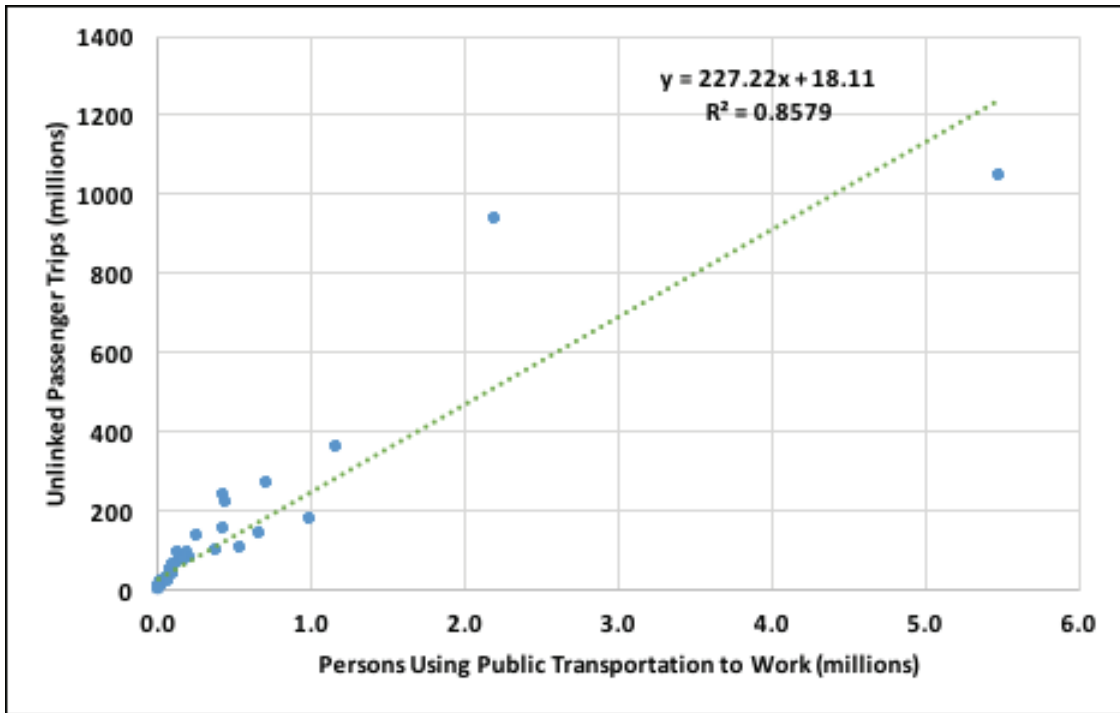


FIGURE 5.2. RELATIONSHIP BETWEEN PEOPLE USING PUBLIC TRANSIT TO COMMUTE TO WORK AND UNLINKED PASSENGER TRIPS BASED ON THE ENTIRE STATEWIDE FLEET FOR EACH OF THE FIFTY STATES (DATA SOURCE: NATIONAL TRANSIT DATABASE, [HTTPS://WWW.TRANSIT.DOT.GOV/NTD](https://www.transit.dot.gov/NTD))

Unlinked passenger trips can then be related to fleet size, again using the National Transit Database for all bus systems on a statewide basis in the United States. Figure 5.3 presents the relationship between unlinked passenger trips and total fleet size.

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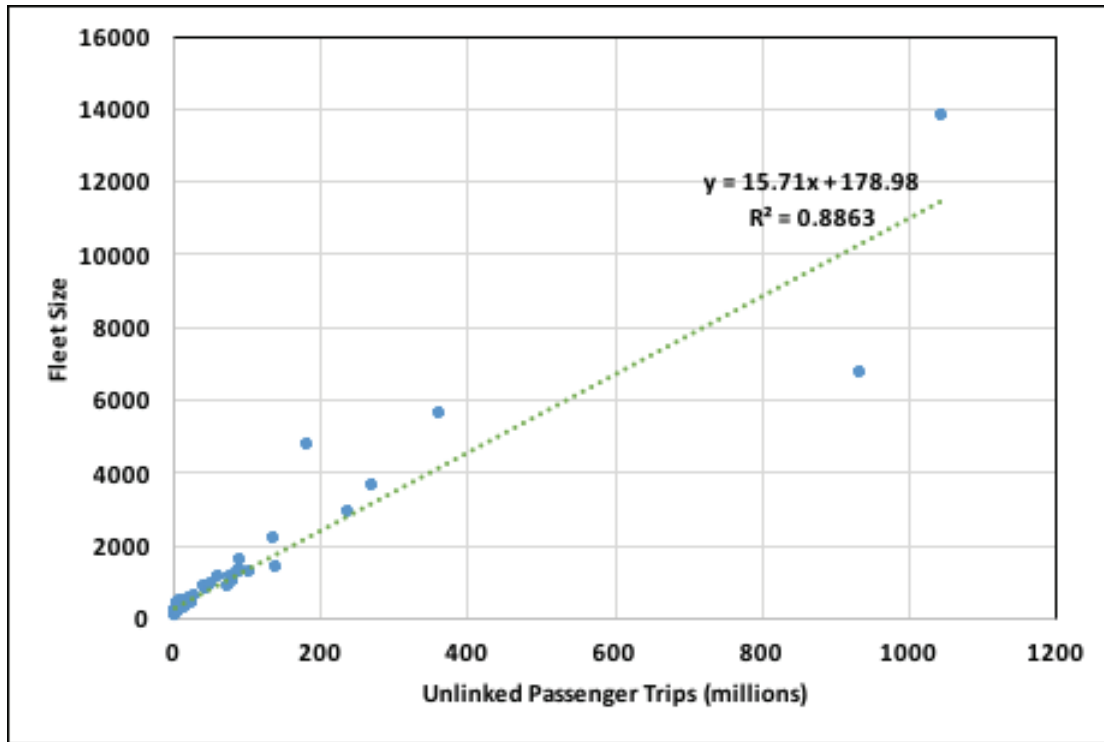


FIGURE 5.3: FLEET SIZE AS A FUNCTION OF UNLINKED PASSENGER TRIPS

The results of these calculations enable the ability to estimate the total fleet size needed to accommodate the assumed ridership in the target years. Table 5.1 summarizes several examples of these calculations.

TABLE 5.1: METHODOLOGY FOR FLEET SIZE VALIDATION (2015) AND
 ESTIMATED FLEET SIZE (2018, 2030, 2050)

Year	Transit Ridership	CT Population	# of People Using Public Transit	Unlinked Passenger Trips (millions)	Statewide Fleet Size	CTtransit Fleet Size
2015 (Actual)				41.6	853	550
2015 (Estimate)	3%	3,573,885	107,217	42.5	845	545
2018	3%	3,576,452	107,294	42.5	845	545
2030	3%	3,705,041	111,152	43.4	859	554
	7%	3,705,041	259,353	77.0	1,388	895
	10%	3,705,041	370,505	102.3	1,784	1,150
2050	3%	3,771,087	113,133	43.8	866	558
	7%	3,771,087	263,977	78.1	1,404	905
	10%	3,771,087	377,109	103.797	1,808	1,166

The first row represents the latest available actual data (2015) for Connecticut: There are 41.6 million annual unlinked passenger trips, serviced by a statewide fleet of 853 vehicles. The second row presents the estimate for 2015 as a comparison to validate the methodology against actual data using the relationships established in this section. Ridership from a population of approximately 3.6 million produces an estimate of 107,217 persons using public transit to work. Using the following equation, the total number of unlinked passenger trips can be estimated as

$$\text{Unlinked passenger trips} = (227.22 \times 0.107217) + 18.11 = 42.5 \text{ million}$$

The next equation depicts and provides an expression for the relationship between fleet size and unlinked passenger trips. Using this expression, total statewide fleet size can be estimated as:

$$\text{Fleet size} = (15.71 \times 42.5) + 178.98 = 845 \text{ vehicles}$$

These results are given in tabular form in Table 5.1. Note that the 2015 estimate closely matches the 2015 actual data for the statewide and CTtransit fleet. The estimated fleet size of 845 buses statewide is within 1% of the actual value of 853. For all other estimates, the current CTtransit fleet size ratio of $550/853 = 0.645$ is used to estimate CTtransit fleet size in future years. For example, the 2030 10% transit ridership statewide fleet is estimated to be 1,784 buses. CTtransit's fleet is then $0.645 \times 1,784 = 1,150$.

5.1.1 Light-Duty Vehicle VMT

The growth in light-duty vehicle VMT is projected from the current baseline, with the projected changes coinciding with the assumptions in DEEP's 2017 Comprehensive Energy Strategy (in draft, 07/26/17) and based on VMT projections provided by CTDOT).

5.2 PRIMARY SCENARIO MATRIX AND ASSUMPTIONS

Transit ridership and light-duty vehicle VMT comprise the primary parameters for the scenario matrix. Table 5.2 depicts the nine resulting scenarios, with Scenario 1 (upper left) being the most conservative with respect to future public transit ridership growth, and Scenario 9 (lower right) being the most optimistic. Scenario 5 represents what is considered the most plausible optimistic scenario and will be utilized for an in-depth sensitivity analysis.

TABLE 5.2. SCENARIO MATRIX

LIGHT DUTY VEHICLES: VMT	TRANSIT RIDERSHIP		
	3% in 2030	7% in 2030	10% in 2030
Linear Increase	1	4	7
Flat	2	5	8
3% Reduction	3	6	9
<i>Scenarios 1 – 9 are shown above</i>			

5.2.1 Assumptions

In addition to the variable parameters comprising the scenario matrix, there are other parameters that will remain fixed for the bulk of the baseline analysis. One scenario is explored in further detail, relaxing some of these assumptions. However, the baseline analysis for the nine scenarios will incorporate the following assumptions that are based on the most recent reputable literature sources.

5.2.1.1 LIGHT-DUTY VEHICLE FLEET ELECTRIFICATION

Battery electric fuel technology has been in development for light-duty vehicles considerably longer than for buses. The market penetration of battery electric buses has increased considerably in the past five years (IEA 2017) due in part to the declining cost and improved performance of batteries (McKinsey 2017). The Governor's Council on Climate Change is evaluating three mid-term GHG emission reduction markers (35%, 45% and 55% below 2001 by 2030) (DEEP 2017). Transportation strategies play an important role in this evaluation, including the percentage of the light-duty vehicle fleet that transitions to battery electric fuel technology. The baseline analysis adopts the most conservative of these three scenarios and the associated light-duty vehicle electrification. The analysis assumes that in 2020, 1% of the light-duty vehicles are battery electric, 18% in 2030 and 92% in 2050.

5.2.1.2 ELECTRICITY PRODUCTION RENEWABLES PORTFOLIO

The research for this study relied on published goals to serve as the baseline assumption regarding the percentage of renewables in Connecticut's energy portfolio. The assumptions adopted regarding Connecticut's renewable energy portfolio are consistent with those made by the Governor's Council on Climate Change in its analysis to meet the state's Global Warming Solution Act (Public Act 08-98) and the draft Comprehensive Energy Strategy (DEEP 2017): 30% Connecticut Class I Renewables by 2030, and 85% by 2050. Although renewables are not necessarily carbon free (Amponsah et al. 2014), their contributions are vastly smaller than non-renewable sources and their life-cycle GHG contributions are mostly associated with infrastructure rather than operations. Further, the assumption is made that the costs associated with renewables will be equivalent to the costs of non-renewables on the consumer side in each of the target years.

5.2.1.3 GHG EMISSIONS FACTORS

All emissions factors used in this baseline analysis are from EPA's Emissions Factors Hub (EPA [e], 2015).

5.2.1.4 NEW CTTRANSIT HARTFORD DIVISION FACILITY

Currently a new operating and maintenance facility is in the early planning stages for the CTtransit Hartford Division. This baseline analysis assumes that the facility will be constructed regardless of the chosen fuel technology and that the cost of the facility will not be significantly impacted by the type of fuel technology. Any differences in facility costs associated with fuel technology are accounted for by the charging and fueling costs considered in the LCCA, previously detailed in Chapter 4.

5.2.1.5 BATTERY ELECTRIC BUS CAPITAL COST ASSUMPTION

Due to the rapid decrease in the cost of batteries and their projected cost/kWh (McKinsey 2017) in the target years, the baseline analysis assumes that by 2030, the cost of a battery electric bus will decrease from \$800,000 to \$700,000 due to a decrease of \$100,000 in the cost of the electric battery. This decrease is consistent with what has been experienced in the personal electric vehicle market. In 2010, a Nissan Leaf cost \$33,000 (CNN 2010, website) – with its battery accounting for \$18,000 of that cost (AutoblogGreen 2015, website). In 2015, the cost of the same model was approximately \$30,000 (Autotrader 2015, website) with a battery cost of \$5,500. Therefore, a 69% decrease in battery price yielded a 10% reduction in vehicle cost. McKinsey (2017) estimates a reduction of the cost of batteries from 75% - 90% by 2030. Although an estimate, the \$100,000 decrease in battery electric bus price would require battery prices to decline by 86%, well within this range.

5.2.1.6 FLEET TURNOVER

A typical bus has a service life of at least twelve years, which can often be extended an additional two to three years depending on budgetary and procurement conditions. The baseline analysis assumes that the bus fleet turnover cycle will follow the same practice used by CTDOT over the past 12 years; an assumption confirmed as reasonable by CTDOT. Figure 5.4 presents the bus fleet turnover cycle as a percentage rather than actual number of buses in the fleet replaced in any given year, which allows for vehicle purchase scenarios over time with more than the existing fleet size required to meet passenger demand. This turnover cycle assumes that all vehicles in operation in 2030 will be a single fuel technology. Therefore, vehicle purchases in 2030 and beyond are not considered.

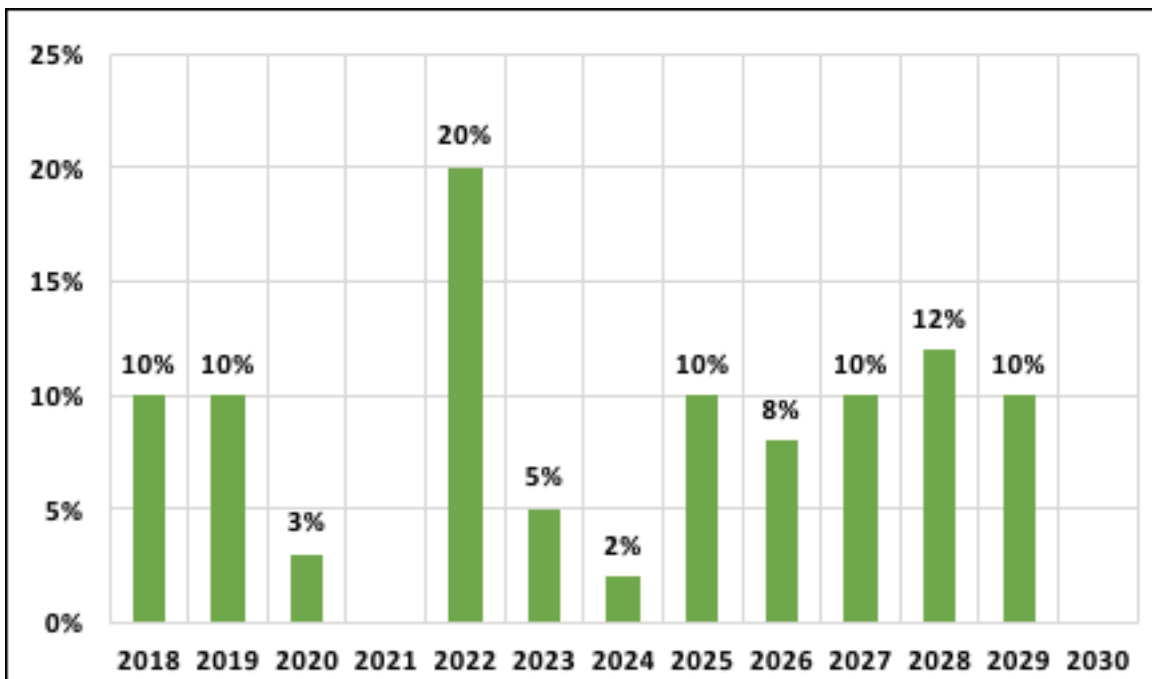


FIGURE 5.4: PERCENTAGE OF THE CTTRANSIT BUS FLEET TURNOVER BY YEAR THROUGH 2030
(SOURCE: CTDOT)

5.3 BASELINE SCENARIO RESULTS

Results from the nine baseline scenarios are consistent within each scenario relative to life-cycle cost and GHG reduction impacts for each fuel technology. Observations from Scenario #5 will frame the presentation and discussion of the results, with the relative observations made about Scenario #5 being applicable across all nine baseline scenarios. The following summarizes the output for Scenario #5, including information about the assumptions associated with it, and GHG and life-cycle cost implications. Appendix H includes a table summarizing the assumptions, context and outputs for each of the baseline scenarios. Figure 5.5 shows the 2050 GHG projected profile. Results from the analysis are by fuel technology and transit ridership. This scenario assumes a full bus fleet conversion by 2030 with ridership percentages remaining flat from 2030 – 2050.

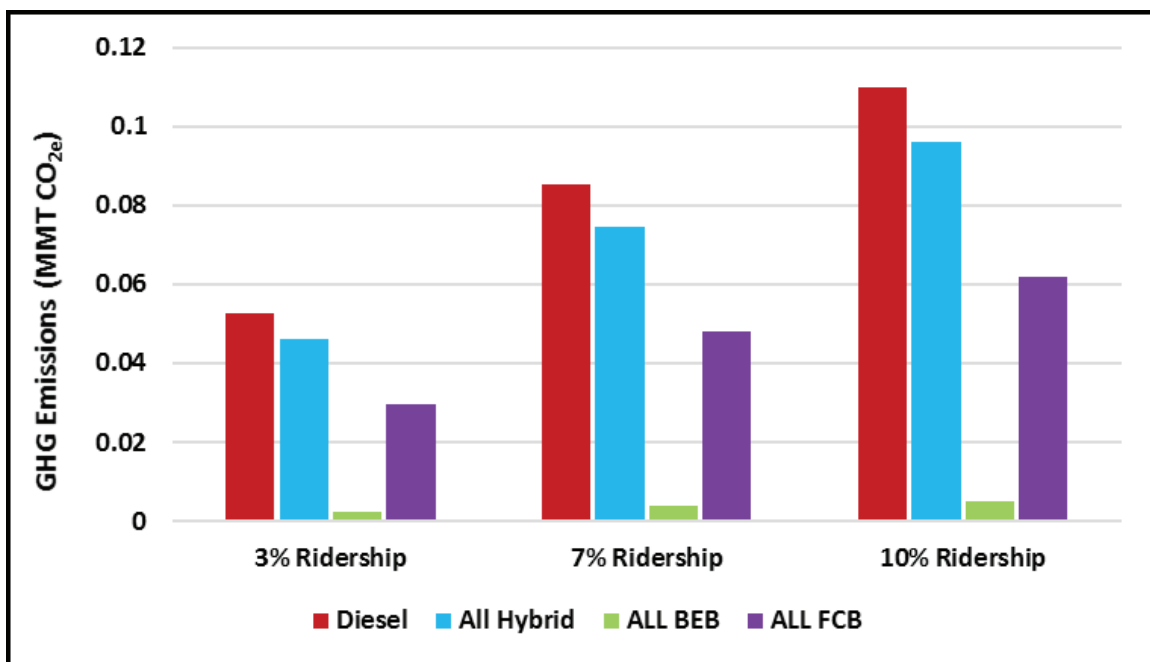


FIGURE 5.5: 2050 GHG PROJECTED PROFILE BY TRANSIT RIDERSHIP AND FUEL TECHNOLOGY (WITHOUT FACILITIES)

Scenario #5

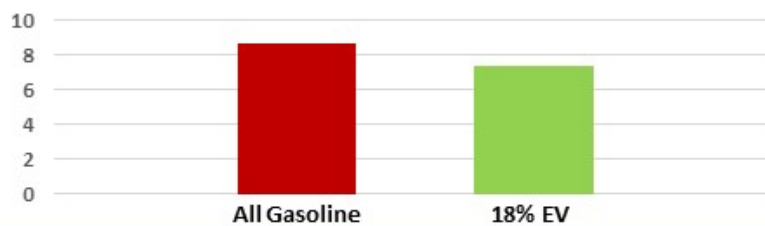
Assumptions

- 2030 Transit Ridership = 7%
- 2030 Fleet Size = 895
- LDV VMT = 19.6 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

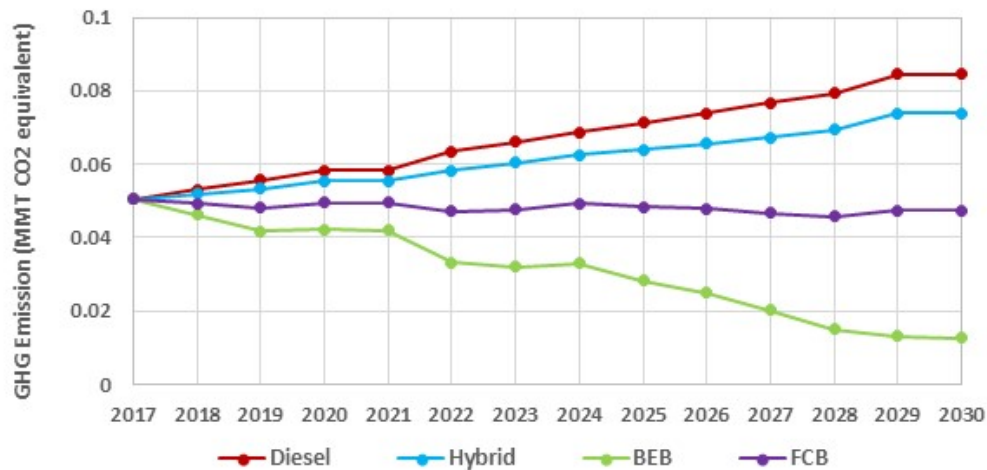
Context:

This scenario represents an increase in transit ridership by 4% and no rise in light duty vehicle VMT. Transit's share of GHG increases slightly in a shrinking footprint. This scenario is moderate from both perspectives and is the basis for sensitivity analysis.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO _{2e})	GHG Reduction (MMT CO _{2e})	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	0.89	0.00	790	N/A
BEB	0.38	0.51	937	288
FCB	0.62	0.27	1,738	3,511
Diesel Hybrid	0.81	0.08	926	1,700

5.3.1 *Baseline Scenarios: Discussion of Results*

Based on the assumptions regarding VMT and light-duty vehicle electrification by 2030, the contribution of the light-duty vehicle fleet will be approximately 8 million metric tons of carbon dioxide equivalent (MMT CO_{2e}), with the CT*transit* system contributing a slightly larger share than currently, though still a very small proportion overall. By 2050, if the state's goal of 92% of the light-duty vehicle fleet being electrified is realized, the total transportation system's GHG footprint reduces substantially to 2.4 MMT CO_{2e} .

The GHG profile of the four fuel technologies account for the fact that the CT*transit* fleet will need to increase to approximately 900 vehicles to accommodate the increase to 7% transit ridership by 2030. Scenario #5 results show

- Hydrogen fuel cell buses (FCB) will help maintain existing GHG contribution levels, even with the increase in fleet size.
- Hybrid diesel-electric and diesel buses will cause the GHG contribution from CT*transit* to increase 46% and 68%, respectively by 2030.
- Battery electric buses are the only fuel technology in this scenario that result in a GHG reduction by 2030; resulting in a 75% reduction relative to 2017 GHG levels.

Also, Scenarios #1-3 show that FCBs and hybrid diesel-electric buses also reduce GHGs, but not to the degree of battery electric buses. For Scenarios #4 and 6-9, the GHG reduction from hydrogen fuel cell and hybrid diesel-electric buses is either negligible, or GHGs increase.

The Fuel Technology GHG Profile table presents baseline analysis numerical results for the nine scenarios. GHG reduction is calculated as the reduction relative to a diesel fleet. The life-cycle cost for each metric ton of GHG emissions is in the last column, with the value reported in dollars per metric ton. The following observations apply to each of the nine scenarios:

- An entirely diesel fleet has the lowest total life-cycle cost, but leads to a substantial increase in GHG.
- Battery electric buses have the second-lowest total life-cycle cost of the alternative fuel technology buses and largest GHG reduction.
- Battery electric buses have the lowest life-cycle cost per metric ton for GHG reduction.
- Hydrogen fuel cell buses have the highest total life-cycle cost and the highest life-cycle cost per metric ton for GHG reduction, and second-highest GHG reduction.

Connecticut is committed to a significant GHG reduction by 2030. Since diesel buses will result in increased GHG emissions, they are not a desirable solution. In terms of potential GHG reduction and the life-cycle cost of achieving that reduction, results from the analysis indicate that battery electric buses have a significant advantage over the other fuel technologies. Further, an analysis of the social benefits associated with GHG and other pollutant reduction was conducted as a secondary metric. The result of this analysis is presented in Table 5.3.

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TABLE 5.3: ESTIMATE OF HEALTH BENEFITS ASSOCIATED WITH GREENHOUSE GAS REDUCTIONS
THROUGH 2030

Transit Ridership	Fuel Type	GHG emission (MT CO _{2e})	Cost of Carbon* (\$ thousands)	SCC Benefit** (\$ thousands)
3%	Diesel	669,000	\$29,748	\$ -
	Hybrid Diesel-Electric	616,000	\$27,272	\$ 2,476
	Battery Electric	350,000	\$14,987	\$14,761
	Hydrogen Fuel Cell	499,000	\$21,883	\$ 7,865
7%	Diesel	894,000	\$47,929	\$ -
	Hybrid Diesel-Electric	812,000	\$43,154	\$ 4,774
	Battery Electric	385,000	\$17,740	\$30,188
	Hydrogen Fuel Cell	624,000	\$32,010	\$15,919
10%	Diesel	1,062,000	\$40,150	\$ -
	Hybrid Diesel-Electric	958,000	\$36,361	\$ 3,789
	Battery Electric	410,000	\$16,582	\$23,568
	Hydrogen Fuel Cell	717,000	\$27,687	\$12,462
*Cost of carbon is calculated by using the social cost of carbon (\$/MT CO _{2e}) for each year through 2030				
**Social cost of carbon (SCC) benefit is calculated by subtracting cost of carbon for each fuel type from diesel				

The estimated health benefits related to the social cost of carbon is the reduction from other pollutants associated with emissions, including nitrogen oxides (NO_x), sulfur dioxides (SO₂), particulate matter (PM) and volatile organic compounds (VOC). These pollutants contribute to health hazards such as heart disease, bronchitis and asthma. The health benefits were calculated for the year 2030 – and are not cumulative over that period. However, as Table 5.4 shows, the potential statewide benefits of a zero-emission fleet range from roughly \$2 million – \$9 million. These results were estimated using the COBRA methodology.

TABLE 5.4: POTENTIAL HEALTH BENEFITS OF ZERO-EMISSION BUS FLEET IN THE YEAR 2030

Transit Ridership	Health Benefits - Low Estimate (\$ thousands)	Health Benefits - High Estimate (\$ thousands)
3%	\$1,866	\$4,219
7%	\$3,017	\$6,819
10%	\$3,876	\$8,760

These results are all a function of the assumptions described in this chapter and Chapter 4. The sensitivity analyses that follow tests these assumptions to identify situations in which the observations noted may be invalid.

5.3.2 Sensitivity Analysis

A sensitivity analysis was conducted for Scenario #5. Baseline assumptions were relaxed (modified) using various combinations of input parameters to determine if the results as shown for Scenario #5 are invalid. That is, this analysis seeks to find combinations of interest rates, price declines, light-duty vehicle electrification, and other assumptions in which the observations for life-cycle cost and GHG impacts of the fuel technologies change relative to each other.

5.3.2.1 LIGHT-DUTY VEHICLE ELECTRIFICATION

Table 5.5 depicts the impact on the transportation sector’s GHG footprint from modifying baseline light-duty vehicle electrification assumptions as follows:

- Baseline assumptions: 18% light-duty vehicle electrification by 2030 and 92% light-duty vehicle electrification by 2050.
- Modified assumptions: 9% and 46% light-duty vehicle electrification by 2030 and 2050, respectively; 50% of the light-duty vehicle electrification used for the baseline assumption

TABLE 5.5: SENSITIVITY ANALYSIS RESULTS FOR TOTAL LIGHT-DUTY VEHICLE GHG EMISSIONS BY METRIC TONS OF CARBON DIOXIDE EQUIVALENT (MTCO_{2e}) THROUGH 2030 FOR MODIFIED LIGHT- DUTY VEHICLE ELECTRIFICATION ASSUMPTION

2030		
Assumptions		GHG Emissions MTCO _{2e}
Transit Ridership	Baseline and Modified	
3%	<i>Baseline: 18% & 92%</i>	8,348,188
	Modified: 9% & 46%	9,132,459
7%	<i>Baseline: 18% & 92%</i>	7,623,916
	Modified: 9% & 46%	8,340,145
10%	<i>Baseline: 18% & 92%</i>	7,395,199
	Modified: 9% & 46%	8,089,941
2050		
Assumptions		GHG Emissions MTCO _{2e}
Transit Ridership	Baseline and Modified	
3%	<i>Baseline: 18% & 92%</i>	3,009,499
	Modified: 9% & 46%	7,177,304
7%	<i>Baseline: 18% & 92%</i>	2,407,599
	Modified: 9% & 46%	5,741,843
10%	<i>Baseline: 18% & 92%</i>	2,335,371
	Modified: 9% & 46%	5,569,588

The results are as expected, with the overall GHG footprint from light-duty vehicles in Connecticut being greater than in the baseline assumptions, substantially so in 2050. This does not alter the results, but simply changes the context in which the GHG emissions impact from fuel technologies must be interpreted. Regardless of fuel technology, the GHG emission reductions would be a smaller percentage of the overall GHG footprint if light-duty vehicle electrification were half of the baseline assumptions.

5.3.2.2 RENEWABLE ELECTRICITY PORTFOLIO

Another assumption drawn from DEEP and the Governor’s Council on Climate Change is the percentage of the state’s electricity portfolio that will be Class I renewable in 2030 and 2050.

Table 5.6 depicts the impact on public transit’s GHG footprint from rolling stock only (facilities are not included) by modifying baseline assumptions for the state’s renewable electricity portfolio as follows:

- Baseline assumptions: 30% Class I renewables by 2030
- Modified assumptions: 20% Class I renewables by 2030; which is the minimum allowable by state statute for 2020

TABLE 5.6: SENSITIVITY ANALYSIS RESULTS FOR TOTAL GHG EMISSION BY METRIC TONS OF CARBON DIOXIDE EQUIVALENT (MTCO_{2e}) REDUCTIONS THROUGH 2030 (WITHOUT FACILITIES)

Assumptions		All Diesel MTCO _{2e}	All Hybrid MTCO _{2e}	All BEB MTCO _{2e}	All FCB MTCO _{2e}
Transit Ridership	Baseline and Modified				
3%	<i>Baseline: 30%</i>	669,466	615,722	350,456	499,234
	Modified: 20%	669,466	615,722	359,630	499,234
7%	<i>Baseline: 30%</i>	893,844	811,727	384,778	624,307
	Modified: 20%	893,844	811,727	403,703	630,948
10%	<i>Baseline: 30%</i>	1,061,632	958,218	409,624	717,398
	Modified: 20%	1,061,632	958,218	435,054	723,833

As expected, this modified assumption significantly impacts the GHG emissions reduction potential of battery electric buses. However, for all ridership scenarios, battery electric buses still outperform other fuel technologies. From a practical perspective, this means that the life-cycle cost per metric ton of CO_{2e} reduction would increase for battery electric buses, but would still be less than other fuel technologies.

5.3.2.3 ECONOMIC ASSUMPTIONS

Table 5.7 shows the impact on the LCCA from modifying two important baseline economic assumptions, as follows:

- Baseline assumptions:
 1. Inflation and discount rates are equivalent at 3%.
 2. Battery electric buses decline in price; approximately 15% by 2030. (This assumption is based on the decline in the price of electric light-duty vehicles since their introduction approximately a decade ago.)

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- Modified assumptions:
 - Inflation and discount rates are not equivalent, with one analysis assuming a discount rate of 2% and inflation rate of 4% and vice versa for the second analysis.
 - Battery electric and hydrogen fuel cell buses prices are equivalent, with a 0% or 15% cost reduction.

TABLE 5.7: SENSITIVITY ANALYSIS RESULTS FOR LCCA THROUGH 2030
 WITH MODIFIED ECONOMIC ASSUMPTIONS

Assumptions		All Diesel (\$ millions)	All Hybrid (\$ millions)	All BEB (\$ millions)	All FCB (\$ millions)
Transit Ridership	Baseline and Modified				
3%	<i>Baseline</i>	\$539	\$622	\$627	\$1,123
	BEB/FCB cost reduction: 0%	\$539	\$622	\$654	\$1,123
	BEB/FCB cost reduction: 15%	\$539	\$622	\$627	\$1,069
	Inflation 2%; Discount 4%	\$472	\$546	\$555	\$984
	Inflation 4%; Discount 2%	\$619	\$712	\$714	\$1,289
7%	<i>Baseline</i>	\$790	\$926	\$937	\$1,738
	BEB/FCB cost reduction: 0%	\$790	\$926	\$980	\$1,738
	BEB/FCB cost reduction: 15%	\$790	\$926	\$937	\$1,650
	Inflation 2%; Discount 4%	\$689	\$810	\$827	\$1,520
	Inflation 4%; Discount 2%	\$911	\$1,065	\$1,071	\$1,999
10%	<i>Baseline</i>	\$977	\$1,154	\$1,167	\$2,199
	BEB/FCB cost reduction: 0%	\$977	\$1,154	\$1,224	\$2,199
	BEB/FCB cost reduction: 15%	\$977	\$1,154	\$1,167	\$2,084
	Inflation 2%; Discount 4%	\$850	\$1,007	\$1,029	\$1,920
	Inflation 4%; Discount 2%	\$1,129	\$1,329	\$1,337	\$2,531

Results from the modified assumptions for inflation and discount rates, and battery electric and hydrogen fuel cell bus equivalent cost reductions indicate that diesel buses have the lowest life-cycle cost, but are not a viable alternative, as diesel buses are not consistent with the state’s commitment to GHG reduction. For the alternative fuel technology buses, hybrid diesel-electric buses have the lowest life-cycle cost, followed by battery electric buses, with hydrogen fuel cell buses having the highest life-cycle cost.

5.3.2.4 BUS FLEET FUEL TECHNOLOGY MIX

Tables 5.8 and 5.9 show the impact on public transit’s GHG emissions and life-cycle cost respectively from modifying the assumption for the bus fleet fuel technology mix for the purpose of fleet resiliency, as there may be emergency situations that require vehicles with varying fuel technologies, as follows:

- Baseline assumption: 100% of the bus fleet is the same type of fuel technology by 2030, with no additional purchases of diesel or hybrid diesel-electric buses.
- Modified assumption: 25% of the bus fleet is diesel or hybrid-diesel electric buses and 75% of the bus fleet is battery electric or hydrogen fuel cell buses by 2030.

The 25% - 75% modified assumption was used as an example; the actual percentage of the bus fleet that should be diesel-based is beyond the scope of this project.

TABLE 5.8: SENSITIVITY ANALYSIS RESULTS FOR TOTAL GHG EMISSIONS BY METRIC TONS OF CARBON DIOXIDE EQUIVALENT (MTCO_{2e}) THROUGH 2030 (WITHOUT FACILITIES) FOR ALTERNATE FLEET MIX

Assumptions		Diesel MTCO _{2e}	Hybrid MTCO _{2e}	BEB MTCO _{2e}	FCB MTCO _{2e}
Transit Ridership	Baseline and Modified				
3%	<i>Baseline</i>	670,000	616,000	350,000	499,000
	Fleet mix 25%—75%		628,000	425,000	537,000
7%	<i>Baseline</i>	894,000	812,000	385,000	624,000
	Fleet mix 25%—75%		830,000	507,000	687,000
10%	<i>Baseline</i>	1,062,000	958,000	410,000	717,000
	Fleet mix 25%—75%		982,000	567,000	798,000

As expected, the total GHG reduction through 2030 decreases when 25% of the fleet is diesel. While not shown in Table 5.8, if 25% of the fleet is hybrid diesel-electric buses rather than diesel buses, then the GHG reduction would increase slightly, but not substantially.

Table 5.9 shows that maintaining a battery electric bus/diesel mixed fleet will remain the second lowest life-cycle cost for alternative fuel technology buses, with a decreased life-cycle cost of approximately 4% due largely to the lower capital cost associated with diesel buses. The hydrogen fuel cell bus/diesel mixed fleet also results in a life-cycle cost reduction due to the lower capital cost of diesel buses.

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TABLE 5.9: SENSITIVITY ANALYSIS RESULTS FOR LIFE-CYCLE COST (\$ MILLIONS) FOR ALTERNATE FLEET MIX

Assumptions		Diesel (\$ millions)	Hybrid (\$ millions)	BEB (\$ millions)	FCB (\$ millions)
Transit Ridership	Baseline and Modified				
3%	<i>Baseline</i>	\$539	\$622	\$627	\$1,123
	Fleet mix 25%—75%	\$539	\$601	\$605	\$977
7%	<i>Baseline</i>	\$790	\$926	\$937	\$1,738
	Fleet mix 25%—75%	\$790	\$892	\$900	\$1,501
10%	<i>Baseline</i>	\$977	\$1,154	\$1,167	\$2,199
	Fleet mix 25%—75%	\$977	\$1,110	\$1,120	\$1,893

5.4 SUMMARY

There is uncertainty associated with future predictions, especially when predictions involve economic factors. The analysis presented in this chapter used assumptions based on established literature and similar analyses conducted in Connecticut for other GHG contributors by sector. The sensitivity analysis was conducted to verify the validity of the baseline scenario results by relaxing (modifying) some of the baseline assumptions and then evaluating the baseline and modified results. The baseline results were determined to be valid and provided the confidence to conclude the following:

- Battery electric buses are the best fleet option to reduce public transit’s GHG emissions and contribute to Connecticut’s GHG emission reduction targets.
- Diesel buses have the lowest life-cycle cost, but are not a viable alternative, as diesel buses are not consistent with the state’s commitment to GHG reduction. For the alternative fuel technology buses, hybrid diesel-electric buses have the lowest life-cycle cost, followed by battery electric buses, with hydrogen fuel cell buses having the highest life-cycle cost.

6.0 RECOMMENDATIONS

The eight transit divisions under the *CTtransit* brand operate a fleet of 549 buses on behalf of CTDOT (CTDOT-contracted bus operations). CTDOT owns the rolling stock and facilities in three of the *CTtransit* divisions (Hartford, New Haven, and Stamford), and only the rolling stock in the remaining divisions (Bristol, Meriden, New Britain, Wallingford, and Waterbury). For the *CTtransit* bus fleet and the three operating and maintenance facilities CTDOT owns, the annual greenhouse gas (GHG) emissions are estimated to be 0.07 MMTCO_{2e}, a small fraction of the roughly 15 MMTCO_{2e} (million metric tons carbon dioxide equivalent) emitted by the transportation sector in Connecticut or the 8 MMTCO_{2e} from light-duty vehicles statewide.

Of the *CTtransit* emissions, 0.05 MMTCO_{2e} is from bus fleet (mobile) emissions, with the remainder split between purchased gases at facilities at 0.015 MMTCO_{2e}, and 0.0025 MMTCO_{2e} each for both electricity consumption and refrigeration. This study concludes that the most important strategies that *CTtransit* can deploy to control GHG emission reduction in Connecticut are associated with the rolling stock, though other strategies were considered. The recommendations are consolidated into four categories: rolling stock, facilities, resilience, and monitoring.

Additionally, the source(s) of electricity as fuel for the battery electric buses must be considered as well, in order to attain maximum GHG emission reduction and to justify the initial capital investments for a battery electric bus fleet. The maximum GHG emission reduction will be achieved only if the state meets its Class I renewable energy source goals for generating electricity.

6.1 RECOMMENDATION #1: ROLLING STOCK

Reducing GHG emissions from the *CTtransit* rolling stock was found to be the most impactful strategy. Nine baseline scenarios, the year 2050 GHG profile, and sensitivity analyses were conducted and confirm that battery electric buses are the best fleet option to reduce public transit's GHG emissions and contribute to Connecticut's GHG emission reduction targets. The scenarios presented and analyses conducted were based on assumptions presented in Chapter 5. Battery electric buses were shown to have the second lowest life-cycle cost of the alternative fuel technologies, with hybrid diesel-electric buses comparatively having a slightly lower life-cycle cost of between 0.2% - 6%. This result holds true under all assumptions in the baseline and sensitivity analyses.

Supporting this recommendation further, the local pollutant reduction from eliminating diesel buses from the *CTtransit* fleet has a combined health benefit estimated at \$2 million - \$9 million in the year 2030, not including intermediate years. These benefits are in addition to the social cost of carbon benefits associated with GHG reduction.

6.2 RECOMMENDATION #2: FACILITIES

As reported, CTtransit facilities produce the least significant proportion of CTtransit GHG emissions, though there are several strategies that can help to reduce this further.

- High Performance Building Standards: CTDOT advised that public transit's operating and maintenance facilities are exempt from the state's high performance building standards as defined in CGS Chapter 298 §16a-38k(a), with additional guidance from the Connecticut Department of Administrative Services: Capital Projects High Performance Buildings Guidelines, as follows:

... to adopt state building construction standards that are consistent with or exceed the silver building rating of the Leadership in Energy and Environmental Design's rating system for new commercial construction and major renovation projects, as established by the United States Green Building Council, including energy standards that exceed those set forth in the 2004 edition of the American Society of Heating, Ventilating and Air Conditioning Engineers (ASHRAE) Standard 90.1 by not less than twenty per cent, or an equivalent standard, including, but not limited to, a two-globe rating in the Green Globes USA design program, and thereafter update such regulations as the Commissioner of Energy and Environmental Protection deems necessary.

CTDOT further advised that energy efficient options would be used whenever possible in the construction of public transit facilities.

Therefore, it is suggested that the state's high performance buildings guidelines, including LEED or Green Globes USA design program specifications, be used as a best practice whenever possible for the construction of public transit facilities, including the new CTtransit Hartford Division Facility. Additionally, internationally recognized standards for achieving near-zero energy consumption and measurable carbon reduction in facilities, such as Passive House, should be considered to further reduce GHG emissions.

- Virtual Net Metering: CTDOT should research the potential and possibility of deploying behind-the-meter installations of renewable energy and the advantages of virtual net metering, and if benefits are determined, include these as part of facilities planning, maintenance and the rehabilitation of existing facilities. According to DEEP, virtual net metering allows state and municipal customers with United Illuminating and/or Eversource who "...operate behind-the-meter generation (Customer Host) to assign surplus production from their generator to other metered accounts (Beneficial Accounts) that are not physically connected to the Customer Host's generator." (DEEP website) Energize Connecticut, an initiative to help homeowners and businesses optimize energy efficiency and clean energy improvements, provides additional guidance for state customers to encourage the installation of Class I and Class III distributed generation (Energize CT website).
- Other Options: CTDOT should explore other ways to reduce the GHG emissions, including the recommendations in a 2014 CASE study conducted for CTDOT, *Energy Efficiency and Reliability Solutions for Rail Operations and Facilities* (CASE website), as applicable to bus operating and maintenance facilities. These recommendations included conducting an energy audit, transitioning to LED lighting, utilizing radiant floor heating (potentially reducing methane usage, which is purchased by CTtransit primarily for heating), and use of solar PV systems in conjunction with virtual net metering.

6.3 RECOMMENDATION #3: RESILIENCE

System resilience is a potential negative consequence from converting to an entirely battery electric bus fleet. If there is an extended power outage, *CTtransit* might not be able to maintain basic operations or assist in an emergency response for areas that lack electricity. While specific recommendations to address this challenge are beyond the scope of this study, CTDOT should review the 2017 TCRP report, *Improving the Resilience of Transit Systems Threatened by Natural Disasters Volumes 1,2, and 3: A Guide*. Additionally, the following are important considerations that must be included as part of the GHG reduction strategy:

- **Emergency Scenarios:** What emergency scenarios and duty cycle should the *CTtransit* fleet be able to withstand and/or assist with? This decision will frame the minimum amount of operations and rolling stock diversity that need to be maintained for an emergency during which no electrical recharge is available.
- **Leveraging Existing Resources:** What existing energy resources can CTDOT leverage in an emergency, and for what duration and capacity (# of diesel or hybrid diesel-electric buses)? Such resources may include the state's reserve diesel fuel that currently provides several days' worth of operations. This fuel could be used to power a mixed fleet of diesel/hybrid diesel-electric buses or generators in an emergency to charge the battery electric bus fleet. Emergency operations could also incorporate use of existing facility power plants such as combined cycle fuel cell or micro turbines.
- **Other Benefits:** Consider the potential benefits of battery electric buses and hybrid diesel-electric buses, such as use of the buses to power emergency shelters, medical facilities or other critical response infrastructure during power outages.

6.4 RECOMMENDATION #4: MONITORING

Given the uncertain nature of predictions through 2030 and 2050, it is almost certain that the assumptions underlying this analysis will need to be modified to provide an accurate portrayal of future conditions. To mitigate this situation, CTDOT should adopt a strategy of revisiting this study's analysis on a periodic basis to update the assumptions and/or perform additional sensitivity analyses.

The following supports this recommendation:

- Conservative assumptions for electricity production (percent of Class I renewables), light-duty vehicle fleet electrification, and battery electric bus price reductions were used whenever possible. If actual numbers are more favorable than the conservative assumptions used for this study's analysis and/or the price of battery electric buses decline more significantly than assumed in the analysis, the results would further support the recommendation to convert to a battery electric bus fleet.
- The baseline scenario analysis assumed a bus fleet turnover cycle that follows the practice used by CTDOT over the past 12 years. CTDOT should evaluate whether an optimized fleet replacement schedule could reduce life-cycle costs and result in even greater GHG reductions.
- To facilitate CTDOT's periodic review and update of strategies to reduce GHG emissions, the methodology used for this study's analysis is available as a tool for the

department's use. The Greenhouse Gas Inventory and Life-cycle Cost Tool will be accessible by March 1, 2018, to CTDOT staff via the University of Connecticut's t-HUB: The Public Transportation Data Hub of Connecticut.

The Greenhouse Gas Inventory and Life-cycle Tool should be used to update assumptions and/or perform additional sensitivity analyses. However, the tool was not designed to optimize a bus fleet turnover strategy. Alternative turnover strategies could be evaluated and updated from a set of feasible alternatives, such as a delayed transition to battery electric buses, a mixed fuel technology fleet, or a more uniform turnover of vehicles than the existing fleet turnover cycle.

The Greenhouse Gas Inventory and Life-cycle Tool can also be utilized to input data based on future operating practices and policy developments. CTDOT should use the tool to inform transit-supportive legislation and policies, such as transit-oriented development and complete streets. The input data for this analysis can then be updated based on actual ridership, interest rates, discount rates to provide an improved estimate of GHG emission reductions, and expected life-cycle cost.

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TOPICS INCLUDED:

1. Building Energy Conservation
2. Bus Fleet Studies
3. Climate Change
4. Economic Analysis
5. Electric Bus Technologies
6. Emissions Models
7. Greenhouse Gas Emissions
8. Hydrogen Fuel Cell Bus Technology
9. Miscellaneous
10. Other Bus Studies Topics
11. Performance Metrics
12. Sustainability

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APPENDIX B

MODELS FOR ESTIMATING TRANSPORTATION EMISSIONS

Model Acronym	Model Name	Developer	Description
APTA GHG Calculator	Net Carbon Footprint Calculator for Transit	APTA	A GHG calculator (APTA 2017) in the form of an Excel spreadsheet which uses the methodology described in reference (APTA[a], 2009).
COMMUTER	Analysis of Voluntary Mobile Source Emission Reduction and Commuter Choice Incentive Programs	EPA	An EPA assessment tool that provides estimates on how commuter benefits can impact nitrogen oxide, particulate matter and air toxic emissions, and fuel use and costs.
EMFAC2014	EMission FACTors Model	California Air Resources Board	Mobile source emissions model; to assess emissions from on-road vehicles including cars, trucks, and buses in California.
GHGenius	Calculation Model for GHGs generated from the time a fuel is extracted or grown to the time that it is converted in a motive energy vehicle to produce power	Natural Resources – Government of Canada	To consider the environmental impacts of introducing alternative transportation fuels and the vehicles that use them into the marketplace (GHGenius, 2004). Specifically, the upstream fuel-cycle emissions estimates from GHGenius are composed of emissions associated fuel production, dispensing, storage and distribution, fuel feedstock transport, and CO ₂ and CH ₄ and leaks and flares (ICF International[a], 2011, p. 105).
GreenDOT	Greenhouse Gas Calculator for State Departments of Transportation	NCHRP	A spreadsheet-based calculator tool, available through NCHRP. It calculates CO ₂ emissions from the operations, construction, and maintenance activities of state DOTs. GreenDOT is designed to calculate emissions for geographical areas ranging from a single project to an entire state, and over time periods ranging from one day to several years. The two most likely uses of the tool are: (1) calculate agency-wide emissions, and (2) calculate emissions related to a specific project, covering a period of days or years.” (ICF International[a], 2011, 58)
GREET FLEET	Fleet footprint calculator (GHG Regulated Emissions and Energy use in Transportation)	USDOE, Argonne National Laboratory	GREET Fleet is a simple spreadsheet calculator that can be used to estimate the lifecycle (well to wheels) GHG emissions of on-road and off-road fleets. For on-road vehicles, the user can estimate emissions either inputting data on fuel use or inputting data on fleet size, VMT, and fuel economy by vehicle type (ICF International[a], 2011, 60).
Mobile6	Motor Vehicle Emission estimates	EPA	MOBILE6 has been replaced by MOVES as EPA’s official model for estimating emissions from cars, trucks and motorcycles.

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MOVES2014a	Motor Vehicle Emissions Simulator	EPA	An emissions model developed by EPA that can be used for multiple purposes, including emissions inventories of different geographic scales, as well as the modeling of a specific roadway segment. The primary application of MOVES is calculation of specific emission factors (including GHG emissions) by mile for different vehicle and fuel combinations. MOVES can calculate emission factors based on the characteristics of a specific vehicle and the project facility, including congestion patterns, grade, and pavement quality. MOVES can be used to directly calculate total emissions from state DOT vehicles (ICF International[a], 2011, p. 59; US EPA[f] website).
NMIM	National Mobile Inventory Model	EPA	A consolidated emissions modeling system for EPA's MOBILE6 and NONROAD models. It generates county inventories using MOBILE6 and NONROAD at scales ranging from individual counties to the nation.
SGEC	Simplified GHG Emissions Calculator	EPA	A simplified calculation tool to help small business and low emitter organizations estimate and inventory their annual greenhouse gas (GHG) emissions. The calculator will determine the direct and indirect emissions from all sources at a based on activity data.
SIT	State Inventory Tool	EPA	An interactive spreadsheet model designed to help states develop GHG emissions inventories. Provides a streamlined way to update an existing inventory or complete a new inventory.
TAFV	Transitional Alternative Fuels and Vehicles Model	USDOE, Oak Ridge National Laboratory	A model for predicting choice of alternative fuel and among alternative vehicle technologies for light-duty motor vehicles (Green, 2001).
VISION	Model Used to Estimate the Impact of Highway Vehicle Technologies and Fuels on Energy Use and Carbon Emissions to 2050	USDOE, Argonne National Laboratory	Provides estimates of the potential energy use, oil use and carbon emission impacts of advanced light- and heavy-duty vehicle technologies and alternative fuels through the year 2050 (updated 2016) (The Vision Model).

APPENDIX C

EXAMPLES OF TRANSIT SYSTEM SUSTAINABILITY PLANS

Combining definitions of sustainability from the European Union and The Centre for Sustainable Transportation in Canada, a sustainable transportation system, “...allows the basic access needs of individuals to be met safely in a manner consistent with human and ecosystem health, and with equity within and between generations. ... is affordable, efficient, offers choice transport mode, and supports a vibrant economy. ...limits emissions, pollution, and wastes; minimizes consumption of resources and land.” (Atkinson-Palombo, 2016). As noted in Chapter 2, sustainability is a method of harvesting or using a resource so that the resource is not depleted or permanently damaged (see Chapter 2 for a more detailed discussion on sustainability).

Examples of transit agency plans that address sustainability are provided below.

- 1. Alameda-Contra Costa Transit District (AC Transit)**
Headquartered in Oakland, California, AC Transit serves primarily Alameda and Contra Costa Counties. AC Transit has proven to be a leader in working to reduce the carbon intensity of their operations. They are developing internal CO₂ emission reduction targets and have adopted a goal of 15% reduction by 2020 from 2006 for entity-wide Scope 1 and 2 emissions as measured by the following performance metrics: emissions per total vehicles miles, per vehicle revenue hours and per passenger mile traveled (Cameron-Cole and ESA, 4). One way identified to assist in reaching their goal is to purchase an additional 12 hydrogen fuel cell buses that are lighter weight, have better lithium ion batteries, and many other features. The plan also calls for the replacement of 70 conventional diesel buses with alternative fuel buses between FY2013 and FY2019. AC Transit also plans to add photovoltaic solar panels, facility lighting retrofits, energy efficient HVAC systems, high-speed rollup doors, timers for lighting and thermostats. The AC Transit Climate Action plan also addresses ways to increase ridership, reduction in the use of non-revenue AC Transit owned vehicles, perform energy audits, increase recycling and waste reduction. “If AC Transit is unable to achieve its 2020 emission reduction targets through operational changes, they will consider purchasing high quality carbon offsets to account for the shortfall.” (Cameron-Cole and ESA, pp. 12-21)
- 2. Central Puget Sound Regional Transit Authority (Sound Transit)**
Sound Transit plans, builds and operates express bus, light rail and commuter train services in the urban areas of King, Pierce and Snohomish counties in Washington State (Bergener et al. 2011). Sound Transit defines sustainability as “...making the planet a better place by creating and maintaining a healthy environment, community, and economy. Sustainability is defined or categorized in three ways: people, planet, and prosperity.” As noted by APTA, Sound Transit’s sustainability efforts are categorized in three ways: People, Planet, and Prosperity. The focus of their sustainability efforts is to, “Seek to promote pedestrian, bicycle, and rideshare access to transit systems is improved, deploy the most fuel efficient vehicles, 100 percent of waste diverted from landfills, and ensure operational efficiency and financial savings are maximized by fully evaluating economic environmental and social cost.” (Bergener et al. 2011, p. 12) Sound Transit incorporates performance goals, targets and measures in their sustainability plan.

3. New York Metropolitan Transit Authority (MTA)

New York City's, "MTA accounts for 65 percent of all New York City commutes while using just 5 percent of New York City's total energy consumption. Likewise, the fact that New Yorkers consume one quarter as much energy per capita as the average American is largely attributable to the MTA system." (NY MTA, p. 17) *Greening Mass Transit & Metro Regions: The Final Report of the Blue Ribbon Commission on Sustainability and the MTA* is likely the most comprehensive study on sustainability of a major transit system in the United States. The report contains nearly 100 recommendations, some of which require legislative and/or policy action by decision-makers at the federal, state, and local levels (NY MTA). The MTA strives to deliver projects that adhere to a mission of "achieving sustainability" through environmental benefit, better service for riders, and cost savings Bergener et al. p. 29).

4. Seattle Department of Transportation (TriMet)

Seattle DOT in Seattle, Washington, has identified transit's role in meeting Seattle's GHG reduction goals. Using APTA's recommended practice for quantifying GHG emissions, TriMet conducted a detailed assessment of its carbon footprint. Data in the 2007 National Transit Database indicates that TriMet's total operational footprint was 76,000 metric tons of CO₂. The detailed APTA footprint analysis will allow TriMet to determine both its debits—the amount of GHG emitted by source—as well as its credits—the amount of GHG not emitted due to TriMet's ability to shift mode choice and foster compact development. "The footprint analysis will allow TriMet to identify its biggest sources of emissions and create targets for reductions." (Ou et al. 2010)

APTA noted the following transit agencies in its publication, *Leading Sustainability Initiatives Through your Organization*:

5. San Francisco Municipal Transit Authority (SFMTA)

SFMTA plans for the incorporation of sustainability into nearly all initiatives, and San Francisco funds these activities through mechanisms such as congestion pricing and parking that encourage the adoption of public transit. A major focus is also on a livable streets initiative (Bergener et al. 2011, p. 15).

6. Knoxville Area Transit (KAT)

The focus of KAT's sustainability plan is, "Leveraging work with their local municipal partners to improve projects that were already underway, for example renovations and construction using LEED principals." (Bergener et al. 2011, p. 22)

7. Metropolitan Atlanta Rapid Transit Authority (MARTA)

An FTA report titled, *Transit Greenhouse Gas Emissions Management Compendium*, contains a good example of a step-by-step analysis of Atlanta, Georgia's, MARTA GHG footprint in 2008 (Southworth et al. 2011). The inventory calculations were performed using the format of the 2009 APTA, *Recommended Practice for Quantifying Greenhouse Gas Emissions from Transit* (APTA[a], 2009). The MARTA GHG inventory is presented for other transit agencies to consider as an example to show base year GHG data for use in future projections of GHG reduction calculations.

8. Southeastern Pennsylvania Transportation Authority (SEPTA)

SEPTA defined a sustainability plan that was integrated with the agency's overall strategic vision. They created a new "Sustainable Return on Investment" that allows for broader definition of cost/benefit analysis. "Everything we do in sustainability has a positive cost effect." (Bergener et al. 2011, p. 24)

9. Santa Clara Valley Transportation Authority (VTA)

Based in San Jose, California, VTA's goals are to, *"Improve system ridership, productivity and efficiency, improve farebox recovery, improve transit's role as a viable alternative mode, and use transit investments and resources more effectively."* (Bergener et al. p. 35)

APPENDIX D PERFORMANCE METRICS: EXAMPLES

As noted in Chapter 2, performance metrics are strongly encouraged at the federal level to provide a measurement of accountability and transparency for transit agencies. This appendix has examples of performance measures from a variety of sources including:

- A. American Public Transportation Association (APTA)
- B. Public Transportation and Municipal/Regional Public Bus Transit Agencies
 - 1. AC Transit
 - 2. Massachusetts Department of Transportation
 - 3. Sound Transit
- C. Victoria Transport Policy Institute

A. AMERICAN PUBLIC TRANSPORTATION ASSOCIATION

In an APTA report titled, *Quantifying and Reporting Transit Sustainability Metrics*, the following nine performance metrics are identified for transit agencies to consider:

- Water usage and pollutant discharge
- Criteria air pollutant emissions
- GHG emissions
- GHG savings
- Energy use
- Recycling levels/waste
- Operating expense
- Unlinked passenger trips
- Vehicle miles traveled (APTA[c], 2012, p. 1)

The following are APTA's Guidelines for Climate Action Planning (APTA[b], 2011), including evaluation categories, indicators, and sample targets:

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Evaluation Category	Indicators	Sample Targets
Operations	<ul style="list-style-type: none"> • Increase in ridership • Reduction in auto/non-transit VMTs • Reduced need for off-street parking • Conversion of on-street parking to transit, bicycle and pedestrian uses • Shorter commute times 	<ul style="list-style-type: none"> • mode share of 30% • 10% reduction per capita by 2035 • % parking spaces occupied • % on-street parking spaces reduced
Vehicles	<ul style="list-style-type: none"> • Reduce transit fleet vehicle emissions 	<ul style="list-style-type: none"> • zero emissions by 2020
Facilities	<ul style="list-style-type: none"> • Increase in energy efficiency and renewable energy • Provision of infrastructure to support transit and non-transit electric vehicles 	<ul style="list-style-type: none"> • respectively, 107 MW and 50 MW citywide
Solid Waste and Recycling	<ul style="list-style-type: none"> • Optimization of waste reduction 	<ul style="list-style-type: none"> • 100% diversion by 2020
Employee Travel Demand	<ul style="list-style-type: none"> • Reduction in total VMTs 	<ul style="list-style-type: none"> • at least 10% reduction by 2035
Construction and Capital Projects	<ul style="list-style-type: none"> • Diversion of construction and demolition waste from landfills 	<ul style="list-style-type: none"> • 100% diversion by 2020

B. STATE TRANSPORTATION AGENCY AND MUNICIPAL/REGIONAL PUBLIC TRANSIT AGENCIES

1. Alameda-Contra Costa Transit District (AC Transit), Oakland, CA, Performance Metrics for their Climate Action Plan (Cameron-Cole and ESA, 2011)

AC Transit GHG Perf. Metric	2006	2020	How will achieve
Metric Tons (MT) CO₂ Per Passenger Mile Traveled	0.0003	0.00026	Increase ridership; improve fuel economy; increase use of low-carbon fuels
MT CO₂ Per Vehicle Mile	0.0028	0.0024	Improve fuel economy; increase use of low-carbon fuels
MT CO₂ Per Vehicle Revenue Hour	0.0378	0.0321	Improve fuel economy; reduce dead-heading; increase use of low-carbon fuels

2. Massachusetts Department of Transportation

The Massachusetts Department of Transportation (MassDOT) developed performance measures as a result of implementing their GreenDOT plan in 2010. Massachusetts transportation performance is based upon the premise that measures must be, "...valid, significant, easily interpreted, available, and able to track trends over time." (Codd et al. p. ES1) A subset of MassDOT measures pertinent for bus transit include metric tons of GHG emissions per year from the statewide transportation sector; vehicle miles traveled by motor vehicles; person miles traveled (PMT) by public transit, bicycling, and walking; and *MassDOT facility energy and water use* (Codd et al. pp. 2-7).

3. Central Puget Sound Regional Transit Authority, (Sound Transit), Seattle, WA, “Save Energy” Targets and Performance Measures for Sustainability (Bergener et al. 2011)

Goal	Targets (Long-Term)	Performance Measures
Save Energy	<ul style="list-style-type: none"> • All fleets deploy the most fuel-efficient, clean, and cost-effective vehicles that optimize the use of proven technology • 40% of GHG emissions are reduced (per vehicle-revenue-mile) • Electricity use is carbon neutral 	<ul style="list-style-type: none"> • Energy use • GHG emissions • Percent electricity from renewable sources • Criteria air pollutant emissions

C. Victoria Transport Policy Institute

Todd Litman (Litman 2016, p. 12) from the Victoria Transport Policy Institute identifies the following performance factors related to transit service:

- Route coverage
- Frequency
- Capacity
- Average vehicle occupancy
- Transit supply
- Travel speed
- Ride travel time

Litman also identifies a variety of performance measures not directly related to the quality of transit service, but closely linked to the costs and benefits of transit service provision and investments in transit service, including:

- Bike routes, bike paths, bike parking
- Bus shelters
- Comfortable seats
- Commuter incentives (such as employer passes)
- Disability accommodation (universal design)
- Fare rates
- Hours of operation
- Improved security
- Land use patterns (such as TOD)
- Marketing
- Number of jobs in area (employment density)
- Park and ride facilities
- Population size
- Rider information tools (such as Google Transit, Transit App)
- Special mobility services
- Transit (such as high-occupancy vehicle lanes) priority
- Walk, wait, transfer ease for pedestrians and cyclists

APPENDIX E

SAMPLE BATTERY ELECTRIC BUS PROCUREMENT GUIDELINES: TECHNICAL SPECIFICATIONS

This appendix includes background and guidance for use in developing procurement documents for the purchase of battery electric buses. Additionally, this appendix includes sample Technical Specifications for the charging environment, operating environment, and respect for the environment. These specifications do not include sample guidance for developing and maintaining a battery electric bus program.

A. BACKGROUND

The American Public Transit Association's (APTA) *Standard Bus Procurement Guidelines: A Standardized Request for Proposal Contract Form for the Transit Industry* provides a Request for Proposal (RFP) template for use by transit agencies in developing a RFP. The guidelines include 11 sections, with the Technical Specifications Section – the focus of this appendix – in Section 6. The APTA guidelines are in Microsoft Word format, which allows users to modify the template to insert their standard contract language as needed. For more detail on each section, see APTA website: <http://www.apta.com/resources/reportsandpublications/Documents/APTA-Bus-Procurement-Guidelines-2011.doc>.

As of 2017, APTA was in the process of updating the guidelines to include sample language for the procurement of battery electric buses, with the expectation that a Beta version will be available in early 2018. APTA advised that a Beta version will facilitate updates to the guidelines as needed to keep current with the rapid pace of change in the battery electric bus marketplace. APTA's procurement guidelines for battery electric buses should be monitored for updates.

Sections of APTA's guidelines include:

1. Notice of Request for Proposals
2. Instructions to Proposers
3. General Conditions
4. Special Provisions
5. Federal Requirements
6. Technical Specifications
7. Warranty Requirements
8. Quality Assurance
9. Forms and Certifications
10. Contract
11. Appendixes

In addition to the APTA guidelines, the following presentations to the committee, interviews and other references provided the information included in Section B: Technical Specifications of this appendix.

- APTA: Jeff Hiott, Director of Operations and Standards, March 22, 2017. *Trending to Zero – North America’s Bus Industry Moves to Zero Emissions; Presentation date as noted, with interview February 21, 2017*
- Lane Transit District, Eugene, Oregon: Kelli Hoell, Transportation Development Planner, January 27, 2017
- Metro Transit, King County, Washington: Peter Melin, PE, Project Director, May 19, 2017. *Transitioning to a Zero Emission Fleet*

Of the RFPs reviewed, the Technical Specifications language that was most helpful was from APTA, Long Beach Public Transportation Company (Battery Electric Bus Project 15-001 RFP), and Martha’s Vineyard Transit Authority (30’ and 35’ Battery Electric Buses, VTA Project #2017-06 RFP). Copies of sample RFPs are available for download at: <https://app.box.com/s/qgyxb30yvdoqb6iwt6pnx4bxphwwdgc>

B. TECHNICAL SPECIFICATIONS (APTA SECTION 6)

As noted, APTA is in the process of updating its standard bus procurement guidelines to include Technical Specifications standards for battery electric buses. Transit agencies developing a RFP for battery electric buses may opt to use APTA’s Technical Specifications template, which includes 12 subsections. Many of these subsections are independent of the propulsion system and therefore remain the same regardless of bus type (i.e., diesel, hybrid, or battery electric bus).

APTA’s Technical Specifications subsections include:

- General
- Dimension
- Vehicle Performance
- Powerplant
- Structure
- Chassis
- Electrical, Electronic and Data Communication Systems
- Driver Provisions, Controls and Instrumentation
- Heating, Ventilating, and Air Conditioning
- Exterior Panels, Finishes and Exterior Lighting
- Interior Panels and Finishes
- Passenger Accommodations

The Technical Specifications language most relevant to battery electric buses – specifications related to the propulsion system – is provided as outlined below. The outline is organized using APTA’s Technical Specifications template:

- B.1 General
 - B.1.1 Scope (APTA TS 1)
 - B.1.2 Definitions (APTA TS 2)
 - B.1.3 Overall Requirements (APTA TS 5)
- B.2 Vehicle Performance
 - B.2.1 Power Requirements (APTA TS 7)
 - B.2.1.1 Top Speed (APTA TS 7.1)
 - B.2.1.2 Gradeability (APTA TS 7.2)
 - B.2.1.3 Acceleration (APTA TS 7.3)
 - B.2.2 Fuel Economy/Range (Design Operating Profile) (APTA TS 8)
- B.3 Powerplant
 - B.3.1 Engine Propulsion System (APTA TS 9.2)
 - B.3.2 Propulsion System Controller (APTA TS 9.2.5)
- B.4 Data Communications
 - B.4.1 General (APTA TS 45.1)
 - B.4.2 Drivetrain Level (APTA TS 45.2)
 - B.4.2.1 Diagnostics, Fault Detection and Data Access (APTA TS 45.2.1)
 - B.4.2.2 Programmability (Software) (APTA TS 45.2.2)
 - B.4.3 Multiplex Level (APTA TS 45.3)
 - B.4.3.1 Data Access (APTA TS 45.3.1)
 - B.4.3.2 Diagnostics and Fault Detection (APTA TS 45.3.2)
 - B.4.3.3 Programmability (Software) (APTA TS 45.3.3)

Additionally, LBT’s Technical Specifications, and if noted, Technical Specifications for Martha’s Vineyard Transit Authority (VTA), provide additional detail for battery electric buses, chargers and charging stations, as follows:

- B.5 Charging Stations
 - B.5.1 Charging Infrastructure (LBT TS 85)
 - B.5.2 Wireless Communication System (LBT TS 85.1.1)
 - B.5.3 Depot Charging Stations (LBT TS 85.2)
 - B.5.4 Charge Management System (LBT TS 85.2.1)
- B.6 Operating Environment (LBT TS 85.3)
- B.7 Respect for the Environment (LBT TS 5.10)

B.1 General

B.1.1 Scope

APTA’s Technical Specifications scope statement is as follows:

Buses shall have a minimum expected life of twelve (12) years or 500,000 miles, whichever comes first, and are intended for the widest possible range of passengers (APTA 2017 Draft, p. 1). In addition, the Long Beach Public Transportation Company's (LBT) Technical Specification scope statement their RFP for a battery electric bus is provided. Specific words or phrases that were not included by APTA are bolded and underlined.

These Technical Specifications ("Specifications") define requirements for **heavy-duty battery electric transit buses**, which, by the selection of specifically identified alternative configurations, may be used for both suburban express service and general service on urban arterial streets. Buses shall have a minimum expected life of twelve (12) years or 500,000 miles, whichever comes first, and are intended for the widest possible spectrum of passengers, including children, adults, the elderly and people with disabilities.

The Scope of Work, as defined in Section 1, NR1 Battery Electric Bus Project, includes, but is not limited to, the **manufacture and delivery of battery electric transit buses, and related charging equipment** in the base year, with options for additional buses and relative charging equipment over a five-year period. The options may or may not require supporting charging equipment, to be determined at the time of executing said options, which may include multiple on-route charging stations and/or depot charging stations for overnight charging. Pricing for the optional buses and/or charging equipment exercised in year one shall be based on the base year and annually adjusted per the established PPI index.

This specification is **customized for a unique zero-emission**, all-electric transit service at Long Beach Transit. This specification defines requirements for a battery electric bus fleet and supporting charging equipment, which may include multiple on-route charging stations, if required, and/or depot charging stations for overnight charging. Funding for this project is specific to battery electric and does not include options for on-board range extenders such as turbines, hydrogen, fuel cells, etc. The conceptual intent is that the **"charging" infrastructure be "open" and capable of supporting buses of varying type / model, such that the system of buses and chargers would be scalable for future growth without proprietary constraint.**

The intent of this RFP is to solicit proposals for a transportation solution that incorporates battery electric buses and the necessary charging infrastructure with a data management system (DMS) capable of monitoring the equipment state of health, performance, state of charge, etc. The DMS shall have the capability to manage the "charger" equipment for consideration of utility economics. It is further assumed that this DMS shall include the necessary data communications to support near real-time access to the subject equipment (buses and chargers), via wired and/or wireless communications.

Also, at a high conceptual level due to the inherent sensitivities of all electric vehicle performance relative to mass and energy efficiency, particular considerations shall be given to vehicle weight, component weight, parasitic loads, power management, thermal / solar loads, etc. (LBT RFP, p. 2).

B.1.2 Definitions

APTA definitions relevant for battery electric buses include:

- **Ambient Temperature:** The temperature of the surrounding air.
- **Battery Management System (BMS):** Monitors and manages battery cell or module voltage, current, state of charge, and temperature to ensure safe and optimal operation of the traction battery. The BMS adjusts the control strategy algorithms to maintain the batteries at uniform state of charge and optimal, safe temperature.
- **End of Life:** A condition reached when an energy storage system fails to meet specified capacity, power or function in specified use conditions.
- **Energy Density:** The amount of energy stored in a device per unit of volume or mass.
- **Energy Storage System (ESS):** A component or system of components that stores electrical energy and for which its supply of energy is rechargeable by the on-vehicle system (engine/regenerative braking generator) or an off-vehicle energy source.
- **Motor (Traction):** An electric motor used to power the driving wheels of the bus.
- **State of Charge (SOC):** Quantity of electric energy remaining in the battery relative to the maximum rated amp hour (Ah) capacity of the battery expressed in percent. This is a dynamic measurement used for the energy storage system. An absolute SOC is based on total battery capacity at the beginning of useful life. A relative SOC is based on total degraded capacity at the time of measurement. The actual relationship between the SOC and energy stored expressed as a percentage shall be linear (APTA 2017 Draft, pp. 3-10).

Additionally, the following terminology was defined in the LBT RFP:

- **Capacity (electrical energy storage device):** Two levels of capacity shall be defined, gross and usable. Gross capacity shall be the capacity energy (kWh) of the entire battery pack and shall include usable, unusable, and/or reserve capacity energy. Usable capacity shall be the capacity energy between the design operating range within the battery management system for normal operation.
- **Usable Battery Capacity:** Usable battery capacity is measured in kWh and would be the energy available for normal operations. Usable Battery Capacity would be the usable energy from the ESD [Electrical Storage Device] as managed through the BMS [Battery Management System], assumed to be less than the gross capacity. It is calculated based on a useful range of something above 0% SOC and something less than 100% SOC, i.e., as an example, if the range was between 10% and 90% SOC, then the usable battery capacity would be 80% of gross battery capacity.
- **Warrantable End of Life (WEOL):** WEOL is a measure of battery degradation determined as the point at which the batteries can no longer provide the energy or power required to meet the design operating profile. It is expressed as a percentage of remaining battery capacity as compared to the gross capacity at the beginning of useful life. For purposes of this specification, WEOL shall be a measure of the useful and intended life of the energy storage device. This measure shall be a percentage of the remaining useful capacity based on degradation from the beginning capacity, i.e., kWh, and is used in the overall calculation of mileage range. WEOL shall be used as a

condition for battery replacement and potentially initiate warranty claims (LBT RFP, pp. 3-10).

B.1.3 Overall Requirements

Examples of service life and cost of ownership requirements in the LBT Technical Specifications, and APTA for weight Technical Specifications:

- **Service Life:** The minimum useful life of the bus in transit shall be at least 12 years or 500,000 miles. It shall be capable of operating at least 40,000 miles per year, including the 12th year.
- **Cost of Ownership:** The Agency is interested in the long-term cost of ownership, particularly the maintenance requirements that are routine, scheduled and/or reasonably predictable. In addition to the Proposer's submittals, describing and defining the service and maintenance requirements for the equipment, a "Cost of Ownership" template has been developed and included in the forms to be filled out by the Proposer as an element of the submittal package. This form itemizes tasks in three areas: PMI, scheduled maintenance and major component replacement (LBT RFP, pp. 11-12).
- **Weight:** It shall be a design goal to construct each bus as light in weight as possible without degradation of safety, appearance, comfort, traction or performance (APTA 2017 Draft, p. 16).

B.2 VEHICLE PERFORMANCE

B.2.1 Power Requirements

APTA Technical Specifications for power requirements includes:

The propulsion system shall be sized to provide sufficient power to enable the bus to meet the defined acceleration, top speed, route, mileage, GVWR [gross vehicle weight rated] and gradeability requirements, and shall operate all propulsion-driven accessories. This should be verified using actual road test results and/or computerized vehicle performance data.

The loss of power to the bus shall not cause the driver to lose control of the bus nor to lose steering or braking. The bus shall be able to be safely brought to a controlled stop (APTA 2017 DRAFT, p. 24).

In addition, the top speed, gradeability, and acceleration requirements are defined as the following:

B.2.1.1 TOP SPEED

Agency to specify top speed limit. The bus shall be capable of safely maintaining the vehicle speed according to the recommendations by the tire manufacturer. Values are assumed to be sustained. Manufacturer shall supply Agency with data if there is a variance between peak performance and sustained vehicle performance.

NOTE: Top speed can affect gradeability. In particular, going higher than the standard 55 mph will lead to redesign costs and performance trades such as reduced gradeability (APTA 2017 Draft, p. 24).

B.2.1.2 GRADEABILITY

The propulsion system shall enable the bus to achieve and maintain a speed of 40 mph on a 2½ percent ascending grade and 10 mph on a 10 percent ascending grade continuous (APTA 2017 Draft, p. 24).

B.2.1.3 ACCELERATION

The acceleration shall meet the requirements as given in Table 1 and shall be sufficiently gradual and smooth to prevent throwing standing passengers off balance. Acceleration measurement shall commence when the accelerator is depressed (APTA 2017 Draft, p. 24).

TABLE E.1. MAXIMUM START ACCELERATION TIMES ON A LEVEL SURFACE¹
 (SOURCE: APTA STANDARD BUS PROCUREMENT GUIDELINES, DRAFT 2017, P. 25)

Speed (mph)	Maximum Time (sec)
10	5
20	10
30	18
40	30
50	60
¹ Vehicle weight + GVWR	

B.2.2 Fuel Economy / Range (Design Operating Profile)

The APTA guidelines state:

The bus must be able to achieve operational requirements under standard operating conditions and in agency-specific conditions. These conditions make up the Design Operating Profile. The standard operating conditions are defined by the Bus Research Testing Center at Altoona, Pennsylvania (“Altoona”), and are used as a benchmark and as a means to compare the performance of various buses across a set standard. The agency-specific conditions are established to ensure that the buses will be able to meet the unique operational requirements of the transit agency (APTA 2017 Draft, p. 26).

From LBT:

Altoona fuel economy tests shall be run on the following four duty cycles using maximum auxiliary loads and gross vehicle weight rated (GVWR) with the results reported in kWh per mile.

- Manhattan: 6.8 mph average speed
- Orange County: 12.7 mph average speed
- UDDS: 19 mph average speed
- Idle Time (LBT RFP, p. 20-21)

An example of agency-specific conditions for the LBT Design Operating Profile include:

- ...the bus must have a design operating profile that meets the requirements of the route model presented in [Tables 2 -4 and Figures 1- 4], including speed, elevation and grade. It is assumed that buses will start daily duty cycle at Maximum Standard Operating SOC. Batteries shall not be depleted below minimum Standard Operating SOC during normal operation.
- LBT’s primary goal is to place the proposed battery electric buses on the route shown in Figure 1, but LBT has a secondary goal to demonstrate the same proposed buses on alternate routes with LBT’s network. Thus, it is critical that the proposed bus and charging solution have the flexibility to be placed on alternate routes at LBT’s discretion. The Proposer shall provide a narrative in the Technical Proposal describing the flexibility of their proposed bus and charging solution to meet this goal (LBT RFP, p. 25).
- The Contractor shall provide the following narratives with their technical proposal
 - Description of proposed propulsion system
 - Description of methods used to validate that the proposed system will meet the Agency Design Operating Profile and results of that validation
 - Description of the Bench Test that Contractor will use to confirm propulsion system performance
 - Description of prior Bench Test experience with demonstration of vehicle performance including, but not limited to duty cycle, efficiency, battery SOC, acceleration, and gradeability (LBT RFP, p. 21).

TABLE E.2. MINIMUM OPERATING PROFILE DATA SUMMARY

(SOURCE: LONG BEACH PUBLIC TRANSPORTATION COMPANY RFP 15 001, P. 22)

Maximum Speed	40 mph
Maximum Grade	9%
Route Distance	8 miles
Route Duration	1 hour
Distance from Depot to Start of Route	4 miles
Furthest Distance from Depot	5 miles



FIGURE E.1. MINIMUM OPERATING PROFILE – ARIAL VIEW OF ROUTE
(SOURCE: LONG BEACH PUBLIC TRANSPORTATION COMPANY RFP 15 001, P. 22)

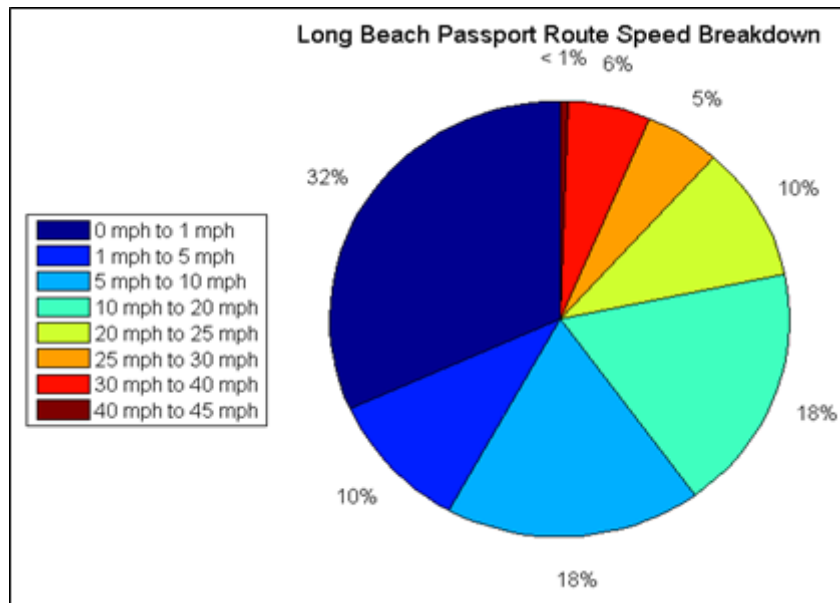


FIGURE E.2. MINIMUM OPERATING PROFILE – ROUTE SPEED BREAKDOWN
(SOURCE: LONG BEACH PUBLIC TRANSPORTATION COMPANY RFP 15 001, P. 23)

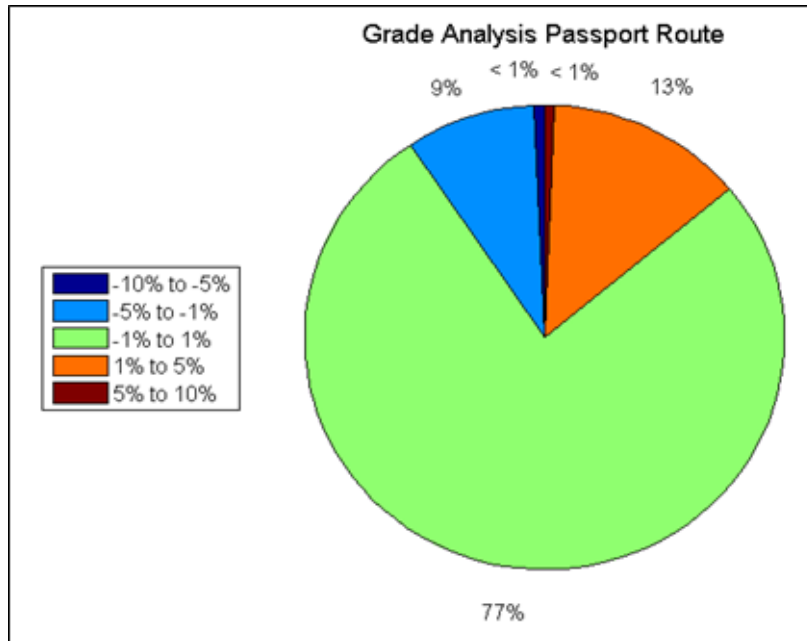


FIGURE E.3. MINIMUM OPERATING PROFILE – ROUTE GRADE BREAKDOWN
(SOURCE: LONG BEACH PUBLIC TRANSPORTATION COMPANY RFP 15 001, P. 22)

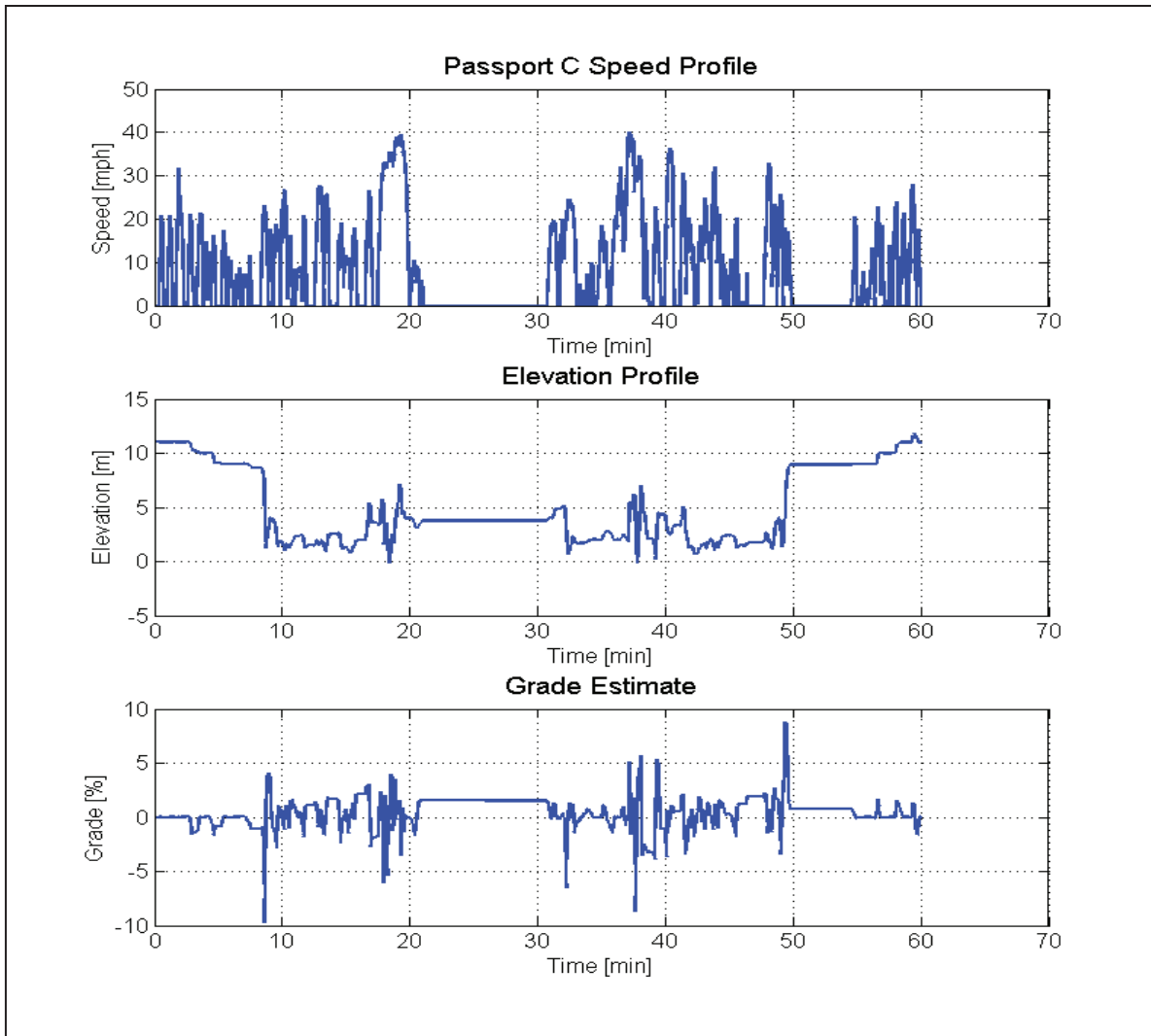


FIGURE E.4. MINIMUM OPERATING PROFILE – SPEED, ELEVATION, AND GRADE PROFILES
 (SOURCE: LONG BEACH PUBLIC TRANSPORTATION COMPANY RFP 15 001, P. 24)

TABLE E.3. MINIMUM OPERATING PROFILE – CURRENT WEEKDAY BLOCKING PROFILE
 (SOURCE: LONG BEACH PUBLIC TRANSPORTATION COMPANY RFP 15 001, P. 25)

Block	# Trips	Bus No.	Start	End	Duration				Mileage		
					In-Service	Layover	Pull	Total	In-Service	Pull	Total
30-1	36	Bus 1	5:04	0:40	15h30	3h50	0h16	19h36	154.6	3.2	157.8
30-2	24	Bus 2	5:34	19:22	10h30	3h02	0h16	13h48	103.1	3.2	106.3
30-3	22	Bus 3	8:24	21:20	9h42	2h58	0h16	12h56	94.5	3.2	97.7
30-4	28	Bus 4	9:20	1:09	12h09	3h24	0h16	15h49	120.3	3.2	123.5
30-5	14	Bus 5	10:02	18:21	6h16	1h47	0h16	8h19	60.1	3.2	63.3
Route Total	124				54h07	15h01	1h20	70h28	532.6	16.0	548.6

TABLE E.4. MINIMUM OPERATING PROFILE – CURRENT WEEKEND BLOCKING PROFILE
(SOURCE: LONG BEACH PUBLIC TRANSPORTATION COMPANY RFP 15 001, P. 25)

Block	# Trips	Bus No.	Start	End	Duration				Mileage		
					In-Service	Layover	Pull	Total	In-Service	Pull	Total
30-1	26	Bus 1	5:06	19:17	11h08	2h47	0h16	14h11	111.7	3.2	114.9
30-2	30	Bus 2	5:36	22:22	12h55	3h35	0h16	16h46	128.9	3.2	132.1
30-3	20	Bus 3	8:24	19:47	8h46	2h21	0h16	11h23	85.9	3.2	89.1
30-4	28	Bus 4	9:14	0:39	12h06	3h03	0h16	15h25	120.3	3.2	123.5
30-5	18	Bus 5	9:39	20:07	7h56	2h16	0h16	10h28	77.3	3.2	80.5
30-6	18	Bus 6	10:09	20:32	7h56	2h11	0h16	10h23	77.3	3.2	80.5
30-7	24	Bus 7	11:38	1:09	10h26	2h49	0h16	13h31	103.1	3.2	106.3
Route Total	164				71h13	19h02	1h52	92h07	704.4	22.4	726.8

B.3 POWERPLANT

The draft APTA guidelines include the following:

B.3.1 Engine: Propulsion System Description

The bus shall be powered by an electric propulsion system. Function and operation of the bus shall be transparent to the bus operator and passengers. The OEM shall ensure that the bus structure can successfully accept the installation of the propulsion system and be operated on the stated duty cycle for a period of 12 years without a structural failure. At a minimum, the propulsion system shall comply with applicable local, state and/or federal emissions and useful life requirements.

The propulsion system shall be rated for the GVWR or greater of the bus (APTA 2017 Draft, p. 30).

Additionally, Martha’s Vineyard Transit Authority includes the following propulsion system description:

The bus shall be powered by a battery electric propulsion system.

The Contractor shall assure that the bus structure can successfully accept the installation of the propulsion system and be operated on the stated duty cycle for a period of 12-years without a structural failure. The propulsion system shall utilize an appropriately sized permanent magnet (PM) traction motor. The propulsion system shall comply with applicable local, state, and/or federal emissions and useful life requirements, as a zero emission bus. The propulsion system shall be rated for the GVWR or greater of the bus (VTA RFP, pp. 27-28).

B.3.2 Propulsion System Controller (PSC)

The PSC regulates energy flow throughout system components in order to provide motive performance and accessory loads, as applicable, while maintaining critical system parameters (e.g., voltages, currents, temperatures, etc.) within specified operating ranges.

The controller shall monitor and process inputs and execute outputs as appropriate to control the operation of all propulsion system components (APTA 2017 Draft, p. 33).

LBT added the following PSC requirements:

- The overall propulsion system and PSC shall include and manage support systems such as steering, air, HVAC [heating, ventilations and air conditioning], and defroster (LBT RFP, p. 26).

- The PSC shall provide the following functionality:
 - Storage of the application file necessary to execute propulsion system commands
 - Storage of the bus’s data file generated on a day to day basis, to include:
 - At a minimum, duty cycle information (time stamp, vehicle speed, elevation, location, ambient temperature, etc.), and energy profile information (i.e., voltage and current from the traction motor, auxiliary systems, ESS, power electronics, onboard charging system, etc.) at 1 second intervals
 - History of charging sessions, energy in, time stamp, SOC, etc.
 - Incidents and alarms
 - Health monitoring and diagnostics information
 - Expert level software such that the bus is optimized per duty cycle on the fly, i.e., “adaptive learning” to consider, route, time of day, etc. The objective is to maintain the bus’s level of expected performance, meanwhile minimizing the cost of the electric utility used for charging. If the proposed PSC controller does not have the capability to perform “adaptive learning,” the Contractor must perform parameter tuning to help optimize the efficiency of the vehicle to the given route.
 - A means of executing “limp home” instruction such that the bus is able to return to the depot from the furthest point on the route without charge assistance.²⁸
 - A wireless means of communication to the on route and depot charging stations, and/or if probed, via a WLAN [wireless local area network] in close proximity
 - The system is assumed to include current / power sensors at strategic locations throughout the propulsion system components such that real time comparisons can be made between anticipated power flow and actual power. This feature shall facilitate health checking of components to indicate, “open”, “shorted” and/or components that have considerable variance.
 - The system is assumed to include the necessary sensor inputs at strategic locations, such as temperature, voltage, pressure, etc., such that the entire array of devices is monitored in real time. This feature shall be able to execute commands for the self preservation of component life, health, reliability and safety. The on-board diagnostic system shall trigger a visual and audible alarm to the operator when the motor controller detects a malfunction and the protection systems are activated.
 - The system shall protect the traction motor(s) against progressive damage. The system shall monitor conditions critical for safe operation and automatically derate power and/or speed.
 - The system shall include a subsystem capable of monitoring the level of connectivity between all propulsion components and associated cabling / connectors to the bus’s chassis and low (12/24 Vdc) systems to insure isolation. The energy storage module

²⁸ Martha’s Vineyard Transit Authority reported the purchase of a back-up battery, which will be connected to a gasoline generator and secured on a service truck for emergency use. VTA found this to be the most cost effective solution. For more information, see www.vineyardtransit.com.

shall have at least two automatic means / devices of disconnect and one manual capable of interrupting the positive and negative connections within the module enclosure, and rated for disconnect at maximum current.

- The system shall have an interlock that prevents engagement when the charger is connected to the traction battery (LBT RFP, pp. 26-27).

In addition, the LBT RFP calls out the following for battery electric buses:

- Propulsion System Service
- Primary Propulsion Unit and Traction Motor
- Power Electronics / Inverter
- Traction System
- Energy Storage System
- Energy Storage System Safety
- Battery Containers
- Battery Management System
- Battery Thermal Management

B.4 DATA COMMUNICATIONS

B.4.1 General

The APTA Standard Bus Technical Specifications for general data communications states:

All data communication networks shall be either in accordance with a nationally recognized interface standard, such as those published by SAE, IEEE or ISO, or shall be published to the Agency with the following minimum information:

- Protocol requirements for all timing issues (bit, byte, packet, inter-packet timing, idle line timing, etc.) packet sizes, error checking and transport (bulk transfer of data to/from the device).
- Data definition requirements that ensure access to diagnostic information and performance characteristics.
- The capability and procedures for uploading new application or configuration data.
- Access to revision level of data, application software and firmware.
- The capability and procedures for uploading new firmware or application software.
- Evidence that applicable data shall be broadcast to the network in an efficient manner such that the overall network integrity is not compromised.

Any electronic vehicle components used on a network shall be conformance tested to the corresponding network standard (APTA 2017 Draft, pp. 82-83).

B.4.2 Drivetrain Level

The APTA Standard Bus Technical Specifications for drivetrain level data communications states:

Drivetrain components, consisting of the motor(s), motor inverter(s), engine, transmission, retarder, anti-lock braking system and all other related components, shall be integrated and communicate fully with respect to vehicle operation with data using SAE Recommended Communications Protocols such as J1939 and/or J1708/J1587 with forward and backward compatibilities or other open protocols. At a minimum, drivetrain components shall be powered by a dedicated and isolated ignition supply voltage to ensure data communication among components exists when the vehicle ignition is switched to the “on” position (APTA 2017 Draft, p. 83).

B.4.2.1 DIAGNOSTICS, FAULT DETECTION AND DATA ACCESS

Drivetrain performance, maintenance and diagnostic data, and other electronic messages shall be formatted and transmitted on the communications networks.

The drivetrain level shall have the ability to record abnormal events in memory and provide diagnostic codes and other information to service personnel. At a minimum, this network level shall provide live/fail status, current hardware serial number, software/data revisions and uninterrupted timing functions (APTA 2017 Draft, p. 83).

B.4.2.2 PROGRAMMABILITY (SOFTWARE)

The drivetrain level components shall be programmable by the Agency with limitations as specified by the subsystem Supplier (APTA 2017 Draft, p. 83).

B.4.3 Multiplex Level

The APTA Standard Bus Technical Specifications for multiplex data communications is included under data access, diagnostics and fault detection, and programmability as follows:

B.4.3.1 DATA ACCESS

At a minimum, information shall be made available via a communication port on the multiplex system. The location of the communication port shall be easily accessible. A hardware gateway and/or wireless communications system are options if requested by the Agency. The communication port(s) shall be located as specified by the Agency (APTA Draft 2017, p. 83).

B.4.3.2 DIAGNOSTICS AND FAULT DETECTION

The multiplex system shall have a proven method of determining its status (system health and input/output status) and detecting either active (online) or inactive (offline) faults through the use of on-board visual/audible indicators. In addition to the indicators, the system shall employ a diagnostic and fault detection system, which shall be accessible via either a personal computer or a hand held unit. Either unit shall have the ability to check logic function (APTA Draft 2017, pp. 83-84).

B.4.3.3 PROGRAMMABILITY (SOFTWARE)

The multiplex system shall have security provisions to protect its software from unwanted changes. This shall be achieved through password protection, limited distribution of the

configuration software, limited access to the programming tools required to change the software, and hardware protection that prevents undesired changes to the software. Provisions for programming the multiplex system shall be possible through a PC or laptop. The multiplex system shall have proper revision control to ensure that the hardware and software are identical on each vehicle equipped with the system (APTA Draft 2017, p. 84).

B.5 CHARGING STATIONS

LBT added a section to their Technical Specifications on Charging Stations, as follows:

B.5.1 Charging Infrastructure

These general requirements apply to all charging stations that may be delivered under the Contract. The Contractor shall provide Charging Equipment and Charger Interface and the control and data system needed to recharge the bus propulsion system batteries. The subject equipment deliverables shall begin downstream of the SC Edison Service Meter, and shall include the main service panel, sub-panels, step/down transformers, and all circuit breakers and disconnect switches. The Contractor shall provide all Charging Equipment and Charger Interface design requirements and specifications to the Agency and their designated architectural, civil, electrical, and mechanical engineering contractors to enable Charging Station site design, permitting, and construction.

The Contractor shall provide close coordination with the Agency and its engineering contractors during site design and construction of the charging stations. The Contractor shall be responsible for equipment start-up and testing to ensure that the charging equipment meets all stated specifications and functionality prior to site acceptance.

The chargers shall be UL Classified²⁹ for the intended purpose and location environment. The charging systems shall be capable of delivering the optimal battery charge profile as specified by the battery manufacturer and charging the installed traction battery to a fully charged state from the minimum recommended state-of-charge including necessary cool-down time as specified by the battery manufacturer. The chargers shall be capable of connection to a 480-volt, 3-phase, 60-Hz electrical supply. The chargers shall be equipped with an E-Mon Class 3200 submeter (or approved equal) that:

- measures and displays kWh consumed and real time load in kW within 1% accuracy,
- is capable of RS-485 communications, and,
- records kWh and kVARh delivered, kWh and kVARh received. Data stored in 15-minute intervals for up to 72 days or 5-minute intervals for up to 24 days. Maintains interval data storage in a first-in, first-out format.

Battery chargers shall be configured to automatically apply a charging protocol appropriate to the battery's state-of-charge (SOC), in accordance with the battery manufacturer's recommended practices. Battery charger shall be configured to automatically initiate and sustain charging at any battery state-of-charge if properly connected when so signaled by an

²⁹ Best practice for the electrical standards for battery electric buses should be monitored for updated standards, including reviewing guidance from IEEE and the US Department of Energy

external timing circuit or control input. The battery charger shall be configured to automatically terminate the charge on attainment of a full state-of-charge or in the event of hazardous or anomalous conditions. Battery chargers shall be able to apply commissioning, equalization or conditioning charges according to the battery manufacturer's recommended practices when so configured by operation of keyboard or switch panel inputs. The battery charger shall be configured to automatically restart after unintended interruption of a charging episode due to interruption or temporary degradation of electrical service. The battery chargers shall be configured to interface with on-board battery management and interlock systems.

The actual charge profiles that the subject chargers deliver while charging, commissioning, equalizing, and conditioning the battery systems of the subject buses shall be recorded by the Contractor and shall be submitted to the battery manufacturer for review and approval. Written confirmation from the battery manufacturer attesting to the appropriateness of the delivered charge profile shall be submitted to Procuring Agency concurrent with or prior to delivery of the first bus.

The buses must be immobilized during all charging operations. Upon successful engagement of the charging interface, the bus shall be interlocked such that propulsion is rendered non-tractive and the brakes applied.

Conductive cabling connecting depot and convenience chargers to the bus shall be of fifteen-foot (max) length and shall connect to a receptacle at the front of the bus, curbside. The connectors shall be industry standard and of simple design and heavy-duty construction and shall not be energized except when mated with the bus mounted receptacle. A single bus-mounted receptacle shall serve both the depot charging station and the opportunity charging station. The bus mounted receptacle shall be of simple and ergonomic design, of not more than 25 pounds (plug and cord), not more than two plugs, and heavy-duty construction, and shall not be energized except when mated with the charger connectors.

Chargers shall not produce harmonic distortion in excess of 5% THD. Charging circuits shall be isolated from the vehicle chassis such that ground current from the grounded chassis does not exceed 5 mA.

The bid package shall contain a complete description of the charging systems (including anticipated AC energy consumption for buses operating on the specified operating profile, power factors, harmonic distortion, and accuracy of charge parameters). (LBT RFP, pp. 116-117)

B.5.2 Wireless Communication System

The Charging Stations shall be equipped with a wireless communication system to transmit information on each charge event, including, but not limited to bus ID, charger status, faults, beginning SOC, charge amount, ending SOC, charge duration, energy consumption at the Mains Supply, energy consumption at the charge interface, max power, ambient temperature, etc. (LBT RFP, p. 118)

B.5.3 Depot Charging Stations

Contractor's charging equipment shall be installed at the Agency bus depot for overnight charg-

ing and conditioning of the batteries. Contractor shall provide charging equipment to allow for simultaneous charging of all buses. Any equipment associated with the Charging Station must be vandal resistant and weatherproof.³⁰

Contractor may vary the size of the Charging Equipment at the Agency bus depot to allow for overnight charging and battery conditioning with a maximum charge time of four hours, per bus. Buses shall be charged to Maximum Standard Operating SOC at a rate that maximizes life of the batteries.

The Charging Interface may be conductive or inductive. The Charging Interface shall be a design that is considered “industry standard” with respect to the connector to the charging equipment, connector to the bus, connection methods, communications protocol, and data exchanged between the charging equipment and the vehicle. In the event that no industry standard exists, the Agency shall have the right to license the design of the Charging Interface to allow for the Charging Interface to be used with alternate charging equipment and bus manufacturers.

The bus must be immobilized during all charging operations. Upon successful interface to the charging interface, the bus shall be interlocked such that propulsion is rendered non-tractive and the brakes applied.

The depot chargers shall be capable of discharging the on-board energy storage system to facilitate making repairs; preferred means of discharge shall be to return the power to the utility grid (LBT RFP, pp. 118-119).³¹

B.5.4 Charge Management System

The Depot Charging Stations shall be capable of being controlled and scheduled by a centralized charger management system that allows a user to control charging start and stop times, charging SOC, etc., for each charger on the system (LBT RFP, p. 119).

B.6 OPERATING ENVIRONMENT

Martha’s Vineyard Transit Authority Technical Specifications for Operating Environment:

The bus achieves normal operation in ambient temperature ranges of -20°F to 120°F, at relative humidity between 5% and 100%, and at altitudes up to 3000 feet above sea level. Degradation of performance due to atmospheric conditions is minimized at temperatures below 10°F, above 115°F or at altitudes above 3000 feet [above sea level]. Speed, gradeability and acceleration performance requirements are met at, or corrected to, 77°F, 29.31 in. Hg, dry air per SAEJ 1995 (VTA RFP, p. 16).

B.7 RESPECT FOR THE ENVIRONMENT

The LBT added a Technical Specification related to the environment, as follows:

In the design and manufacture of the bus, the Contractor shall make every effort to reduce the amount of potentially hazardous waste. In accordance with Section 6002 of the Resource

³⁰ The National Electrical Manufacturers Association guidance on charging equipment weatherproofing should be considered in the development of RFP specifications.

³¹ The possible discharge of electricity to the grid should be explored in cooperation with Connecticut public utilities. Conditions to consider include amount of discharge, frequency, time of use, and conversion requirements.

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Conservation and Recovery Act, the Contractor shall use, whenever possible and allowed by the specifications, recycled materials in the manufacture of the bus and charging equipment. The Contractor shall provide a plan for reuse or recycling of replaced battery cells and/or battery packs both during and after the warranty period.

APPENDIX F

ELECTRIC BUS DEPLOYMENT EXAMPLES

An increasing number of transit agencies in the United States are embracing battery electric bus technology. The following examples are provided to supplement those battery electric bus deployments described in Chapter 2.

A. TIGGER GRANT BATTERY ELECTRIC BUS PURCHASES

The Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) program was initiated within the American Recovery & Reinvestment Act (ARRA) of 2009. According to the Federal Transit Administration, the TIGGER Program was then continued in Federal Fiscal Year 2011 through the Department of Defense and Full-Year Continuing Appropriations Act, 2011 (Pub. L. 112-10). A total of \$49.9 million was appropriated for grants to public transit agencies for capital investments to reduce the energy consumption or greenhouse gas emissions for their public transportation systems.

The following is a summary of selected TIGGER projects related to the procurement of battery electric buses.

- **Chicago Transit Authority (CTA)**
Chicago, IL; TIGGER- D2010-GGER-009

CTA is the second largest bus transit organization in the United States. The TIGGER project provided two new battery electric buses from New Flyer Industries to replace older diesel buses. CTA's initial purchase of these buses entered service in October 2014 for demonstration of the technology (Eudy, Caton & Post, 2014, p. 95). According to CTA, it was the first major US transit agency to test the feasibility and durability of battery electric buses in extreme hot/cold weather and with heavy passenger loads. *"The buses operate using a Siemens electric propulsion system that's powered by rechargeable lithium ion (Li-ion) batteries. The Li-ion batteries are designed for the life of the vehicle, which is about 12 years. The batteries can store up to 300 kWh of electricity, and are monitored for safety and performance by a state-of-the-art battery management system. Charging a bus takes about 3 to 5 hours. The electric buses also are equipped with regenerative braking systems."* and *"CO₂ reductions of 121-tons per year, per electric bus. Over the anticipated 12 year lifetime of the bus, this equates to 1,452 tons per bus."* (CTA website)

- **Foothill Transit Fast-Charge Electric Bus Project**
West Covina, CA; TIGGER D2010-GGER-004

Foothill Transit is deploying twelve 35' Model BE35 Proterra LLC battery electric buses with fast-charge capability using Eaton 500 kW fast chargers as part of its fleet in West Covina, located in Los Angeles County. The agency plans to completely electrify a specific 16.75-mile route between La Verne and Pomona by replacing all of the buses that operate on this route with battery electric buses and installing two charging stations at approximately midpoint along the route (Eudy, Caton & Post, 2014, p. 14; Prohaska, Eudy, Kelly, 2016). During 2016, two additional 40' battery electric buses were added to

the fleet. As of September 2016, their fleet of battery electric buses surpassed one million miles of use. On their website, Foothill Transit has set 2030 as a goal for an all (100%) battery electric fleet of buses. During 2017, an additional 13 electric buses are to be added, bringing the battery electric fleet to 10% of their total bus fleet.

According to Foothill Transit, *“Our all-electric bus requires no oil change, reduces maintenance costs by \$135,000 and saves \$225,000 in fuel costs over the course of its life.”* (Foothill Transit.org website) NREL will study the electric buses and states that, *“The electric buses under study – Proterra EcoRide BE35 transit buses with eight 368V lithium-titanate battery packs offering 88kWh of energy – can be completely charged in less than 10 minutes via two 500kW fast chargers located mid-way along the route.”* (USDOE/NREL website)

See the following references for information on an on-going study of Foothill battery electric buses as of June 2016: Prohaska, Eudy & Kelly, 2016; Eudy, Prohaska, et al. 2016. Prohaska, Eudy and Kelly note that it is important to understand the effects of road grade, heating, ventilating, and air conditioning when determining the efficiency of battery electric buses.

- **Howard County Transit Electric Bus Project**
Maryland DOT; TIGGER-D2010-GGER-013

Three battery electric buses replaced three diesel buses in July 2017. The battery electric buses use an inductive charging system and have an energy information station at a transit shelter. The battery electric buses are charged through a Momentum Dynamics inductive charger. This project demonstrates and evaluates the energy efficiency and cost effectiveness of opportunity charging of battery electric bus batteries. The non-contact charger provides energy to the batteries through electromagnetic induction. These buses serve the “Green Route,” which includes the Mall in Columbia, the Village of Wilde Lake, Howard Community College, and Howard County General Hospital (Eudy, Caton & Post, 2014, p. 58; Magill website; CTE Current Projects website).

- **King County Zero Emission, Fast Charge Bus Project**
King County Metro
Seattle, WA; TIGGER-D2010-GGER-025

Under the TIGGER program, King County initiated a RFP for up to two battery electric buses with fast-charge stations (Eudy, Caton & Post, 2014, p. 163). Ultimately, three buses were purchased and placed into service in February 2016 (USDOT, May 2017). Additionally, as of January 2017, King County Metro announced that they would buy up to 120 battery electric battery buses by 2020. The order for the first 20 buses is pending for implementation in 2017 and 2019. *“The 40-ft Proterra battery buses have an estimated range of about 25 miles, with a quick charging time of just 10 minutes.”* (Washington, King County website)

- **Long Beach Transit all Electric Bus Pilot Project (LBT)**
Long Beach, CA; TIGGER-D2011-GGER-002

LBT is replacing ten 40-foot diesel buses with ten battery electric buses and supporting charging infrastructure. Two on-route charging units and an overnight charging station are planned as part of this project (Eudy, Caton & Post, 2014, p. 141). According to a

press release, in late 2016, LBT reported that it is placing seven of the ten battery electric buses on the Passport Route, a line that carries passengers to points in downtown Long Beach and the city's shoreline area free of charge. The other three buses will service various other routes. The manufacturer of the battery electric buses is BYD Co. LTD (Transportation Technology website).

- **City of McAllen On-Line Electric Vehicle Project**
McAllen, TX; TIGGER-D2011-GGER-012

The City of McAllen plans to implement inductively charged battery electric bus technology on part of its fixed-route fleet. Three of McAllen's older diesel buses are to be retrofitted as battery electric buses capable of charging through an electric roadway. This electric roadway will be installed on one of the City of McAllen's current bus routes (Eudy, Caton & Post, 2014, p. 120).

As of January 29, 2016, the city reports that *"In a partnership with Wireless Advanced Vehicle Electrification (WAVE) and Complete Coach Works (CCW), the City of McAllen has completed a project to install WAVE technology on two buses that include an all-electric, Zero-Emission Propulsion System (ZEPS) provided by CCW. WAVE technology transfers power through the air, from an embedded charging pad placed in the pavement to a receiving pad mounted on the vehicle's undercarriage seven to eight inches above, minimizing the need for on-board power storage. An embedded charging pad has been placed in the roadway at one of the McAllen stops so that the bus route will be unchanged. The embedded pads will measure about three feet square. The pads are flat and seamlessly blend with the asphalt, allowing any vehicle to driver over it and causing no harm to anyone that passes over it...The bus will arrive over the charging pad every hour, during the standard layover of about 10-15 minutes so that the bus can charge, causing no disruption to the route..."* (Texas, City of McAllen website)

- **Seneca Electric Bus Project**
Clemson Area Transit (CATbus)
Seneca, SC; TIGGER-D2011-GGER-010

This CATbus project replaced all three of their diesel transit buses with 35' fast-charge battery electric buses from Proterra, plus an additional spare battery electric bus. Two fast-charge station installations were installed and two more battery electric buses were added later (Eudy, Caton & Post, 2014, p. 87). As of February 2015, CATbus declared itself the world's first 100% battery electric bus fleet (Barnett website).

- **STAR Metro Electric Bus Project (StarMetro)**
Tallahassee, FL; TIGGER D2010-GGER-006

Three diesel buses were replaced with five Proterra lithium titanate battery fast-charge battery electric buses. The project included installation of a fast charger on the route at a layover point. The buses started operations in August 2013. The fast charger is installed on-route and can fully charge a bus in less than 12 minutes. The agency also installed a slow charger at the depot to provide additional charging as needed. The estimated time for this charger to fully charge a bus is 1.5 hours. According to StarMetro, *"Based on the data analysis, StarMetro has an annual energy savings of 76%. Because the buses offset all the fuel use of the diesel buses, the project results in 100% fewer GHG emissions. This is the equivalent of removing approximately 33 cars from the road each year."* (Eudy, Caton & Post, 2016, pp. 20-21)

- **VIA Fast Charge Electric Bus Project**
San Antonio, TX; TIGGER-D2009-TGGR-037

VIA replaced three diesel buses with three Proterra EcoRide BE35 battery electric buses in early 2013. The buses use a quick-charge station that can fully charge the batteries in less than 10 minutes.

“VIA contracted with its local energy provider, CPS Energy, to receive 100% of the electricity used by the buses through its Windtricity program. Windtricity uses wind-powered turbines to generate grid electricity. VIA also installed solar PV panels at the bus charging station for supplemental power. The buses are being used in a downtown circulator service. As of the end of 2013, the buses accumulated in excess of 11,000 on-road miles.” (Eudy, Caton & Post, 2014, p. 119)

“Based on the data analysis, VIA has an annual energy savings of 74%. The analysis calculates the difference between the diesel bus fuel use and electric bus electricity use on the basis of energy content in MBtu. Because the electric buses offset all of the fuel use of the diesel buses, the project results in 100% fewer GHG emissions.” (Eudy, Caton & Post, 2014, p. 119; Eudy, Caton & Post, 2016, pp. 24-5)

B. THE CENTER FOR TRANSPORTATION AND THE ENVIRONMENT (CTE) ELECTRIC BUS PROJECTS

- **Boston Electric Bus Deployment**

Massachusetts Bay Transportation Authority (MBTA) is partnering with CTE to deploy five battery electric New Flyer Xcelsior XE60 heavy-duty, low-floor, 60' articulated buses and a 450 kW on-route rapid charger. The team will deploy the buses on the Silver Line Bus Rapid Transit System in Boston.

- **Duluth Electric Bus Deployment**

CTE will partner with Duluth Transit Authority in Duluth, MN and Proterra for battery electric buses to be delivered in March 2018. This Federal Transit Administration LoNo funded program will deploy six Proterra 40' fast charge battery electric buses with two in-route fast charge stations.

- **Lexington Electric Bus Deployment**

CTE, in partnership with Lextran, the Transit Authority of the Lexington Fayette Urban County Government in Lexington, Kentucky, is managing a bus replacement project in which five diesel transit buses will be replaced with five 40' Proterra battery electric transit buses. The buses will be charged in-route using a fast-charging station that, on average, recharges the buses in less than 10 minutes. Lextran anticipates collecting and reporting performance and evaluation data through March 2018 and operating the buses through 2028.

New York City Transit

NYC Transit and New York MTA have a combined fleet of about 5,700 buses for public transportation in New York City. The fleet currently consists of a mix of diesel, hybrid diesel-electric and CNG buses. In 2015, NYC Transit commissioned Columbia University to perform a study for an analysis comparing the current fleet of buses to battery electric buses. The analysis centers on the economics of the battery electric bus alternative, as well as on greenhouse gas emissions and air pollution. Due to benefits calculated, the study concludes that New York should move forward in the process of obtaining battery electric buses. The benefits presented include: saving approximately 500,000 metric tons of CO_{2e} emissions per year; fuel and bus maintenance savings that more than offset the higher cost for procurement of battery electric buses (including the cost of the recharging infrastructure) over the 12-year lifetime of a bus; and air pollution reduction health benefits of \$150,000 per battery electric bus due to the reduction of respiratory and other diseases (translates to \$100 per New York City resident). The report further notes that the conversion of New York's 5,700 buses to 100% battery electric by 2025 would contribute 0.5% toward the total US GHG emission reduction goal of 1,000 million metric tons per year by 2025, from 2015 actuals (Aber, 2016, p. 13).

APPENDIX G

APTA'S ENERGY SAVING STRATEGIES FOR TRANSIT FACILITIES

Energy Harvesting (APTA[b], 2011, p. 9)

- Plan facilities to reduce energy consumption during the design phase, as the size and placement of station facilities also affects energy consumption.
- Orient and design aboveground facilities to take advantage of prevailing winds and maximize the use of natural ventilation to replace or augment mechanical ventilation.
- Orient and design aboveground facilities to maximize the use of natural lighting to replace or augment electrical lighting with the help of photo sensors.
- Consider incorporating solar thermal systems to replace or augment fuel-based space and water heating.
- Consider incorporating passive solar systems to replace or augment fuel-based space heating (e.g., SolarWall technology).
- Consider incorporating ground-source heat pump systems to replace or augment fuel-based space heating and cooling.

Energy Conservation and Recovery (Ibid., p. 9)

- Use heat recovery units (also known as energy recovery ventilators) to provide heating and cooling.
- Design fenestration and shading to avoid unwanted solar gain by using low-emissivity glass or external light shelves.
- Design facilities with increased wall and roof insulation, including vegetative roofs.
- Use motion sensors to minimize idle lighting.
- Use air-quality sensors and variable-frequency ventilators to adjust air exchange.
- Use rapid roll-up doors to minimize losses of conditioned air in maintenance and repair facilities.
- Consider process heat recovery for domestic hot water.
- Incorporate light and temperature controls at facilities' offices.
- Employ regenerative braking systems on buses to capture energy from braking vehicles and charge batteries on buses.

Energy Efficiency (Ibid., p. 9)

- Use premium-efficiency motors and other equipment.

- Design for efficient lighting (lumens per watt), as well as task lighting.
- Consider the use of small-scale photovoltaic systems (with or without inverter) for signage, emergency phones, canopy lighting, closed circuit systems, microwave transmitters and other applications to power small-load equipment.
- Incorporate intelligent control systems for new electrical meters to permit measurement of electricity consumed and to promote conservation efforts.
- Install permanent carbon dioxide monitoring systems that provide feedback on space ventilation performance that affords operational adjustments and energy savings.

On-site Generation (Ibid., p. 9)

- Consider integrating a photovoltaic system to provide electrical power for all or some loads.
- Consider integrating wind turbines to provide electrical power for all or some loads.
- Consider integrating co-generation equipment to provide electrical power and heat for all or some demand.
- Consider integrating fuel cells to provide electrical power for all or some loads, as well as some heat for domestic uses.

Partner with Local Power Utility (Ibid., p. 10)

- Ensure early dialogue with the local utility when exploring new approaches to energy efficiency, production and purchasing. Review scope of work with the utility and potential impacts, including challenges and benefits. Establish a general understanding of the extent of utility impact. Get support from the utility.
- Leverage the utility's expertise in energy production to produce and/or purchase renewable energy.
- Leverage the transit agency's long-term facility ownership.
- Utilize energy efficiency and renewable energy pilot projects to study the effectiveness of possible improvements (Gallivan, 2013, p. 38).

For Operations and Maintenance of Existing Facilities, the following recommendations are also from APTA:

Establish GHG Monitoring on Facilities (APTA[b], p. 13)

- Establish a baseline of greenhouse gas emissions of facility and infrastructure use.
- Monitor energy use in all forms (electricity, fuel, natural gas) as well as industrial use of gases with high global warming potential (including refrigerants).

Implement Pollution Reduction Strategies (Eliminate, Reduce, Reuse and Recycle) (Ibid., p. 23)

- Reduce hazardous waste and chemical usage in all agency facilities through the use of an inventory and criteria for what is to be eliminated, what is to have limited use, and processes to ensure proper management of these wastes and chemicals.

- Establish a system to divert organic waste to composting facilities, where available.
- Establish a reduced idling policy for buses and other revenue and nonrevenue vehicles.
- Introduce methods that extend the life of lubricants.
- Reduce pesticide and herbicide use. Utilize integrated pest management. Refer to the EPA's Integrated Pest Management program at www.epa.gov/pesticides.
- Reduce vehicle wash water use reduction through efficient system design (spray, pressure, reused water cycles). Take care to ensure that recycled water does not contain contaminants such as chlorides.
- Implement waste reduction and recycling programs, such as recycling electronic devices, lamps and ballasts.
- Document the final destination of recycled products such as motor oil and computer components.
- Divert waste from landfills. Recycle paper products, bottles, cans and compostable materials such as landscape and food waste.
- Keep records of existing hazardous material quantities in stock, and store them in an established, secure on-site location by type as close as possible to where they will be used, along with standard MSDS precautions and spill response supplies.
- Optimize employee travel by using teleconferencing equipment, transit ridership, cycling, walking, carpooling and other sustainable options:
 - have a green mobility plan (bike, telecommute, webcasting, car-sharing, ride-sharing, no-parking policy, etc.) for the agency/organization, and offer transit passes as part of employee benefits.
 - establish a business travel policy focused on sustainability, encouraging the reduction of carbon emissions and air pollutants.
- Reduce the carbon footprint of meetings (e.g., establishing collaborative sites and using email distribution of documents as part of a paper-reduction policy).
- Initiate training for employees on sustainability overall and systems or practices such as EMS [Energy Management Systems], SMS ISO [Service Management System: International Organization for Standardization] 14001.

APPENDIX H OUTPUT FROM BASELINE SCENARIOS

This appendix includes a summary of the assumptions and contexts for baseline Scenario #'s 1 through 9, followed by the output for each scenario. The following assumptions are common for each scenario:

- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

Scenario	2030 Transit Ridership	2030 Fleet Size	LDV VMT (billions)	Context
1	3%	554	22.1	<ul style="list-style-type: none"> • FLAT OR DECLINING TRANSIT RIDERSHIP AND A RAPID RISE IN VMT • TRANSIT'S SHARE OF GHG IS AN INCREASINGLY SMALLER PIECE OF A GROWING FOOTPRINT • MOST PESSIMISTIC FROM A TRANSIT PERSPECTIVE
2	3%	554	19.6	<ul style="list-style-type: none"> • FLAT OR DECLINING TRANSIT RIDERSHIP AND FLAT LDV VMT • TRANSIT'S SHARE OF GHG IS AN INCREASINGLY SMALLER PIECE OF A SHRINKING FOOTPRINT • ALTHOUGH TRANSIT RIDERSHIP IS FLAT, THIS SCENARIO IS MILDLY OPTIMISTIC IN TERMS OF LDV VMT REDUCTION
3	3%	554	18.2	<ul style="list-style-type: none"> • FLAT OR DECLINING TRANSIT RIDERSHIP AND A 3% DECREASE IN LIGHT-DUTY VEHICLE VMT. • TRANSIT'S SHARE OF GHG IS AN INCREASINGLY SMALLER PIECE OF A SHRINKING FOOTPRINT • VERY OPTIMISTIC IN TERMS OF LDV VMT REDUCTION
4	7%	895	22.1	<ul style="list-style-type: none"> • INCREASE IN TRANSIT RIDERSHIP BY 4% TO 7% AND A RAPID RISE IN LDV VMT • TRANSIT'S SHARE OF GHG INCREASES SLIGHTLY IN A GROWING FOOTPRINT • MODERATE FROM A TRANSIT PERSPECTIVE AND PESSIMISTIC FROM A LDV VMT PERSPECTIVE
5	7%	895	19.6	<ul style="list-style-type: none"> • INCREASE IN TRANSIT RIDERSHIP BY 4% AND NO RISE IN LIGHT-DUTY VEHICLE VMT • TRANSIT'S SHARE OF GHG INCREASES SLIGHTLY IN A SHRINKING FOOTPRINT • MODERATE FROM BOTH PERSPECTIVES AND IS THE BASIS FOR SENSITIVITY ANALYSIS

SUSTAINABILITY STRATEGIES TO MINIMIZE THE
 CARBON FOOTPRINT FOR CONNECTICUT BUS OPERATIONS
 APPENDICES

6	7%	895	18.2	<ul style="list-style-type: none"> • INCREASE IN TRANSIT RIDERSHIP BY 4% AND A 3% DECREASE IN LIGHT-DUTY VEHICLE VMT • TRANSIT'S SHARE OF GHG INCREASES WITHIN AN OVERALL SHRINKING TRANSPORTATION GHG FOOTPRINT • MODERATE IN TERMS OF TRANSIT AND OPTIMISTIC FROM THE LDV VMT PERSPECTIVE
7	10%	1150	22.1	<ul style="list-style-type: none"> • INCREASE IN TRANSIT RIDERSHIP BY 7% TO 10% AND A RAPID RISE IN LDV VMT • TRANSIT'S SHARE OF GHG INCREASES IN A FLAT OVERALL TRANSPORTATION GHG FOOTPRINT • VERY OPTIMISTIC FROM A TRANSIT RIDERSHIP PERSPECTIVE
8	10%	1150	19.6	<ul style="list-style-type: none"> • INCREASE IN TRANSIT RIDERSHIP BY 7% TO 10% AND NO RISE IN LDV VMT • TRANSIT'S SHARE OF GHG INCREASES IN A SHRINKING OVERALL TRANSPORTATION GHG FOOTPRINT • VERY OPTIMISTIC IN TERMS OF TRANSIT RIDERSHIP AND MODERATE FOR LDV VMT
9	10%	1150	18.2	<ul style="list-style-type: none"> • INCREASE IN TRANSIT RIDERSHIP OF 7% AND 3% DECREASE IN LIGHT-DUTY VEHICLE VMT • TRANSIT'S SHARE OF GHG INCREASES IN A SHRINKING TRANSPORTATION GHG FOOTPRINT • THIS SCENARIO IS THE MOST OPTIMISTIC BOTH IN TERMS OF TRANSIT AND MODERATE FOR LDV VMT

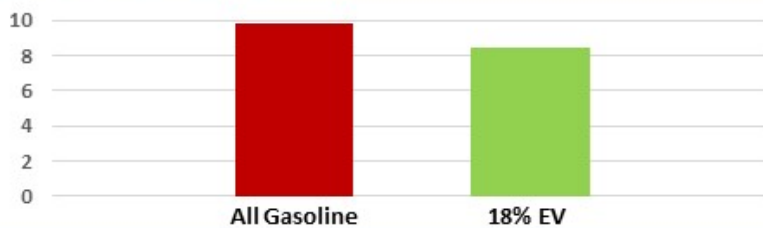
Scenario #1

Assumptions

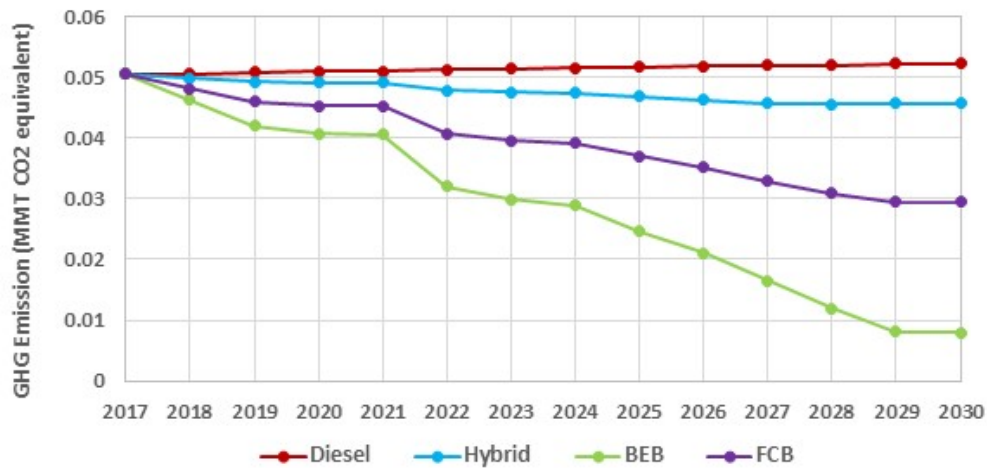
- 2030 Transit Ridership = 3%
- 2030 Fleet Size = 554
- LDV VMT = 22.1 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

Context: This scenario represents a flat or declining transit ridership and a rapid rise in VMT. Transit's share of GHG is an increasingly smaller piece of a growing footprint. This is the most pessimistic of the scenarios from a transit perspective.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO _{2e})	GHG Reduction (MMT CO _{2e})	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	0.67	0.00	539	N/A
BEB	0.35	0.32	627	275
FCB	0.50	0.17	1,123	3,435
Diesel Hybrid	0.62	0.05	622	1,660

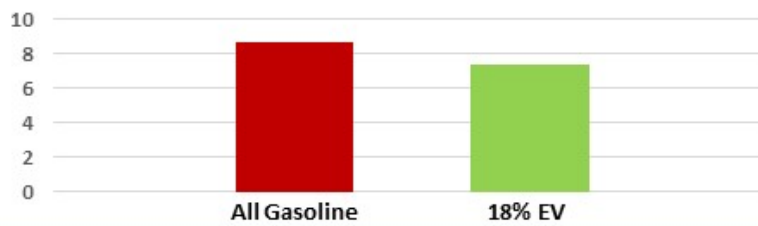
Scenario #2

Assumptions

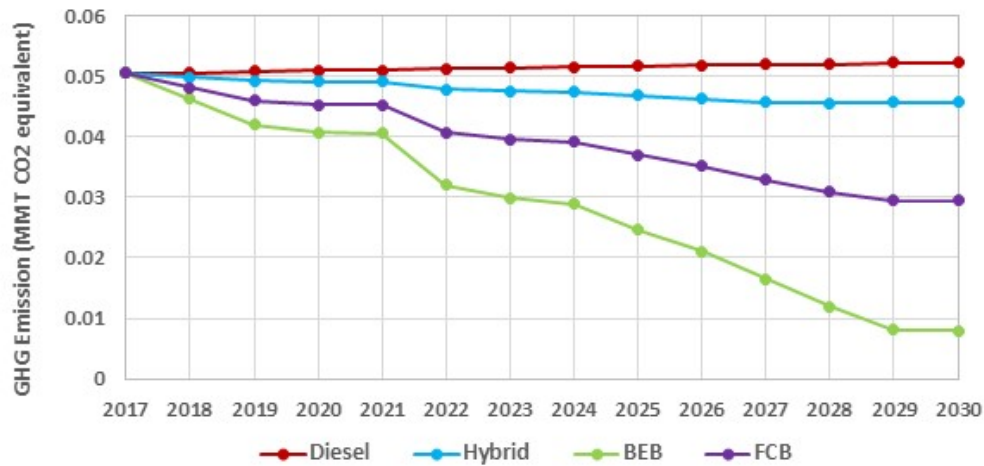
- 2030 Transit Ridership = 3%
- 2030 Fleet Size = 554
- LDV VMT = 19.6 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

Context: This scenario represents a flat or declining transit ridership and flat light duty vehicle VMT. Transit's share of GHG is an increasingly smaller piece of a shrinking footprint. Although transit ridership is flat, this scenario is mildly optimistic in terms of LDV VMT reduction.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO ₂ e)	GHG Reduction (MMT CO ₂ e)	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	0.67	0.00	539	N/A
BEB	0.35	0.32	627	275
FCB	0.50	0.17	1,123	3,435
Diesel Hybrid	0.62	0.05	622	1,660

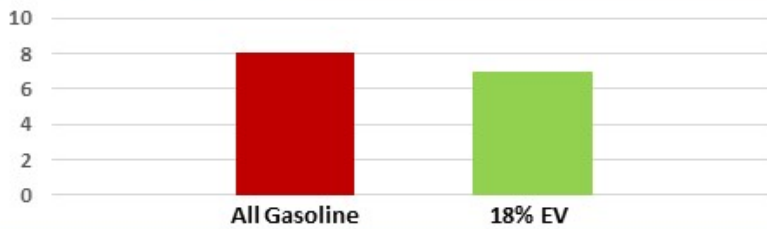
Scenario #3

Assumptions

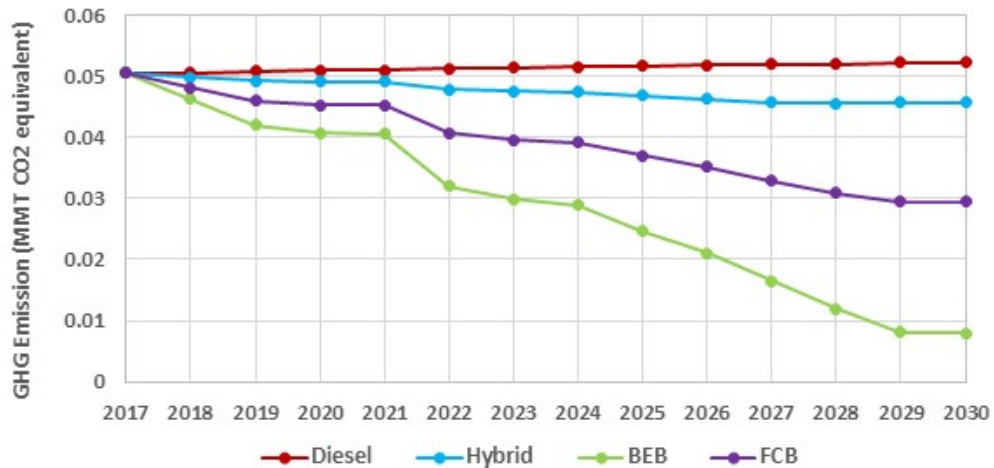
- 2030 Transit Ridership = 3%
- 2030 Fleet Size = 554
- LDV VMT = 18.2 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

Context: This scenario represents a flat or declining transit ridership and a 3% decrease in Light duty vehicle VMT. Transit's share of GHG is an increasingly smaller piece of a shrinking footprint. This scenario is very optimistic in terms of LDV VMT reduction.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO ₂ e)	GHG Reduction (MMT CO ₂ e)	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	0.67	0.00	539	N/A
BEB	0.35	0.32	627	275
FCB	0.50	0.17	1,123	3,435
Diesel Hybrid	0.62	0.05	622	1,660

Scenario #4

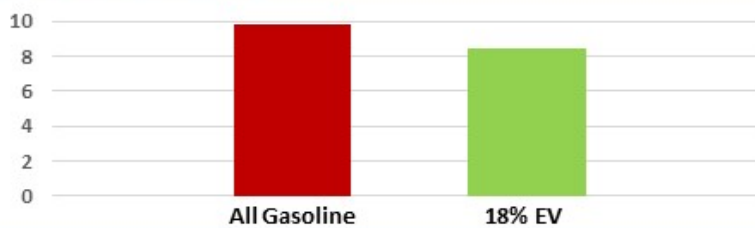
Assumptions

- 2030 Transit Ridership = 7%
- 2030 Fleet Size = 895
- LDV VMT = 22.1 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

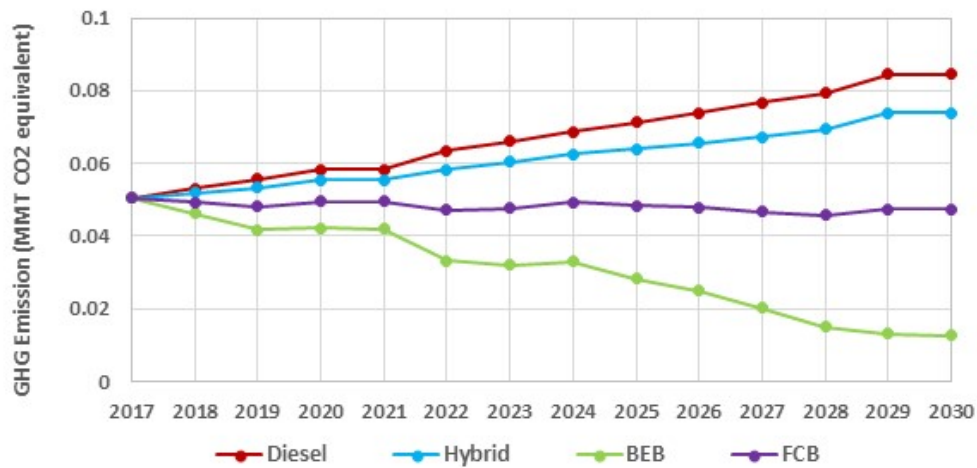
Context:

This scenario represents an increase in transit ridership by 4% to 7% by 2030 and a rapid rise in light duty vehicle VMT. Transit’s share of GHG increases slightly in a growing footprint. This scenario is moderate from a transit perspective and pessimistic from an LDV VMT perspective.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO _{2e})	GHG Reduction (MMT CO _{2e})	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	0.89	0.00	790	N/A
BEB	0.38	0.51	937	288
FCB	0.62	0.27	1,738	3,511
Diesel Hybrid	0.81	0.08	926	1,700

Scenario #5

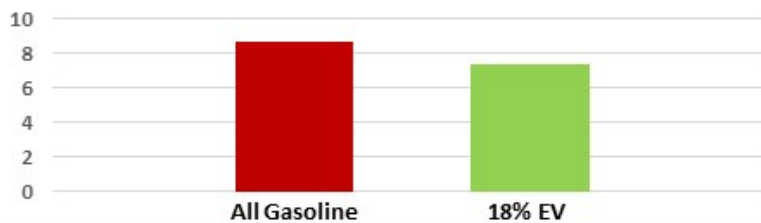
Assumptions

- 2030 Transit Ridership = 7%
- 2030 Fleet Size = 895
- LDV VMT = 19.6 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

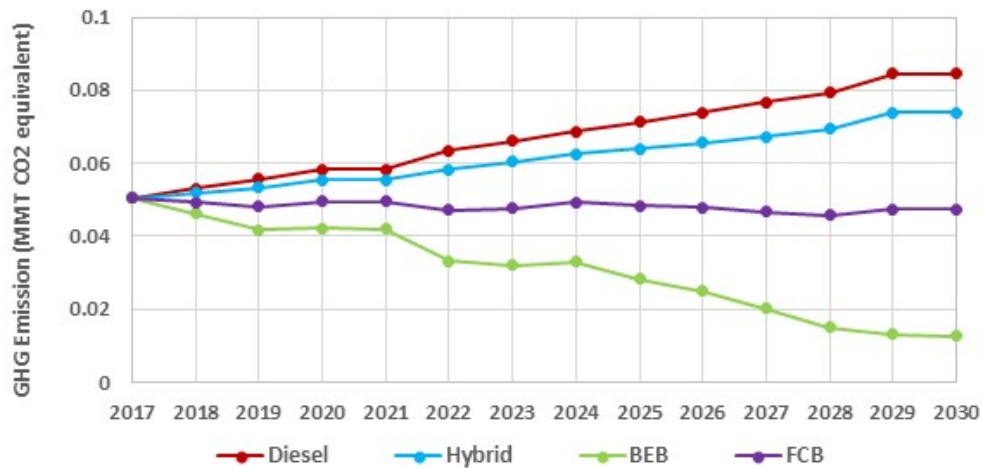
Context:

This scenario represents an increase in transit ridership by 4% and no rise in light duty vehicle VMT. Transit's share of GHG increases slightly in a shrinking footprint. This scenario is moderate from both perspectives and is the basis for sensitivity analysis.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO _{2e})	GHG Reduction (MMT CO _{2e})	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	0.89	0.00	790	N/A
BEB	0.38	0.51	937	288
FCB	0.62	0.27	1,738	3,511
Diesel Hybrid	0.81	0.08	926	1,700

Scenario #6

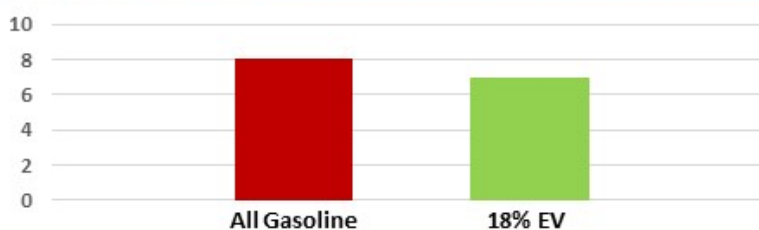
Assumptions

- 2030 Transit Ridership = 7%
- 2030 Fleet Size = 895
- LDV VMT = 18.2 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

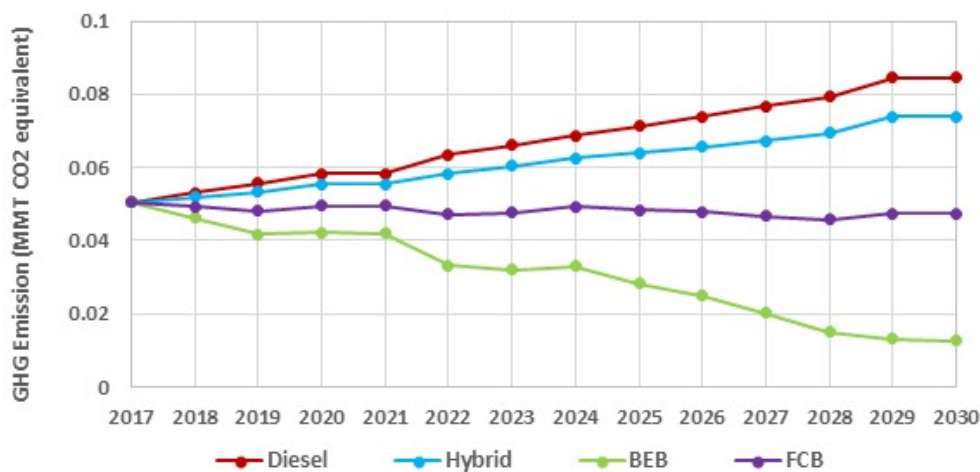
Context:

This scenario represents an increase in transit ridership by 4% and a 3% decrease in light duty vehicle VMT. Transit's share of GHG increases within an overall shrinking transportation GHG footprint. This scenario is moderate in terms of transit and optimistic from the LDV VMT perspective.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO ₂ e)	GHG Reduction (MMT CO ₂ e)	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	0.89	0.00	790	N/A
BEB	0.38	0.51	937	288
FCB	0.62	0.27	1,738	3,511
Diesel Hybrid	0.81	0.08	926	1,700

Scenario #7

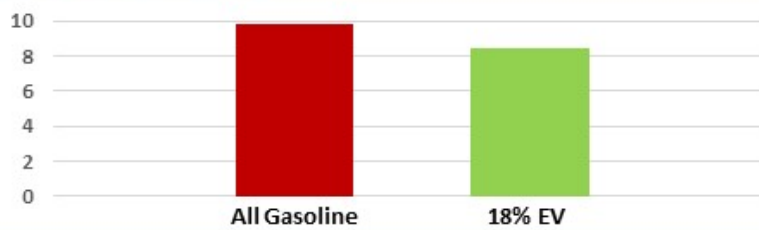
Assumptions

- 2030 Transit Ridership = 10%
- 2030 Fleet Size = 1150
- LDV VMT = 22.1 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

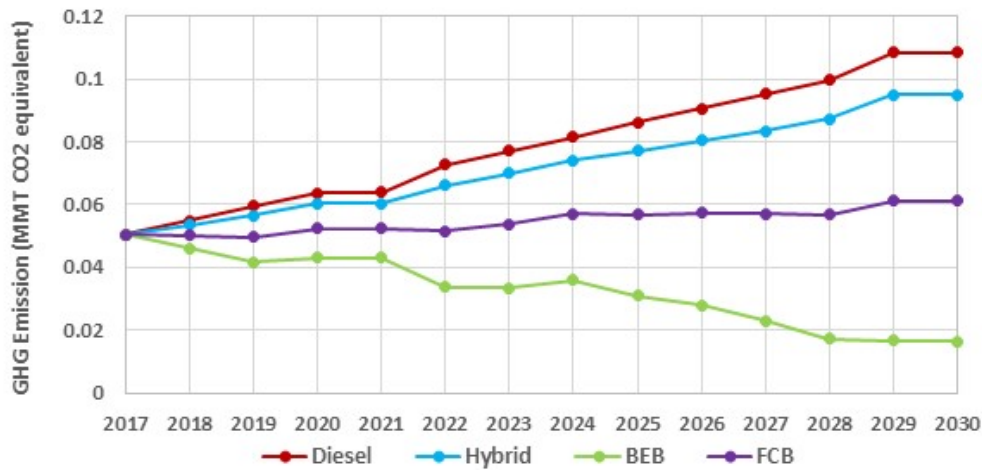
Context:

This scenario represents an increase in transit ridership by 7% to 10% by 2030 and a rapid rise in light duty vehicle VMT. Transit's share of GHG increases in a flat overall transportation GHG footprint. This scenario is very optimistic from a transit ridership perspective.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO ₂ e)	GHG Reduction (MMT CO ₂ e)	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	1.06	0.00	977	N/A
BEB	0.41	0.65	1,167	292
FCB	0.65	0.42	2,199	2,910
Diesel Hybrid	0.99	0.08	1,154	2,213

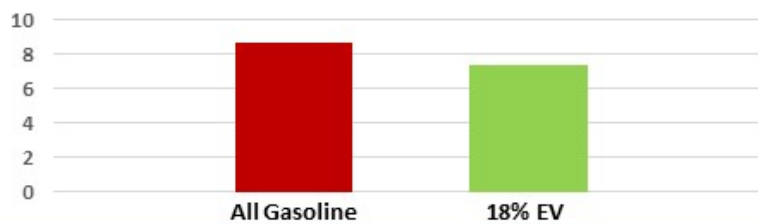
Scenario #8

Assumptions

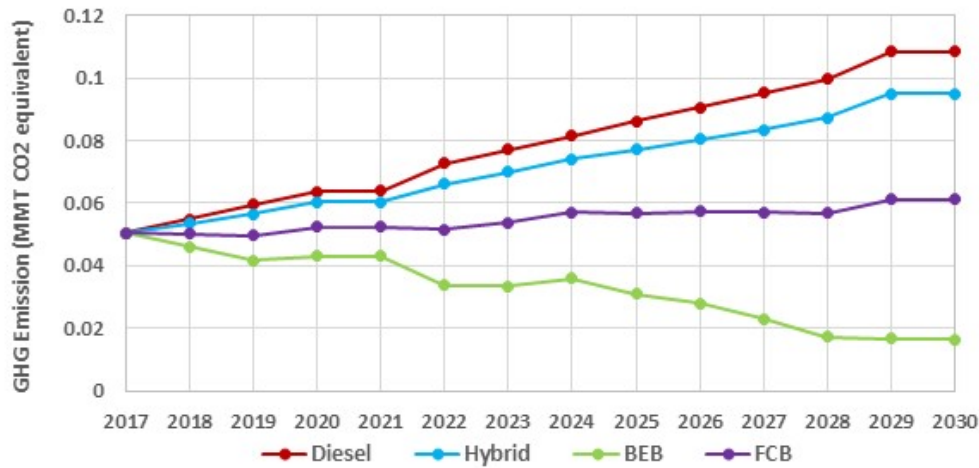
- 2030 Transit Ridership = 10%
- 2030 Fleet Size = 1150
- LDV VMT = 19.6 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

Context: This scenario represents an increase in transit ridership of 7% to 10% by 2030 and no rise in light duty vehicle VMT. Transit’s share of GHG increases in a shrinking overall transportation GHG footprint. This scenario is very optimistic in terms of transit ridership and moderate for LDV VMT.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO ₂ e)	GHG Reduction (MMT CO ₂ e)	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	1.06	0.00	977	N/A
BEB	0.41	0.65	1,167	292
FCB	0.65	0.42	2,199	2,910
Diesel Hybrid	0.99	0.08	1,154	2,213

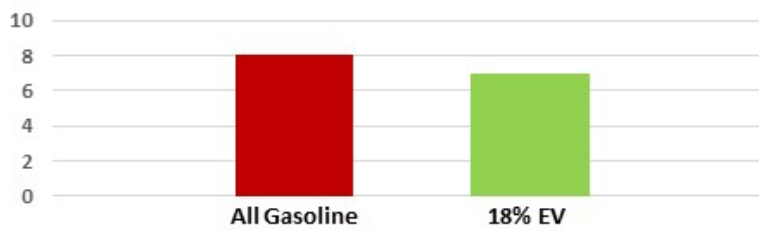
Scenario #9

Assumptions

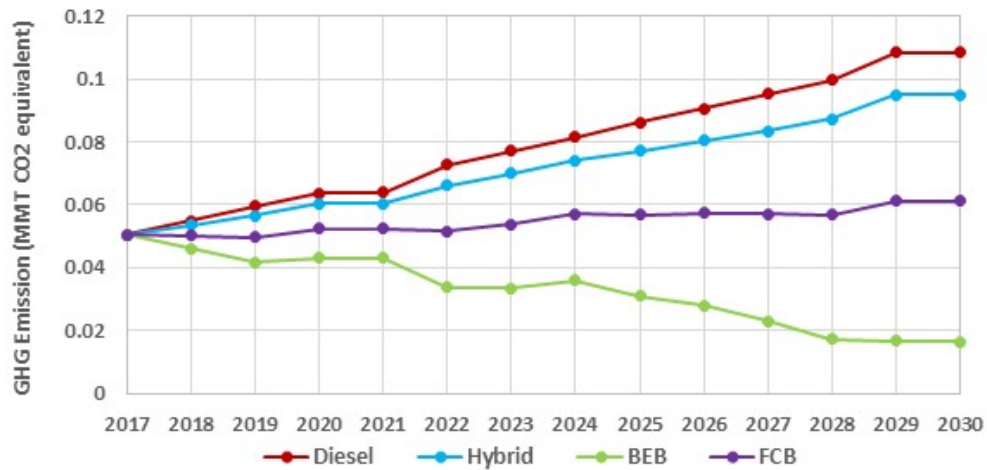
- 2030 Transit Ridership = 10%
- 2030 Fleet Size = 1150
- LDV VMT = 18.2 billion
- 2030 LDV Electrification = 18%
- CT % Renewables = 30%
- Existing Fleet Turnover Schedule

Context: This scenario represents an increase in transit ridership of 7% and 3% decrease in light duty vehicle VMT. Transit's share of GHG increases in a shrinking transportation GHG footprint. This scenario is the most optimistic both in terms of transit and LDV VMT.

2030 CT LDV GHG Emissions



Fuel Technology GHG Profile



Fuel Technology	Total GHG (MMT CO ₂ e)	GHG Reduction (MMT CO ₂ e)	Total LCC (\$ millions)	Additional LCC/ton GHG Reduction (\$/MT)
Diesel Bus	1.06	0.00	977	N/A
BEB	0.41	0.65	1,167	292
FCB	0.65	0.42	2,199	2,910
Diesel Hybrid	0.99	0.08	1,154	2,213

APPENDIX I

STUDY COMMITTEE MEETINGS AND GUEST SPEAKERS

The following is a list of study committee meetings, including presentations given to the CASE study committee by guest speakers and the CASE Research Team. In the electronic version of this report, links to meeting proceedings are highlighted in blue.

NOVEMBER 14, 2016 – MEETING 1

- **Welcome and Introductions**, Richard H. Strauss, Executive Director, CASE
- **Guest Speaker - [Presentation](#)**
Jen McGraw, Sustainability Strategist, Center for Neighborhood Technology
Topic: Low Carbon Transit, Transit Efficiency in 2030 and 2050
- **CTDOT Speaker**, Richard Andreski, Bureau Chief, Public Transportation
- **Research Team - [Presentation](#)**
Nick Lownes, *Study Manager*, UTC Associate Professor In Engineering Innovation; Associate Head & CE Graduate Program Director, Department of Civil & Environmental Engineering, UConn
- **Next Steps**

DECEMBER 12, 2016 – MEETING 2

- **Guest Speaker - [Presentation](#)**
Carol Atkinson-Palombo, PhD, Associate Professor, Department of Geography, UConn
Topic: Measuring Transportation Sustainability
- **Study Committee Speaker - [Presentation](#)**
Ray Necci, Consultant; Former President and COO, CL&P
Topic: Overview of CASE Energy Efficiency and Reliability Rail Operations and Facilities Study Report
- **Research Team**, Nick Lownes, *Study Manager*
Topic: Review Changes to Scope of Work and Work Plan Progress
- **Next Steps**

JANUARY 27, 2017 – MEETING 3

- **Guest Speaker - [Presentation](#)**
Kelli Hoell, Transportation Development Planner, Lane Transit District, Eugene, OR
Topic: Lane Transit Sustainability Strategy/Electric Buses
- **Guest Speaker - [Presentation](#)**
Robert J. Johnston, PhD, Director, George Perkins Marsh Institute; Professor, Department of Economics, Clark University
Topic: Considerations in Environmental Benefits Analysis for Transit Projects
- **Research Team Update - [Presentation](#)**
Nick Lownes, PhD, *Study Manager*
- **Next Steps**

FEBRUARY 27, 2017 – MEETING 4

- **Guest Speaker – Presentation**
Brianne Mullen, Urban Sustainability Program Associate Yale Office of Sustainability
Topic: Yale Sustainability Plan 2025
- **Guest Speaker – Presentation**
Douglas Hausladen, Director, Transportation, Traffic & Parking, City of New Haven
Topic: Sustainability Strategies, Working Together in #NHV
- **Research Team Update – Presentation**
Nick Lownes, *Study Manager*
- **Guest Speaker – Presentation**
Bill Laborde, Chief Policy Advisor, Seattle Department of Transportation
Topic: City of Seattle Climate Action Plan, Transportation Strategies
- **Research Team Update – See above**
Jeffrey Cohen, *Research Team*, Associate Professor, Real Estate and Finance, Center for Real Estate, UConn
- **Next Steps**

MARCH 22, 2017 – MEETING 5

- **APTA Guest Speakers – Hiott Presentation; Teschauer Presentation**
Jeff Hiott, Director, Operations & Standards, *Topic: Trending to Zero – North America’s Bus Industry Move to Zero Emissions*
Mark Teschauer, Program Manager, Environment and Infrastructure
Topic: Draft Update to APTA Recommended Practice on Quantifying Greenhouse Gas Emissions from Transit
- **Committee Member Speaker – Presentation**
Tom Maloney, Chief Technology Officer, CCAT
Topic: Counting CO₂ Molecules and Other Greenhouse Gases
- **Literature Review & Research Team Update – Lownes Presentation; Cohen Presentation**
Nick Lownes, *Study Manager*; Jeff Cohen, *Research Team*
- **Next Steps**

APRIL 21, 2017 – MEETING 6

- **Argonne Guest Speakers – Presentation**
Amgad Elgowainy, Principal Energy Systems Analyst, Life-Cycle Analysis Team Lead and Jeongwoo Han, Energy Systems Analyst, Argonne National Laboratory, Energy Systems Division
Topic: GREET® Fuel and Vehicle Cycle Models, and Carbon Footprint Calculator
- **Study Advisor – Presentation**
Dave Pines, *Study Advisor*, Professor/Civil and Environmental Engineering, University of Hartford
Topic: Battery Electric Bus Procurement Guidelines
- **Research Team Update – Presentation**
Nick Lownes, *Study Manager*
- **Next Steps**

MAY 19, 2017 – MEETING 7

- **Guest Speaker – Presentation**
Peter Melin, PE, Project Director, Zero-emission Fleet Technologies, Metro Transit,
King County, WA
Topic: Transitioning to a Zero Emission Fleet
- **Guest Speakers – Presentation**
Vermont Energy Investment Corporation, Bethany Whitaker, Senior Consultant;
Michelle McCutcheon-Schour, Senior Transportation Analyst
Topic: Electrifying Transit
- **Research Team Update – Presentation**
Nick Lownes, *Study Manager*; Jeff Cohen, *Research Team*
- **Next Steps**

JULY 14, 2017 – MEETING 8

- **Speaker, DEEP Study Contact Speaker – Presentation**
Keri Enright-Kato, Director, Office of Climate Change, Technology & Research
- **Guest Speaker – Presentation**
Joel Rinebold, Director of Energy Initiatives, Connecticut Center for Advanced
Technology, Inc.
- **Guest Speaker – Presentation**
Jaimie Levin, Senior Project Manager, Director of West Coast Operations, Center for
Transportation and the Environment
- **Research Team Update – Presentation**
Nick Lownes, *Study Manager*
- **Next Steps**

AUGUST 31, 2017 – MEETING 9

- **Research Team Update – Presentation**
Nick Lownes, *Study Manager*
- **Brainstorming Findings and Recommendations – Committee Discussion**

MAJOR STUDIES OF THE ACADEMY

2017

- Innovative Technology Deployment: Development of a Virtual Screening Facility Pilot Project for Connecticut's Commercial Vehicle Enforcement Program

2016

- Strategies for Improving Transportation Project Delivery Performance
- Early Childhood Regression Discontinuity Study
- Connecticut Disparity Study: Phase 3

2015

- Winter Highway Maintenance Operations: Connecticut
- Addressing Family Violence in Connecticut: Strategies, Tactics and Policies
- Shared Clean Energy Facilities

2014

- Methods to Measure Phosphorus and Make Future Predictions
- Energy Efficiency and Reliability Solutions for Rail Operations and Facilities
- Connecticut Biomedical Research Program: Analysis of Key Accomplishments
- Connecticut Disparity Study: Phase 2
- Peer Review of a CL&P/UConn Report Concerning Emergency Preparedness and Response at Selective Critical Facilities

2013

- Analyzing the Economic Impacts of Transportation Projects
- Health Impact Assessments Study
- Connecticut Disparity Study: Phase I
- Connecticut Stem Cell Research Program Accomplishments

2012

- Strategies for Evaluating the Effectiveness of Programs and Resources for Assuring Connecticut's Skilled Workforce Meets the Needs of Business and Industry Today and in the Future

- Benchmarking Connecticut's Transportation Infrastructure Capital Program with Other States
- Alternative Methods for Safety Analysis and Intervention for Contracting Commercial Vehicles and Drivers in Connecticut

2011

- Guidelines for the Development of a Strategic Plan for Accessibility to and Adoption of Broadband Services in Connecticut
- Advances in Nuclear Power Technology

2010

- Environmental Mitigation Alternatives for Transportation Projects in Connecticut
- The Design-Build Contracting Methodology for Transportation Projects: A Review of Practice and Evaluation for Connecticut Applications
- Peer Review of an Evaluation of the Health and Environmental Impacts Associated with Synthetic Turf Playing Fields

2009

- A Study of the Feasibility of Utilizing Waste Heat from Central Electric Power Generating Stations and Potential Applications
- Independent Monitor Report: Implementation of the UCHC Study Recommendations

2008

- Preparing for Connecticut's Energy Future
- Applying Transportation Asset Management in Connecticut
- A Study of Weigh and Inspection Station Technologies
- A Needs-Based Analysis of the University of Connecticut Health Center Facilities Plan

2007

- A Study of the Feasibility of Utilizing Fuel Cells to Generate Power for the New Haven Rail Line
- Guidelines for Developing a Strategic Plan for Connecticut's Stem Cell Research Program

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CONNECTICUT ACADEMY OF SCIENCE AND ENGINEERING

The Connecticut Academy is a non-profit institution patterned after the National Academy of Sciences to identify and study issues and technological advancements that are or should be of concern to the state of Connecticut. It was founded in 1976 by Special Act of the Connecticut General Assembly.

VISION

The Connecticut Academy will foster an environment in Connecticut where scientific and technological creativity can thrive and contribute to Connecticut becoming a leading place in the country to live, work and produce for all its citizens, who will continue to enjoy economic well-being and a high quality of life.

MISSION STATEMENT

The Connecticut Academy will provide expert guidance on science and technology to the people and to the State of Connecticut, and promote its application to human welfare and economic well-being.

GOALS

- Provide information and advice on science and technology to the government, industry and people of Connecticut.
- Initiate activities that foster science and engineering education of the highest quality, and promote interest in science and engineering on the part of the public, especially young people.
- Provide opportunities for both specialized and interdisciplinary discourse among its own members, members of the broader technical community, and the community at large.

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