Accelerating Bus Electrification:
Enabling a sustainable transition to low carbon transportation systems

by

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Submitted to the Department of Urban Studies and Planning
in partial fulfillment of the requirements for the degrees of

Master in City Planning
and
Master of Science in Transportation
at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2018

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Abstract

Submitted to the Department of Urban Studies and Planning on December 14, 2017 in partial fulfillment of the requirements for the degrees of Master of City Planning and Master of Science in Transportation

With growing agreement that credible pathways to zero carbon electricity exist, many support the notion that widespread electrification of the transportation sector will be an essential strategy for meeting scientifically-based midcentury climate goals. While transit buses have a relatively small impact on greenhouse gas emissions, they have a larger impact on urban air quality, have commercially available in-service electric models, and have historically commercialized clean technologies that enabled deployment in the rest of the heavy duty vehicle sector. This thesis seeks to understand what factors hinder or enable transit agencies to go beyond initial pilots to largely or wholly electrify their fleets, with the goal of understanding potential policies and strategies that could accelerate such a transition, without inhibiting existing or expanded transit service that also plays a key role in reducing carbon emissions, in order to improve local air pollution and support accelerated electrification of trucks and other heavy duty vehicles.

Using public transit fleets in California, Kentucky, and Massachusetts as case studies, this thesis utilizes quantitative total cost of ownership and well-to-wheels greenhouse gas and air pollutant emissions analysis, and analysis of qualitative interviews with transit agency representatives to investigate the barriers, drivers, and potential solutions that could hinder or enable an accelerated yet sustainable transition to an electrified bus fleet. A total cost of ownership analysis reveals that electric buses may already be more cost effective than diesel buses in many case study utility service areas primarily due to fuel and maintenance cost savings, but are sensitive to key parameters such as annual mileage, electricity tariffs that vary widely by location, fossil fuel costs, policy context, and anticipated maintenance savings, and that cost savings from electric buses are likely to increase over time primarily due to anticipated reductions in battery costs and a faster increase in fossil fuel prices than electricity prices.

While multiple agencies interviewed in California were planning to fully electrify their fleets, primarily due to political pressure and internal leadership, outside California where less supportive policies exist, fewer agencies were planning to procure additional electric buses, primarily due to high first cost and undesirable tradeoffs with maintaining or expanding transit service levels. Interview respondents reported other substantial barriers as well, such as oversubscribed discretionary grant programs, charging infrastructure costs, electricity costs, additional operational complexity, and performance uncertainty and risk, suggesting a need for multiple complementary policies to overcome these barriers and ensure agencies can transition to a new technology without impacting service. Important interventions identified include pursuing favorable electricity tariffs and electric charging infrastructure incentives through regulatory changes, and further leveraging limited public funds such as the Volkswagen settlement to develop low cost financing approaches similar to those utilized in the clean energy sector that can pledge anticipated operating savings to afford the incremental upfront cost. A set of complementary policies is then recommended to accelerate bus fleet electrification in each case study context, in order to achieve carbon reduction and air quality improvements for low income, urban communities without impacting transit service levels, and to help lead the way for the transition of other heavy duty fleets.

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Acknowledgements

To my advisor, Fred Salvucci, thank you for pushing me even in the last hours to make this thesis better, for encouraging me throughout my time at MIT, and for the opportunity to be your TA. I'm grateful to have gotten to spend most Friday afternoons these past few years drinking coffee, listening to your stories and jokes, and learning from your principled, politically strategic, technically smart approach to complex transportation problems that you've applied in your career. To my reader John Attanucci, thank you for lending your experience as a transit professional to provide really insightful and critical feedback on the modeling work in particular, as well as the entire thesis. To my reader and RA advisor Chris Zegras, thank you for your invaluable help in honing my research design, and for the incredibly interesting and educational experience of being part of the CoAXs team. And thank you especially to Harvey Michaels for lending your experience and expertise in the electricity sector to strengthen that aspect of my thesis.

I'm also grateful to have had wonderful collaborators and supporters on this thesis outside of MIT, and want to express my thanks all those who I interviewed or had background conversations with for their time. Thank you in particular to Holmes Hummel of Clean Energy Works who reviewed drafts and offered excellent feedback and insights to guide my research approach, and connected me with key stakeholders in each case study. Thank you especially to the advocates, transit agency staff, and other stakeholders I had a chance to interact with from the Union of Concerned Scientists, Greenlining Institute, Jobs to Move America, Kentuckians for the Commonwealth, the Sierra Club, and others who are doing inspiring work to advance a just, sustainable transition to electric bus and other vehicle fleets.

To the DUSP and MST staff including Sandy Wellford, Ellen Rushman, Duncan Kincaid, Ruth Yiu, and others, thank you for helping me and so many others navigate the thesis process and MIT experience. To my academic advisor, Ezra Glenn, thank you for your encouragement, as well as for lending your support to our efforts for graduate housing. To the professors at MIT who made me work harder, think harder, and learn more than at any other time in my life, thank you, including Ignacio Pérez-Arriaga, Justin Steil, Phil Thompson, Jinhua Zhao, Karl Seidman, Carolina Osorio, and many others.

To the many wonderful friends I met through DUSP and the MST, thank you for continuing to inspire me through your hard work, creative ideas, and pursuit of justice, including the Undercommons crew, the Graduate Student Apartments Now (GSAN) team, and many more. And thank you to my problem set companions in Econ (Rachel, Insiyah, and Sam) and the MST core courses (Ari and Eli), who made some tough classes a joy and a real learning experience. To the CoAXs team, I'm grateful to have learned so much from working with you and from such an interesting, complex research project.

350.org friends – Jamie, Jeremy, Jon, May, Phil, Will, Bill, Anna, Jason, and many more – thank you for never letting me forget the urgency of the climate crisis, and for providing such inspiration to keep working harder to give what I can to the climate movement. Coalition for Smarter Growth and Montgomery County friends – Stewart, Cheryl, Alex, Aimee, Casey, David, Dan, and many more – thank you for providing me with a grounding in the practice and politics of planning, I can't say how well that's served me in providing me a compass to navigate my grad school experience and beyond.

To my family, thank you for supporting me in this educational pursuit and for understanding when I didn't return phone calls in a timely manner. To Max, it's an understatement to say I couldn't have done this without you. Thank you for coming with me to Boston, for believing in me when I struggled to believe in myself, for just being there with me through this experience. I'm so glad you've found such intellectual engagement here in Boston, and I can't wait to support your next steps now.

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1. Introduction

1.1 Motivation and purpose

In 2014, the Intergovernmental Panel on Climate Change reported that without action, greenhouse gas emissions from the transportation sector are likely to double by 2050 (Pyper 2014). Meanwhile, transportation surpassed electricity as the top emitting sector in the United States in 2016 for the first time since the 1970s (Plumer 2016). As emissions from the electricity grid have decreased dramatically in recent years due to a combination of natural gas edging out coal and policy efforts, a consensus amongst climate and energy experts termed “environmentally beneficial electrification” has emerged that “meeting aggressive GHG reduction goals will require electrification of end uses such as space heating, water heating, and transportation.” (Dennis, Colburn, & Lazar, 2016). Researchers have projected multiple credible pathways to achieving 80% cuts in emissions by 2050, all of which rely heavily upon the electrification of the transportation sector (D. J. H. Williams et al., 2015).

This thesis is motivated by the urgency of the climate crisis, and seeks to illuminate equitable pathways for accelerating decarbonization of the transportation sector. Inspired by the incredible growth in investment in renewable energy and energy efficiency in recent years, this thesis at a high level seeks to understand what it would take to address barriers through policy interventions and other strategies in order to accelerate electrification of a small portion of the transportation sector, transit buses. Through in-depth, mixed-methods case studies of a single vehicle class across different contexts, this thesis provides an example for studying the barriers and drivers affecting fleet managers’ decisions to invest in electric vehicles, and identifying solutions to support adoption.

Transit buses were selected as the focus of this research because 1) there are commercially available models that multiple researchers estimate are cost competitive on a total cost of ownership basis; 2) electrifying transit fleets represents an important way to ensure the benefits of public investment in transportation electrification reaches low income, transit-dependent communities most impacted by mobile source air pollution; and 3) transit buses previously have served as a test case in driving clean technology adoption in the heavy duty vehicle sector, which accounts for a large share of mobile source emissions in comparison with the number of vehicles on the road due to their typically lower fuel economy and higher utilization. For these reasons, understanding what it would take to electrify the nation’s transit fleets seemed a worthy effort that could provide valuable insights for accelerating electrification of other fleets.

While transportation electrification appears to be the most likely, rapid way to reduce emissions from the transportation sector, it is clearly not the only nor the optimal pathway. While many decarbonization pathways do not rely upon shifting travel behavior, most acknowledge that such strategies would importantly reduce the demand for electricity, not to mention the numerous health and fiscal co-benefits for communities of investment in smart growth and sustainable transportation options. Transit buses are unique amongst other vehicle fleets in that, while they directly emit air pollutants and greenhouse gas emissions, they indirectly reduce emissions through supporting land use and travel behavior that enables transit-oriented communities to rely less on private vehicles. Buses in particular are the foundation of public transit systems throughout the United States, and the expansion and improvement of bus service is an essential component of strategies to reduce car reliance. As a result, this thesis also considers the impacts of transit service expansions, which pose financial challenges for public transit agencies as well as direct emissions challenges that must be met. Because of transit’s indirect climate benefits, as well as a history of transit agencies serving as guinea pigs for unproven technologies previously, this thesis attempts to inject a note of caution to regulators, government officials, and advocates to carefully consider how to support, rather than simply force, transit agencies to electrify, to avoid unintended consequences of adversely impacting existing and expanded transit service. This thesis instead focuses on strategic pathways that can help accelerate a successful transition to an electric bus fleet that can be replicated in other vehicle sectors and avoid lock-in to more procurements of fossil fuel buses by focusing on support for transit agencies to overcome barriers to electrification.

1.2 Research questions and methods

1.2.1 Research questions

To understand what it would take to electrify the nation's bus fleets, my primary research question asks: What factors increase or decrease the likelihood of public agency procurement of battery electric buses, as defined by total cost of ownership and lifecycle emissions analysis, as well as stated barriers and drivers, according to transit agencies across different contexts? In order to answer this, I investigate the following sub questions through the research methods outlined below:

1) How do lifecycle emissions and total cost of ownership for battery electric buses compare with conventional diesel, hybrid, and CNG vehicles across different contexts, and what factors are the most important in determining this variability?
2) What are the barriers and drivers influencing electric bus deployment that transit agency representatives report?
3) What are agencies' stated intentions to procure additional electric buses, and what are the primary reasons for their procurement decisions?

1.2.2 Methods

To answer these questions, this research uses both qualitative and quantitative methods to study three case studies in Kentucky, California, and Massachusetts in order to assess what factors influence deployment of electric buses. Robert Yin suggests case studies are useful research designs when studying a contemporary issue unfolding in a real-life context, when "the boundaries between phenomenon and context are not clearly evident", and when answering a "how" or "why" question (Yin, 1981). Because electric bus adoption is a current issue, in which I suspected the context might matter but was unsure to what extent, and wanted to understand the underlying factors driving *why* agencies are choosing to invest in electric buses, case studies seemed to be an appropriate approach.

Cases were selected amongst states where multiple public transit fleets are already operating electric buses, and therefore may be more likely to consider larger scale adoption, and that differ along other dimensions I hypothesized would affect electric bus diffusion, such as environmental policy, political, and electricity sector context. California is often the national leader in environmental policy, which has also been true in the case of electric bus deployment, having implemented a wide variety of complementary policies and programs designed to accelerate transportation electrification. Massachusetts often follows close behind California, and has similar climate and clean transportation policies, though has generally far fewer incentives and supportive policies designed to support electric bus deployment, and so offers a counter example to California. Finally, Kentucky represents a much more conservative political and policy context than either Massachusetts or California, which is likely similar to the context for many bus fleets operating in small and medium sized communities, in which very few state or local supportive policies exist and agencies must rely on federal funds and often minimal local funds. The differences in policy and political contexts relevant to electric bus diffusion is further elaborated in Chapter 4.

Gaber and Gaber recommend applying mixed methods to planning research in order to understand the complexity and nuance of many planning problems, and avoid "misdiagnosis of planning issues or misdirection of preferred solutions" (Gaber & Gaber, 1997). They suggest mixed methods can be used for a variety of purposes, including development, or to have one method inform another sequentially, and complementarity, or to "measure overlapping, as well as different, aspects of a phenomena in order to enrich the understanding of that phenomenon". Mixed methods served both purposes for this research, with insights from semi-structured interviews and qualitative analysis used to inform quantitative cost modeling, and both qualitative and quantitative methods used to understand different aspects of the same problem, as well as overlapping aspects from different perspectives. Robert Weiss in Learning from Strangers also highlights that interviews can be useful ways to bridge "intersubjectvities", or to help readers "grasp a situation from the inside"; given that I nor many policymakers have ever managed a bus fleet, understanding people's perspectives who do was a critical part of this research (Weiss, 1995).

Research methods designed to understand barriers and solutions to energy efficiency and clean energy investment also informed the methods of the case studies, based on an assumption that electric vehicle adoption may face similar challenges. Love and Cooper highlight the importance of understanding energy consumption from both a social and technical perspective (Love & Cooper, 2015):

> Research understanding energy consumption is usually approached from either an engineering or social science perspective. The result is either understanding technologies and materials or understanding people. Yet, energy consumption is clearly an interaction between people, materials and technologies. So understanding them with separate studies or data that miss this interaction fails to grasp the sociotechnical nature of energy consumption.

The mixed methods approach of this research was designed to understand the complex interaction between people, organizations, and technologies that interact to influence electric bus adoption decisions.

QUALITATIVE METHODS

The qualitative portion of this research involves different forms of data collection, including a review of relevant public policy affecting electric bus diffusion, analysis of public statements, documents, and data for each case, and semi-structured interviews with 14 transit fleet representatives across 12 transit agencies. A list of interviewees can be found in Section 4.2. Fleets were identified by whether they had procured (or were in the process of procuring) electric buses (though one Kentucky fleet without electric buses was added given the small number of Kentucky fleets), and individual participants were identified either through snowball sampling or cold e-mailing agencies. Given its small size, the sample cannot be considered representative of all transit fleets in the three case study states, but may provide an indication of the perspectives of early adopter agencies of electric buses across different contexts and factors that will likely impact other fleets. Additionally, the interviewees themselves do not fully represent the perspectives of their agencies, some of which are large and complex bureaucracies, since I mostly was only able to speak with one person per agency. In addition to the primary interviews, background conversations with stakeholders representing utilities, government sector, and non-profit actors engaged in work relevant to electric bus deployment were conducted in each state to better understand the policy context and other important factors impacting electric bus deployment, and were identified primarily through snowball sampling. A list of background interview organizations can be found in the Appendix. Interview notes or recordings were coded using qualitative analysis software to identify, categorize, and summarize key barriers and drivers across fleets, as well as to analyze individual agencies' decisions and rationales regarding whether to further electrify their fleets, which are summarized in Section 4.2.

QUANTITATIVE METHODS

The quantitative analysis portion of the case studies seeks to understand the economic and environmental costs and benefits affecting electric bus diffusion, and was actively informed by the insights gleaned from the qualitative analysis. The primary method utilized was the development of a total cost of ownership and well-to-wheels greenhouse gas emissions model to estimate electric bus capital costs, operating costs, and emissions impacts in comparison with other fuel types in different geographies, over different time scales. The model was developed based upon approaches from lifecycle cost and emissions models developed by federal labs and in academic literature, and data inputs systematically gathered for each key parameter that determines a bus's total cost of ownership, including public sources such as the National Transit Database (NTD), National Renewable Energy Laboratory (NREL) and other government studies, electricity tariff data, and manufacturers' or fleets' own data where possible. EPA MOVES and Argonne Labs' AFLEET models were utilized to estimate criteria pollutant emissions.

A sensitivity analysis was then conducted with the model to understand the relative importance of key parameters. The model was then applied to fleets across the three case studies varying limited inputs such as electricity tariff and capital and operating subsidies to understand how total cost of ownership varied across contexts. Additionally, I had the opportunity to complete a fellowship at the Massachusetts Bay Transportation Authority (MBTA) working on their Integrated Fleet and Facilities Planning process, which informed a more detailed analysis of the total cost of ownership and lifecycle emissions impacts of different bus technology and fleet expansion scenarios, the results of which are included in Chapter 5.

SYNTHESIS OF SOLUTIONS

The case studies conclude by synthesizing the results of the qualitative and quantitative analysis to inform recommended strategies for different stakeholders to enact to accelerate electric bus deployment in each case study state. Solutions are identified based on reported effectiveness of existing policies and strategies by interviewees, ideas from interviewees and other stakeholders, and from adapting successful clean energy sector policy interventions to electric bus deployment, in order to systematically attempt to identify sets of complementary strategies that can address the multiple barriers facing agencies transitioning their fleets to electric buses.

1.3 Thesis structure

The remainder of this thesis is structured as follows:

- **Chapter 2** includes background research and a literature review of climate change mitigation strategies in the transportation sector, lessons from the "energy efficiency gap" and adoption of clean energy technologies, and the potential for heavy duty electric vehicle deployment.
- **Chapter 3** outlines the data, assumptions, and approach to the total cost of ownership and well-to-wheels emissions model designed to analyze the cost and emissions benefits and tradeoffs with other bus technologies, and conducts a sensitivity analysis to understand the key drivers of total cost of ownership savings for battery electric buses in comparison with conventional buses.
- **Chapter 4** introduces the three case studies in California, Kentucky, and Massachusetts, and conducts a qualitative analysis of the reported barriers and drivers of electric bus deployment.
- **Chapter 5** presents a quantitative analysis of the estimated total cost of ownership across the case study contexts, as well as a more in-depth case study of the MBTA.
- **Chapter 6** synthesizes the findings from the qualitative and quantitative analysis to recommend policies and strategies that could be adopted to support electric bus adoption.
- **Chapter 7** concludes with a summary of the findings of this research, areas for future research, and a final discussion and conclusion.

2. Background: Emissions reduction in the energy and transportation sectors

2.1 Climate change mitigation in the transportation sector

This section summarizes the literature addressing strategies to reduce emissions from the transportation sector, with a particular focus on the emerging consensus around strategic electrification, and concludes with concerns, considerations, and approaches to ensure strategic electrification can be effective and equitable in the face of coming disruptions in the transportation sector.

2.1.1 History and present context of transportation emissions reduction strategies

Transportation mitigation literature tends to focus on similar sets of strategies for emissions reduction, principally technological change, pricing mechanisms, transit and smart growth strategies, and behavior change (Anable, Banister, & Schwanen, 2011). In some ways, these can be understood as two overarching pathways, with economic instruments, transit investments, and smart growth strategies aimed to enable more permanent behavioral and lifestyle shifts in which people drive less.

PRICING AND BEHAVIOR CHANGE STRATEGIES

While economists tend to champion congestion pricing, gas tax increases, and other pricing mechanisms as "first best" policies for minimizing the externalities of driving, such policies face daunting political challenges, and have been implemented in just a handful of cities worldwide. As with other sectors, transportation mitigation suffers from collective action and principal agent challenges in which costs are more concentrated than the long term benefit of a stable climate (Jenkins, 2014). For example, Jenkins finds that the range of potentially acceptable carbon prices in the United States is between 60% to two orders of magnitude lower than estimates of the full social cost of carbon (Ibid). The gas tax is an important corollary specific to the transportation sector: a recent poll found 66 percent of Americans oppose an increase in gasoline taxes of 25 cents per gallon even if revenues were used entirely to reduce the federal income tax (Leiserowitz et al., 2013). Other transportation behavior-shifting policy has faced similar political challenges: in recounting the experience of the EPA in enforcing air quality standards from 1970 to the early 2000s, Howitt and Altshuler conclude that any policies or mandates aimed at restricting personal travel behavior have proved to be thus far politically infeasible, as policies such as parking pricing, parking freezes, or even employer trip reduction programs inspired sharp political backlash (Howitt & Altshuler, 1999).

TRANSIT AND LAND USE STRATEGIES

Transit investment and transit-oriented development have tended to be somewhat more politically feasible strategies, and have been effective to the extent of enabling more sustainable travel options and lifestyles, though it has also proven difficult to increase transit investment and density, and such strategies may be less effective without reinforcing, less politically feasible driving restraining policies. Numerous researchers across multiple transit-served U.S. city contexts have identified a "transit leverage" or "transit land use multiplier" effect, in which the observed reduction of automobile travel is greater than the direct replacement of car travel by passenger miles of transit travel, on the order of 1.4 to 9 times the direct number of miles displaced by transit (American Public Transportation Association, 2009). Researchers hypothesize that transit enables greater density and land use mixes that in turn enable shorter or fewer auto trips, lower auto ownership, and more trips taken by walking, bicycling, or transit. As a result, strategies to increase transit service and non-auto mode share through transit investment and land use planning have been a key part of some climate strategies, notably California's SB375 law that incentivizes compact development and transit investment to address regional air quality and greenhouse gas emissions, though such strategies can be difficult to enforce and land use patterns are slow to change.

TECHNOLOGY STRATEGIES

Howitt and Altshuler note that "politically feasible auto technology mandates have proved quite cost effective relative to more controversial efforts to regulate personal behavior", which have been the primary mechanism used to regulate mobile source air pollution for decades under the Clean Air Act (CAA). These mandates have been effective, though contain critical flaws, notably their reliance on fleet average fuel economy, and their application to new vehicles only. In 2007, the *Massachusetts v. EPA* supreme court decision found the EPA also has the authority to regulate CO_2 emissions under the CAA, so when efforts towards national cap and trade legislation faltered in 2009, the Obama administration moved in this direction, using the EPA's authority under the CAA to promulgate new, stricter auto emissions standards, raising CAFE standards to 54 miles per gallon by 2025.

CONSENSUS ON A "TECHNOLOGY PATH" FOR TRANSPORT MITIGATION?

While researchers estimate the impact of new fuel economy standards on transportation emissions will be substantial (an estimated 50% reduction per mile for passenger vehicles), they nevertheless anticipate that it is insufficient to reach midcentury climate goals for the transportation sector (James McCarthy, 2016). Authors of the Deep Decarbonization reports estimate that the average fleet fuel economy of light duty vehicles would need to exceed 100 miles per gallon gasoline equivalent by 2050, and 80-95% of miles driven from gasoline would need to shift to electricity or hydrogen (D. J. H. Williams et al., 2015).

As battery prices have fallen precipitously, electric vehicles have become cost competitive, and the electric grid emissions intensity has dropped, a growing body of literature has suggested that a "technology path" of transportation electrification is both a viable and critical strategy for reducing emissions in line with 80% by 2050 goals (Dennis et al., 2016; J. H. Williams et al., 2012). A survey of multiple decarbonization pathways concluded that the studies "overwhelmingly focus on electrification of transport, principally by means of electric vehicles and plug-in hybrid electric vehicles, as the best way to decarbonize the sector." (Loftus, Cohen, Long, & Jenkins, 2015). These scenarios rely heavily on a near decarbonization of the electricity grid by 2050, which recent experience suggests may be feasible if trends continue. Between 2003 and 2013, national electricity emissions intensity (unit of emissions per unit of electricity produced) fell 15%, while some regions such as the northeast fell by 40% (Alexander, 2015). Researchers have also suggested electric vehicles can be a win-win for utilities, by better utilizing utility assets through more off-peak electricity sales, which can also put downward pressure on electricity rates (Plug In America, 2016). Additionally, there is already a greater amount of battery storage deployed in electric vehicles than as stationary storage, presenting enormous potential for in-service or used electric vehicle batteries to support renewable energy integration.

Overall, transportation electrification appears to be an essential strategy for meeting midcentury climate goals that may have important co-benefits for the electricity grid; however, the rate of adoption of electric vehicles thus far is still far below what is required to meet those ambitious pathways, and other researchers suggest that electrification alone may not be sufficient.

IS ELECTRIFICATION ALONE SUFFICIENT FOR A JUST CLIMATE AND TRANSPORTATION FUTURE?

While this "technology path" has historically been more politically acceptable due to its focus on a more limited set of corporate stakeholders, some experts believe that focusing on electrification alone may not be sufficient or desirable for meeting midcentury climate goals, particularly as new trends like shared mobility and automation begin to change the transportation sector.

Some proponents of electrification do not believe there is a need to reduce per capita vehicle miles traveled (VMT), though they acknowledge reduced VMT would lessen the requirements of increased renewable energy deployment to serve new transportation load (D. J. H. Williams et al., 2015). The decarbonization literature also tends not to address the potential for increased VMT in the future; the EIA projects that due to slow turnover in the vehicle fleet and growth in VMT, light duty emissions will be reduced just 20% by 2030 rather than the full 50% per mile reductions established by the CAFE standards (James McCarthy, 2016). While some recent studies suggest personal VMT growth may have stabilized, commercial and heavy duty vehicle travel has continued to rise, and some researchers estimate VMT could more than double with the rise of autonomous vehicles (Wadud, 2016).

The UC Davis Institute of Transportation Studies and ITDP coined the phrase the "three revolutions" to describe the coming trends of electrification, automation, and shared mobility, with the last revolution also including "strong policies for urban planning that favor compact cities, walking, cycling, and public transport" (Fulton et al., 2017) Modeling the potential impacts and interactions of these three trends, the report estimates that automation alone would significantly increase emissions by 2050, while automation and electrification together would reduce emissions consistent with a 2-degree global rise in temperature, and all three trends together would dramatically decrease emissions consistent with a 1.5 degree global target (Fulton et al., 2017). Other researchers have reached similar conclusions with respect to the potential impact of automation, particularly without policies to guide implementation, "finding that automation might plausibly reduce road transport GHG emissions and energy use by nearly half – or nearly double them – depending on which effects come to dominate." (Wadud, 2016).

Additionally, researchers and advocates alike have questioned whether the focus on deployment of electric vehicles will help or hinder existing societal inequalities. Some have begun to notice that electric vehicle investment by the public sector thus far has primarily accrued to the wealthy, with some controversy surrounding such findings that since 2006, 90% of federal income tax credits for buying hybrid and electric vehicles went to the top income quintile of U.S. households (Borenstein et al., 2016). In California, researchers found that 83% of rebates for electric vehicles went to recipients with incomes over $100,000, and that black and Hispanic majority census tracks were less likely to receive rebates even when income was accounted for (St-Louis & Rubin, 2016). Since the data was published for that research, the state passed legislation that made wealthy households ineligible for rebates and increased rebate amounts for low and moderate income people (Ibid).

A JUST SUSTAINABILITY APPROACH TO TRANSPORT ELECTRIFICATION

In addition to privileging higher income drivers, some researchers and advocates have also stressed that the approach of simply replacing today's private vehicles with low emission ones fails to address the existing inequalities in access to a private vehicle and quality public transit for marginalized communities. Mullen and Marsden argue that "the existing policy approach which tries to tackle transport pollution primarily through a shift to low emission vehicles… privileges those with access to private vehicles" (Mullen & Marsden, 2016). As early as 2011, California environmental justice advocates at the Greenlining Institute were highlighting concerns as the state began investing in EVs that "many California communities – particularly communities of color – may get relatively little benefit from EVs, which are often seen as expensive and unattainable", and were stressing the importance of developing equitable approaches in partnership with disadvantaged communities to improve public transportation and create access to new jobs in zero emission vehicle manufacturing and deployment (Song, 2011).

Julian Aygeman has developed the concept of just sustainability, or "a better quality of life for all, now and into the future, in a just and equitable manner, whilst living within the limits of supporting ecosystems" that some researchers have used to consider a more just, equitable transportation future (Iles, 2013). Inspired by Aygeman's just sustainability concept, some researchers have sounded the alarm over the industry and technocrat-dominated discussions of our future transportation systems, and stressed the importance of community-informed, context-sensitive approaches to help "assure that everyone can benefit from less pollution, not only those with money. Without such institutional and political innovations, alternative fuels and technologies may not become sustainable substitutes for the oil-fueled system we have now" (Iles, 2013). The approach of this thesis strives to identify a just sustainability path forward for electrification, inspired by the advocates met through this research that are showing the way to more equitable electric vehicle deployment that seeks to clean up heavy duty fleets that impact public health, increase access to electrified public transport, and spur green job creation in the clean vehicle industry. Adger argues that sustainability policy decisions will be more context-sensitive and durable if we can "pay simultaneous attention to the four criteria that challenge the problem-solving capabilities of most decision makers concerned with environmental governance" (Adger et al., 2003). This thesis attempts to consider these perspectives in identifying solutions to accelerate electrification of public transit vehicles that can simultaneously satisfy these four criteria: efficiency (or cost effectiveness), effectiveness (the ability for the policy to achieve a desired outcome), equity (the distributional consequences of environmental decision-making), and legitimacy (or political acceptability).

2.2 Learning from clean energy adoption strategies

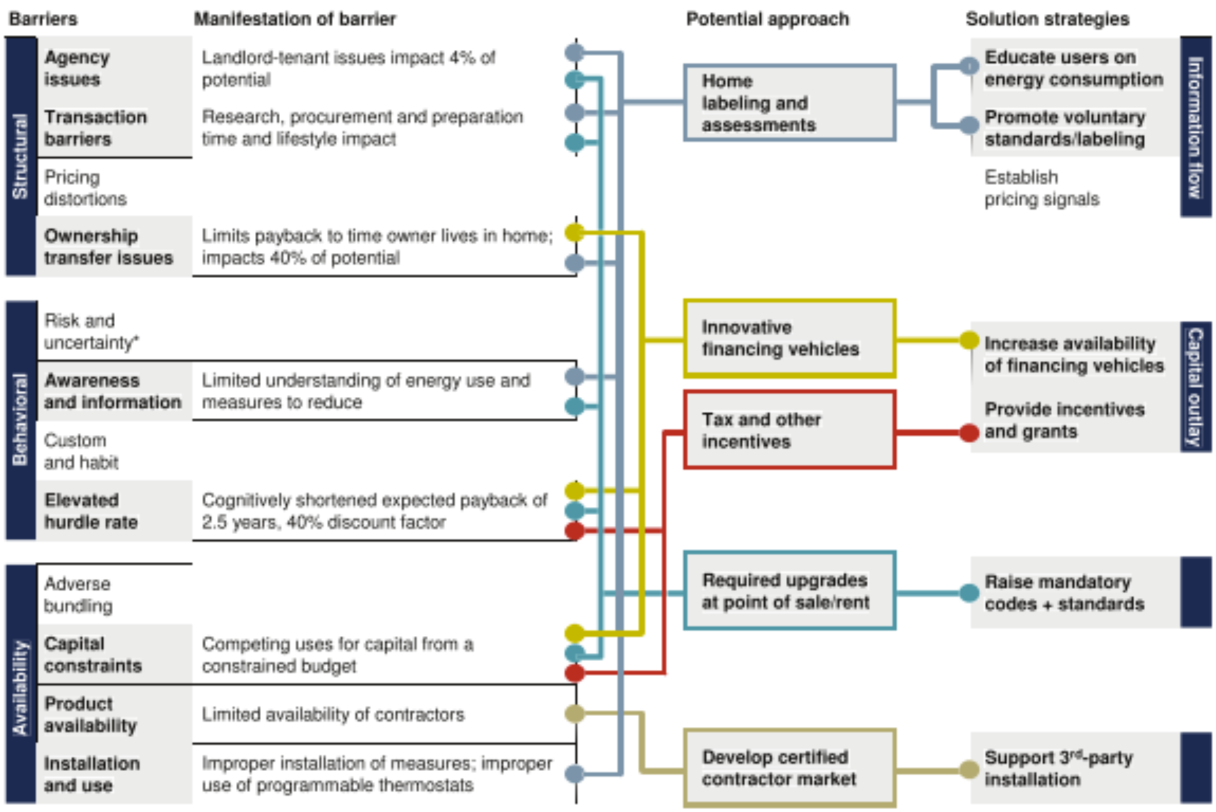
While much has been written about the more gradual diffusion of renewable energy and energy efficiency technologies than would be expected based on their cost effectiveness and societal benefits, there has been a dramatic acceleration in clean energy investment in recent years. As of 2016, wind and solar have achieved majority market share, accounting for two thirds of all new generation capacity on the U.S. grid, and energy efficiency investments increased 17% between 2011 and 2016 to top $7.5 billion in 2016 (Consortium for Energy Efficiency, 2017; Donohoo-Vallett, 2016). While many different policy strategies have been deployed to help achieve these results that are difficult to disentangle, understanding the research and policy approaches to addressing previously gradual diffusion of clean energy and energy efficiency provides useful insights for overcoming barriers to accelerated electric vehicle diffusion.

2.2.1 The energy efficiency gap

Given the similar economics of electric vehicles to energy efficiency investments, understanding the literature of the so-called "energy efficiency gap" and how practitioners have bridged it could offer insights to overcoming the gradual diffusion of electric vehicles. Numerous studies have illustrated a dynamic in energy efficiency whereby despite estimated potential CO_2 reductions and monetary savings from energy efficiency investments, consumers and firms decide to invest in certain technologies at a far slower rate "than would be expected if consumers made all positive net present value investments" (Carvallo, Larsen, & Goldman, 2015). Researchers have debated extensively how large the energy efficiency gap actually is due to hidden costs and uncertainty not accounted for in simple payback calculations, as well as the reasons for consumers making economically suboptimal decisions.

Barriers to energy efficiency investment, or "postulated mechanism(s) that inhibits investment in technologies that are both energy-efficient and (apparently) economically efficient", can be categorized in a variety of ways, but tend to fall into 1) economic barriers such as up-front cost or capital limitations, 2) information barriers such as technology uncertainty or lack of baseline energy use data, 3) organizational barriers such as debt limitations or lack of internal capacity, 4) policy or regulatory barriers, and 5) behavioral barriers (Sorrell et al., 2000). One key finding from the energy efficiency barriers literature has been that barriers are heterogeneous across customer types (such as industrial, commercial, and residential), and thus require different solutions for different sectors. Additionally, researchers have found that barriers are frequently interdependent, such that solution sets must seek to complementarily address multiple barriers (Chai & Yeo, 2012). Figure 2-1 from McKinsey illustrates a systematic approach to identifying barriers and mapping a complementary set of solutions to overcome them.

Figure 2-1: Example of systematic barrier and solution identification (Granade et al., 2009)



2.2.2 The role of finance in accelerating clean energy investment

While incentives funded through tax credits, utility charges, or other means have played a key role in overcoming economic barriers to clean energy and energy efficiency adoption, generally "appropriated funding for energy-efficiency improvements has fallen far short of what is necessary to meet energy reduction targets" (Vaidyanathan et al., 2013). Additionally, the instability of public subsidies has been problematic: "Plotted on a graph, the history of clean-energy production in the United States resembles the blade of a saw, rising and falling each time subsidies came and went." (Peretz, 2009). Policymakers have thus turned to financing to make up for the shortfall in public subsidies, further leverage limited public funds, and create a more durable, self-sustaining approach to stimulate investment that can garner support in an era of fiscal austerity (Vaidyanathan et al., 2013). Figure 2-2 highlights the potential leverage of different approaches to using public funds. Different financing approaches can also help to address particular barriers, such as customer access to capital, cash flow issues, cumbersome application processes, and debt limitations (Leventis, Martin Fadrhonc, Kramer, & Goldman, 2016).

Figure 2-2: Comparing the leverage of public funds (Zimring, Borgeson, Todd, & Goldman, 2013)

Program Incentive	Potential Leverage of Program Funds[27]
25% Rebate	4:1 (for every $1 rebate, $4 total is invested in EE)
50% Rebate	2:1
5% LLR	20:1
10% LLR	10:1

Public and private actors have created a variety of energy efficiency finance mechanisms, which generally refer to "debt or debt-like products that support the installation of energy efficiency measures by allowing costs to be spread over time" (Leventis et al., 2016). Governments and utilities have supported the creation of financing programs, particularly when the private market hasn't engaged due to high risk, uncertain returns, or other reasons, by directly acting as the lender through a state energy office or revolving loan fund, offering credit enhancements like loan loss reserves (LLR) or interest rate buy downs to leverage private capital, passing enabling legislation for certain types of energy efficiency finance, creating standardized energy saving forecasting and verification protocols, and helping to subsidize energy audits to reduce the barriers to investment.

Today, government and utility run energy efficiency finance programs are fairly ubiquitous, with over 200 state, local, and utility programs across nearly every state for most customer classes (Palmer, Walls, & Gerarden, 2012). In 2014, researchers estimated that energy efficiency finance programs in the U.S. were investing $4.8 billion per year, and that loan amounts across different types of financing programs were growing between 4% and 210% per year between 2011 and 2014 (Deason, Leventis, Goldman, & Carvallo, 2016). Financing has played an important role in energy efficiency investment in recent years, though researchers stress that "while financing may address the first cost and other barriers, without support from policies and program design structures that address other barriers to energy efficiency uptake, financing alone is not sufficient to drive demand for energy efficiency" (Leventis et al., 2016).

2.2.3 Parallels in transportation

Transport researchers have similarly identified slower uptake of more fuel efficient vehicles than would have otherwise been expected based on projected fuel and cost savings, though the findings, like for the energy efficiency gap, have been mixed (Cassidy, 2016). Like in energy efficiency, some researchers also highlight that the diffusion of EVs is a sociotechnical challenge, in which barriers to consumer adoption are not only technical and economic, but also political, social, and cultural, and that solving technical and economic issues alone is likely to be insufficient to accelerate adoption (Edbue & Long, 2012). A study on the energy efficiency paradox in trucking sought to understand the reason for gradual diffusion of cost effective technologies such as aerodynamic bumpers and tires that reduce rolling resistance. Through focus groups with long haul truckers, researchers identified a range of social, technical, and economic factors affecting decision-making, including uncertainty and imperfect information about fuel saving measures, split incentives between owners and drivers, and concern about driver acceptance of new measures (Klemick, Kopits, Sargent, Wolverton, & Paper, 2014).

Like in early years of energy efficiency and clean energy deployment, passenger electric vehicle adoption rates have thus far been modest, and even in places like California with the most policy supports, adoption rates are lower than necessary to meet electric vehicle deployment goals and midcentury climate goals (Rezvani, Jansson, & Bodin, 2015). For example, California and the other Zero Emission Vehicle mandate (ZEV) states have a 3.3 million EV cumulative sales goal by 2025, for which an estimated 15% market share is needed by that date, compared with today's 1.2% (Alliance of Automobile Manufacturers, n.d.). Modelers in California suggest that to achieve the state's 2050 emissions target, between 2.5 and 16 million ZEVs (or about 30-100% new vehicle sales) will be needed by 2030, far higher than the Governor's 1.5M ZEV target for 2025 and 320,000 ZEVs currently on the road in California (Yeh et al., 2016). To achieve such levels of deployment, the UC Davis Institute for Transportation Studies estimate a required $300-$600 billion in subsidies between 2015 and 2035 to cover the incremental costs of zero emission passenger vehicles and charging infrastructure, ranging from $12 billion per year up to $55 billion per year required in 2035 (Ogden, Fulton, & Sperling, 2016).

2.3 Heavy duty vehicle electrification

While electric vehicle technology for heavy duty applications is generally less developed than light duty vehicle technology, a wide range of models are in different stages of development and commercialization. While lower range creates operational limitations currently, consistently improving battery technology means vehicle range will likely continue to improve. With many forecasts projecting continued growth in heavy duty vehicle travel and emissions through 2050, determining approaches to accelerate electric vehicle adoption in the heavy duty sector will be essential.

2.3.1 Heavy duty vehicle emissions impacts

Figure 2-3: U.S. vehicle stock, annual miles traveled, and greenhouse gas emissions in 2015 (Federal Motor Carrier Safety Administration, Bureau of Transportation Statistics, and EIA)

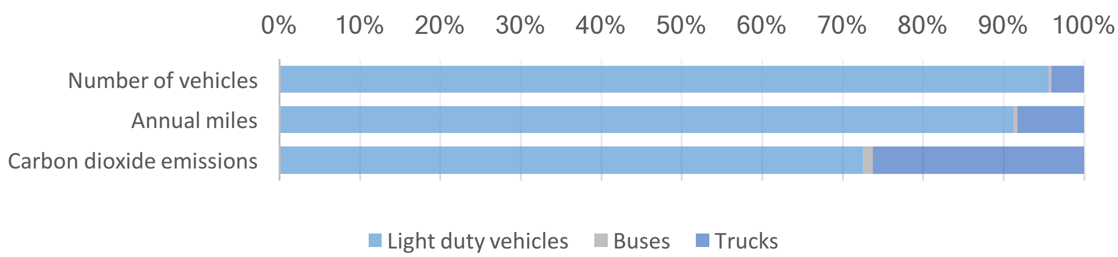


Figure 2-3 highlights that while there are fewer heavy duty than light duty vehicles in operation, their low fuel efficiency and often higher mileage means they have a disproportionately large impact on energy use and emissions, which transportation experts forecast will grow in the coming decades as freight demand and truck travel increases. In 2014, heavy duty trucks and buses in the U.S. accounted nationally for 14% of vehicle miles traveled and 28% of on-road fuel consumed (Bureau of Transportation Statistics, 2017; Federal Highway Administration, n.d.). Nationwide, heavy duty vehicles are estimated to account for 26% of transportation sector NOx and 17% of PM10, with much higher shares in some urban areas (Central Transportation Planning Staff, 2012).

Additionally, heavy duty vehicle sales, mileage, and emissions have been growing, primarily due to a rise in freight demand. Researchers with ICCT estimate the share of emissions from trucks has risen from 18% of U.S. transportation greenhouse gas emissions in 1973 to 26% in 2008 (Eom, Schipper, & Thompson, 2012). Between 1990 and 2013, greenhouse gases from medium and heavy duty trucks increased by 76% (EPA 2013). The International Energy Agency forecasts that globally road freight transport will surpass light-duty on-road passenger transport in energy consumption and emissions by 2050 globally (International Energy Agency, 2017). In the United States, the Energy Information Agency anticipates that freight trucks' share of on-road transportation sector energy use will rise from 25% today to 31% in 2050 (see Figure 2-4).

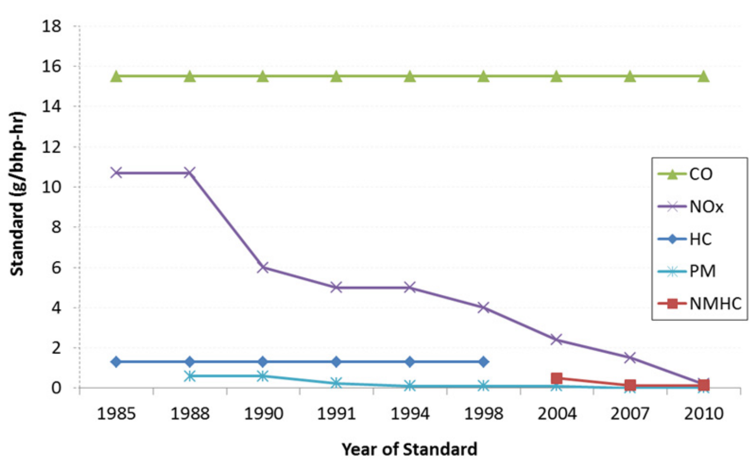
Figure 2-4: Current and projected energy use by transport mode, 2017-2050 (EIA Reference case)

Highway Transport Sector	2017 Trillion BTU	2050 Trillion BTU	% of Total - 2017	% of Total - 2050	Year over year growth, 2015-2050
Light-Duty Vehicles	**16,000**	**12,500**	**70.3%**	**62.2%**	**-0.7%**
Automobiles	6,400	4,600	27.9%	23.0%	-1.0%
Light Trucks	9,700	7,900	42.3%	39.1%	-0.6%
Motorcycles	18	13	0.1%	0.1%	-1.0%
Commercial Light Trucks	**900**	**1,000**	**4.1%**	**5.0%**	**0.4%**
Buses	**270**	**320**	**1.2%**	**1.6%**	**0.6%**
Transit	110	115	0.5%	0.6%	0.2%
Intercity	32	39	0.1%	0.2%	0.6%
School	130	170	0.6%	0.9%	0.9%
Freight Trucks	**5,600**	**6,300**	**24.5%**	**31.2%**	**0.4%**
Medium (10001-26000 pounds)	1,500	2,100	6.6%	10.6%	1.1%
Large (> 26000 pounds)	4,100	4,100	17.9%	20.6%	0.1%

HEAVY DUTY VEHICLE FUEL ECONOMY AND EMISSIONS STANDARDS

In addition to the light duty fuel economy standards that were tightened during the Obama administration, the EPA also introduced new standards for heavy duty vehicles in 2011 and again in 2016. For model years 2017-2027, the standards require 12-24% CO_2 reduction from diesel vocational vehicles (the category of transit buses), which policymakers estimate could be met by upgrades to existing models or hybrid vehicles (International Council on Clean Transportation, 2016). While the benefits of this fleet-wide standard are significant, they are not stringent enough to encourage investment in zero tailpipe emission trucks and buses, or to reach needed carbon reduction targets. While California does have the unique authority under the Clean Air Act to set more stringent standards, at this time their heavy duty standards are harmonized with the federal standards.

Figure 2-5: EPA emission standards for heavy-duty engines, 1985-2010 (Hao Cai, Andrew Burnham, Michael Wang, Wen Hang, 2015)



In 2007 and 2010, emissions standards for heavy duty engines changed dramatically for particulate matter and NOx, as depicted in Figure 2-5. The EPA under the Clean Air Act sets engine standards for transit buses and other vehicles for pollutants considered harmful to public health and the environment, including carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), and particulate matter (PM) emissions. The 2007 emission standards made necessary the use of exhaust after-treatment technology such as diesel particulate filters (DPFs), as well as cooled exhaust gas recalculating (EGR) technology and Selective Catalytic Reduction (SCR) to reduce NOx (Richard Laver, Donald Schneck, Douglas Skorupski, Stephen Brady, Laura Cham, 2007). Additionally, refineries were required to produce, and retail and wholesale fuel outlets to provide, ultra-low sulfur diesel in 2006.

Collectively these changes mean diesel trucks and buses are now far cleaner than they once were, though do still emit criteria and greenhouse gas pollutants, as well as unregulated ultrafine particles which are increasingly becoming a concern of health researchers (Chen et al., 2016; Heinzerling, Hsu, & Yip, 2016). The tightening standards have meant less of a difference for certain pollutants between diesel and CNG heavy duty vehicles, which emit very similar levels of CO_2 from their tailpipes on a per mile basis, for while natural gas has a lower carbon content than diesel fuel, this improvement is diminished by CNG's worse fuel economy (MJB&A, 2013).

AIR QUALITY AND HEALTH IMPACTS

Researchers have estimated that transportation is the largest contributor to pollutant-related deaths, causing 53,000 PM2.5-related early deaths and 5,000 ozone-related early deaths per year (Caiazzo, Ashok, Waitz, Yim, & Barrett, 2013). Researchers have also estimated diesel exhaust PM is responsible for approximately 70% of the known potential cancer risk from air toxics exposure in Southern California, of which more than 70% is from heavy duty diesel trucks (Houston, Krudysz, & Winer, 2008). Multiple studies have documented the unequal impacts of vehicle pollution across racial groups and socioeconomic status, particularly from busy roads and freight hubs where heavy duty vehicle pollution is greatest (Chandler, Espino, & O'Dea, 2016). A study of southern California found minority and high-poverty neighborhoods bear over two times the level of traffic density compared to the rest of the region (Houston, Wu, Ong, & Winer, 2004).

While tightened heavy duty vehicle standards are making a substantial impact on regulated pollutants, there is increasing concern about ultrafine particulate matter, which is not an EPA-regulated pollutant, and may have a more significant impact than other pollutants. As researchers hypothesize, "the ultrafine component of particulate matter might be responsible for many of the observed health effects of PM2.5 and PM10" for a number of reasons, including that their smaller size enables deeper penetration into people's lungs, they can travel more easily into the bloodstream, and they have a greater surface area to mass ratio enabling greater transfer of toxic chemicals (Heinzerling et al., 2016). Researchers have found truck ratio to be the most important predictor of UFP concentrations, and a study of UFP levels in a bus terminal found ten times the level of background particle concentrations (Cheng, Chang, & Hsieh, 2011; Weichenthal, Farrell, Goldberg, Joseph, & Hatzopoulou, 2014).

2.3.2 Heavy duty electric vehicle deployment potential

In addition to transit buses, other urban heavy duty vehicles will likely soon be ripe for electrification, particularly school buses, urban delivery trucks (already being used by FedEx and others), garbage trucks (already deployed in Chicago), and drayage trucks (in demonstration phase in California), all of which have direct pollution impacts on urban populations. Figure 2-6 describes available electric heavy duty vehicles, their state of technology readiness, and the U.S. population of those vehicles.

Figure 2-6: Available heavy duty electric truck and bus technology (California Environmental Protection Agency, 2015; CALSTART, 2013; Edelstein, 2016; Nick Nigro, Dan Welch, 2015; Stewart, 2016)

Vehicle	Est. # in U.S.	Technology readiness	OEMs	Fuel economy (conventional vehicle) (MPDGE)	Average annual VMT	Approx. annual diesel gallons
Transit buses	70,000	Commercially available	Proterra, BYD, New Flyer, Gillig, eBus, etc.	4	40,000	700 million
School buses	480,000	Limited commercial availability	Bluebird Thomas Motiv Lion TransTech Adomani	7	12,000	823 million
Urban delivery trucks	120,000	Limited commercial availability	EVI, Zenith, Motiv	6.6	13,500	245 million
Garbage trucks	150,000	Demonstration phase	BYD, Motiv, Wrightspeed	2-3	25,000	1.5 billion
Tractor trailors	11,000,000	Demonstration phase	TransPower Tesla, BYD, Renault	5.8	66,000	125 billion
Drayage trucks	20,000 (CA)	Demonstration phase	TransPower, Motiv	4	200+ daily miles	-

Technology development and policy support has thus far primarily been focused on heavy duty vehicles whose duty cycles are shorter range and return to the same base daily where they could recharge. In addition to being the most feasible for adoption, these types of vehicles also tend to operate in slow-speed, urban environments where they create the greatest pollution exposure for nearby residents. Using the vehicle population data, average fuel economy, and average annual vehicle miles traveled for each vehicle type, the right column of Figure 2-6 presents a very simple assessment of the fuel consumption for each vehicle class to indicate the potential impact of electrification. While there are relatively fewer transit buses than school buses, their worse fuel economy and higher utilization makes their estimated fuel use similar, while garbage trucks have an even greater potential to reduce greenhouse gases and air pollutants due to their very low fuel economy. While transit buses are the only vehicle type that is currently commercially available, researchers are optimistic that ongoing declines in battery costs will make all of the above technologies cost effective in the coming decade, though most believe long distance tractor trailers will be more of a hurdle to develop (California Environmental Protection Agency, 2015).

SCHOOL BUSES

While electric school bus models still have a much greater cost premium than transit buses, their even greater number, as well as diesel school buses' health impacts on school children and residential areas, suggest that they could be a logical next fleet type to electrify. Research assessing the air quality inside school buses have found within-bus concentrations of particulate matter and air toxics to be 4-12 times higher than ambient pollution levels (Beatty & Shimshack, 2011). With battery costs falling for all vehicle classes, CARB projected in 2015 that "Electric school buses have the potential for significant market penetration in the next 5 to 10 years" (California Environmental Protection Agency, 2015). At the time, CARB estimated that deployment had been slow primarily due to strict safety testing for school buses that takes time, very high incremental costs, as well as the fact that major bus makers like Thomas and Bluebird had not yet entered the market. However, as of 2017 both Thomas and Bluebird introduced and began testing all-electric models, suggesting that with these large manufacturers entering the market, economies of scale and first costs could improve soon (Gray, 2017; Jarmer, 2017).

While school buses are similar in many respects to transit buses, they differ in not getting federal funding for bus purchases, and having far lower utilization rates which hinders operating cost savings. Still, lower utilization could mean a greater potential for providing grid services and earning other revenue streams while parked midday and during the summertime. Vehicle-to-grid services encompass a range of potential revenue streams electric vehicle batteries could earn from providing services to the electric grid, either through selling electricity back to the grid, participating in higher value ancillary services markets, or interrupting or reducing their charging during peak times. A study estimating the vehicle-to-grid potential for electric school buses in Delaware, assuming use in the frequency regulation market, found a positive net present savings after five years of operation for the school district of $38 million if they were to convert their entire fleet (Noel & McCormack, 2014).

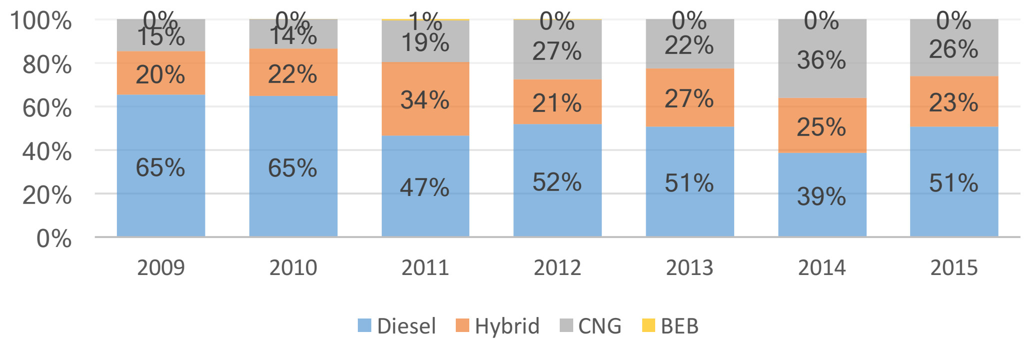
2.3.3 Electric transit buses: present status and potential for widespread adoption

While bus travel represents a relatively small share of national transportation emissions, converting bus fleets could provide an important test case for other publicly and privately owned fleets, with multiple manufacturers offering cost competitive models today. Focusing on transit buses also supports urban planning goals that prioritize high occupancy vehicles over single occupancy, and aim to lower air pollution in low-income neighborhoods where lower rates of private car ownership lead to a greater dependence on transit. Policymakers have also focused on electric bus technology because "buses will provide technology transfer to other medium- and heavy-duty vehicle sectors." (California Governor's Interagency Working Group on Zero-Emission Vehicles, 2016).

RECENT BUS TECHNOLOGY TRENDS

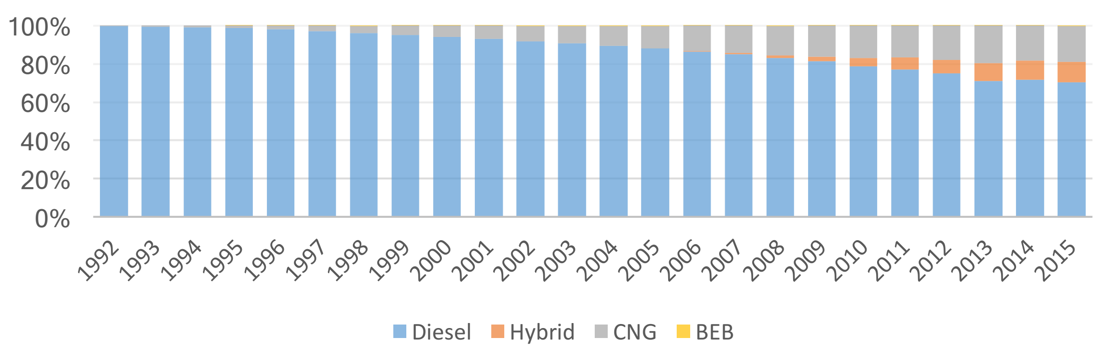
Diesel bus purchases declined from 65% to a low of 39% of new buses purchased in 2014, though saw a resurgence in 2015 with 51% of new buses purchased, according to the Federal Transit Administration's (FTA) annually published Statistical Summaries (see Figure 2-7). Despite hybrids and CNG vehicles having been available for over 10 years, neither are the dominant new technology purchased. Both graphs below include 30', 35', 40', articulated buses, and commuter buses; amongst only purchases of 40' buses, diesel, hybrid, and CNG purchases are close to evenly split, with about one third of new purchases each.

Figure 2-7: Percent new buses purchased with FTA funds by fuel type, 2009-2015 (FTA Statistical Summaries)



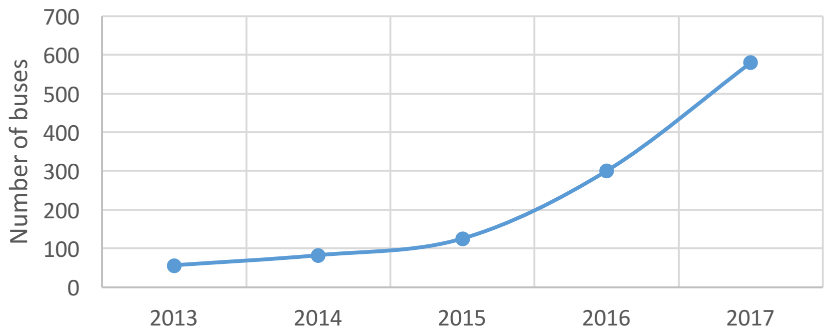
Alternative fuel buses are a growing share of the U.S. transit fleet, though diesel is still a majority of the fleet at 70%, and CNG making up a larger proportion of alternative fueled vehicles compared with hybrids or electric buses (see Figure 2-8). Earlier sociotechnical research highlights the transition of many agencies in the 1990s and early 2000s, often under pressure from traditional environmental and environmental justice groups, to move away from diesel to CNG buses. At the time, some research suggested CNG buses were superior particularly for NOx and PM emissions, though diesel engine retrofit technology evolved quickly in response to new engine standards, and ultimately rendered the research on health and emissions differences between CNG and diesel buses inconclusive. Additionally, most agencies reported higher costs to run CNG buses at the time due to investment in fueling stations, depot retrofits, and higher maintenance costs. Four out of eight major agencies studied returned to diesel after investing in CNG buses, highlighting the risk to transit agencies in being the pioneer into new technologies for the heavy duty sector and potentially ending up with stranded assets (Hess, 2007).

Figure 2-8: Percent fuel type of U.S. bus fleet, 1992-2015 (NTD Revenue Vehicle database)



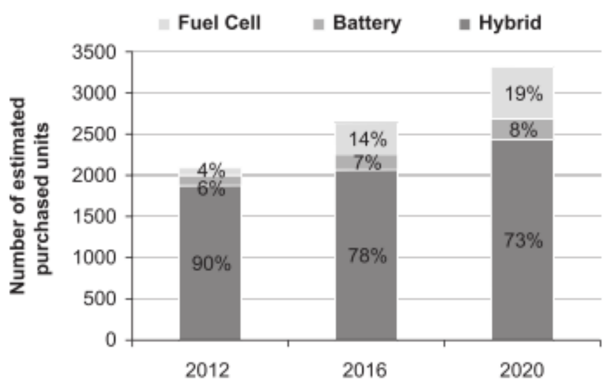
Examining how the hybrid bus fleet has grown since the technology became commercially viable could offer some insights into how the electric bus fleet might grow. Growth of the hybrid bus fleet appears to have been rapid in the early years of the technology's commercialization, seeing a 77% compound annual growth rate between 2006 and 2010, but slowing to 18% between 2011 and 2015, and remaining at less than 10% of the national fleet by 2015. While limited data exists thus far and the fleet size is still very small, annual growth of the U.S. electric bus fleet since 2013 has been approximately 59%. Much of this early growth has relied upon federal discretionary grants, such as the Low or No Emission Vehicle grants from the FTA, which provides $55 million per year through 2020 for low or zero emission transit buses.

Figure 2-9: Growth of U.S. battery electric bus fleet, 2013-2017 (NTD, Clermont & Hanlin, 2017)



Market forecasts have estimated a global compound annual growth rate of electric buses of 26.4%, though researchers estimate 75% of electric buses will be deployed in Asia, and that the North America market will shift towards diesel hybrids as the predominant technology deployed by 2020, with battery electric buses capturing a smaller percentage of the market (Mahmoud, Garnett, Ferguson, & Kanaroglou, 2016).

Figure 2-10: North America zero emission bus market sales forecast (Mahmoud et al., 2016)



ELECTRIC BUS LITERATURE

Thus far, electric transit bus research has used a diversity of methods to investigate questions of relative cost and emissions benefits compared with other bus technologies, and has been undertaken by academics, transit agencies, and government agencies alike. The research has reached a diversity of conclusions with respect to total cost of ownership savings, though there seems to be general agreement that electric buses will have far lower environmental impact, and that cost and environmental factors such as the electricity grid will make electric buses increasingly preferable over time.

Multiple academic researchers have assessed the environmental and economic impacts of electric buses compared with other fuel types, using methods like lifecycle cost assessment, total cost of ownership analysis, and sensitivity analysis. In an early study, Cooney found using lifecycle assessment that electric buses were preferable from a greenhouse gas perspective in only eight states, and that while the impacts of battery production environmentally are significant, they remain small in comparison with in-use environmental impacts of buses (Cooney, Hawkins, & Marriott, 2013). As technology has improved and the electricity grid has become cleaner, researchers have estimated that today’s electric buses emit up to 75% less than diesel buses, due in part to being four times as efficient as diesel buses, and in part because idling is the most frequent engine speed in an urban bus route, which consumes significant fuel for diesel buses but no fuel for electric buses (Chandler et al., 2016).

More recently, researchers from Carnegie Mellon focused on the societal costs of bus electrification, estimating that transit buses contribute to 0.4% of national on-road energy consumption, and have contributed to $440 million in estimated social costs. Their study focused on quantifying the air quality and emissions benefits of different bus technologies, for which electric buses offer the greatest benefits. Their study also estimates that fast charge electric buses have the lowest total cost of ownership of all bus technologies, followed closely by depot charge buses, when considering 80% federal funding and taking into account externality costs (Tong, Hendrickson, Biehler, Jaramillo, & Seki, 2017).

Mahmoud et al provide a comprehensive assessment of zero emission bus technologies based on environmental, economic, and operating characteristics, and find cost and emissions are highly sensitive to energy cost and operating context factors. Their findings suggest hybrids should only be considered an intermediate stepping stone to electric bus technologies, and that incremental cost remains the highest barrier to enabling deployment of zero emission buses (Mahmoud et al., 2016). Nurhadi, Boren, and Ny conduct a sensitivity analysis of electric bus total cost of ownership in Sweden, finding percent change in utilization (annual miles per year), years in operation, and incremental cost are the most significant factors, compared with other factors like maintenance and energy costs (Nurhadi, Borén, & Ny, 2014).

Multiple academic researchers have focused on the impact of different drive cycles and used simulation methods to assess costs and benefits in different operating conditions. Through drive cycle simulation, Lajunen assesses energy consumption and costs of different bus technologies, finding that electric and hybrid buses are less affected by slow speed operations but more impacted by heating and cooling loads than other technologies, and that there is a wide variability in lifecycle cost comparison with diesel buses across different operating conditions (Lajunen, 2014). Ercan and Tatari used a lifecycle assessment model and Monte Carlo simulation to compare the fuel economy and environmental impacts of different bus technologies under different drive cycles, finding that battery electric and hybrid bus energy consumption was not as impacted by slow speed, stop-and-go operation as for fossil-fuel powered buses (Ercan & Tatari, 2015). Using linear programming to optimize for minimized lifecycle costs, greenhouse gases, and air pollutants, Ercan et al find that battery electric buses have the greatest advantage in congested drive cycles such as in Manhattan (Ercan, Zhao, Tatari, & Pazour, 2015). Researchers from the Georgia Institute of Technology developed a transit greenhouse gas emissions calculator that relied on EPA MOVES to produce estimates for emissions that factor in passenger load, drive cycle, and road grade, and found battery electric buses to have the lowest criteria pollutant emissions in nearly all scenarios tested (Li et al., 2014). Ambrose et al use a probabilistic approach to compare the total cost of ownership of electric buses in California with other technologies, and find electric buses are anticipated to cost more than other technologies currently, but less by 2030, except for CNG (Ambrose, Pappas, & Kendall, 2017).

Some electric bus research has come from transit agencies doing their own analysis, or working with consultants to estimate the costs and benefits of switching their fleet. In a report for NYC Transit and the MTA for their 5,700 bus fleet, Aber estimates that electric buses would be cost effective in that context, and even more so when environmental and health benefits are quantified (Aber, 2016). A 2016 analysis by King County Metro found electric buses could meet 70% of their service needs and estimated that transitioning to electric buses through 2034 would cost 6% more than diesel hybrids, though just 2% more when societal benefits were taken into account (King County Metro, 2016). A sensitivity analysis testing different ranges of maintenance cost savings, fuel price scenarios, and charging management found lifecycle costs could range from 27% less than diesel hybrids to 10% more. They also developed an equity analysis to prioritize deployment based on air quality, health, and demographics of census blocks in the Metro service area. Consultants Ramboll Environ evaluated different low and zero emission bus fleet options that could comply with CARB's proposed zero emission bus regulation for LA Metro's 2,200 bus fleet, finding that an investment in renewable natural gas-powered low NOx engines would increase total fleet costs by 1.1% between 2015 and 2055, while battery electric buses were estimated to increase total fleet costs by 2.3-4.7%. The report uses more conservative assumptions than other studies, including a 1:1.4 replacement ratio required for electric buses in the early years of their model.

The California Air Resources Board (CARB) has been active in electric bus research as their Innovative Clean Transit initiative works towards establishing a new regulation aiming to increase the level of investment in zero emission buses. Their research has included in-depth analysis and forecasts of bus purchase costs, maintenance costs, electricity costs, and other factors, aimed at informing a total cost of ownership analysis released in summer of 2017 that estimated depot charge battery electric buses had a lower total cost of ownership than diesel buses in 2016 across most California utility service areas, and that all had a lower total cost of ownership than diesel hybrids (California Air Resources Board Innovative Clean Transit Working Group, 2017a).

While most literature thus far on electric buses has included prospective forecasts of costs and emissions benefits, the National Renewable Energy Laboratory has begun to publish some of the first independent, rigorous evaluations of the fuel economy, maintenance costs, electricity costs, and other performance measures of in-service electric buses at King County Metro and Foothill Transit (Eudy et al., 2016; Eudy & Jeffers, 2017). Additionally, the TCRP will publish a "state of the practice" report on battery electric bus technology in 2018, reporting on the experiences of transit agencies who have deployed electric buses thus far (Center for Transportation and the Environment, 2017). Through a literature review, survey, and case studies, the authors identify and summarize a number of challenges facing further deployment, as well as various benefits of electric buses, including that in-use noise levels are far lower than conventional buses and that they may provide a resilience benefit in emergency situations by serving as back-up power supply (Center for Transportation and the Environment, 2017).

2.3.4 Summary

While the benefits of electric transit buses appear to be substantial, procurement so far represents a small fraction of total new buses, and relies heavily upon limited discretionary grant programs to finance the incremental cost. While U.S. transit agencies procure approximately 5,000 new buses per year in total, as of 2016 there were approximately 600 electric buses (0.8%) of the 73,000 operated by transit agencies nationally (Clermont & Hanlin, 2017; United States Government Accountability Office, 2015). This research builds upon primarily technical and economic electric bus research that has taken place during early pilot deployments to add a mixed-methods perspective and an integrated view of the social, technical, economic, and other factors driving or inhibiting more widespread electric bus deployment, and that can help point in the direction of needed policies to enable more accelerated investment. Transit buses are a vehicle type that has reached the highest level of commercialization amongst heavy duty electric vehicles thus far, and thus insights from this research can potentially also help inform future efforts to drive widespread adoption of other heavy duty vehicle classes that have a similar emissions and public health impact, such as school buses, urban delivery trucks, and refuse trucks.

3. Electric bus total cost of ownership and well-to-wheels emissions analysis

This chapter documents the inputs and approach of the total cost of ownership and emissions model developed for this research, and then applies that model to a generalized case in order to conduct a sensitivity analysis aimed at understanding the relative importance of parameters determining electric bus total cost of ownership compared with conventionally fueled buses, as well as an analysis of well-to-wheels greenhouse gas and criteria pollutant emissions across different regions of the United States.

3.1 Developing a total cost of ownership model

In order to develop a total cost of ownership and emissions model that can be used to assess different bus technologies, a review of multiple available transit bus lifecycle cost and emissions models and relevant literature was undertaken, including contacting bus manufacturers and transit agencies to seek access to additional data to compile the most current data sources on key parameters that determine bus lifecycle costs. What follows is a description of the approach and data sources used to model each parameter.

3.1.1 Bus total cost of ownership and emissions model and data review

Several bus lifecycle cost and emissions models and analyses have been developed by different federal agencies, academics, and other stakeholders, each with a slightly different technology focus. Models reviewed for this analysis include:

- **USDOT Fuel Cell Model (2007):** An in-depth spreadsheet-based model used to analyze different bus technologies' costs and emissions, with a particular focus on fuel cell buses. (Lowell, Chernicoff, & Lian, 2007)
- **TCRP WVU Model (2009):** An in-depth spreadsheet-based model that used a combination of literature, manufacturer's data, and field data to estimate key parameters and create a model for diesel hybrid lifecycle costs (Clark, Zhen, & Wayne, 2009).
- **TCRP Post-2010 Model (2010):** This model builds heavily off of the WVU model above, but with a broader focus beyond just diesel hybrids (Blaylock et al., 2010).
- **Fuel and Emissions Calculator (2010):** This model was built by Georgia Tech to assess different public transit vehicles, with a particular focus on estimating the energy use and emissions from different drive cycles using EPA MOVES (Xu et al., 2015).
- **Vice 2.0 Model (2014):** This is a simple spreadsheet model focused primarily on CNG buses.
- **AFLEET Model (2015):** AFLEET is based on Argonne Labs' GREET model, and includes a recent expansion to cover heavy-duty vehicles. While the model is quite comprehensive with respect to emissions, it is able to model a wide range of vehicles and therefore does not have as much specificity with respect to buses as the other models (Argonne National Laboratory, n.d.).

In addition to the models above, several relevant academic and government reports were also reviewed, particularly data and lifecycle cost analysis from CARB's Innovative Clean Transit initiative (Innovative Clean Transit, 2017). While some of these data inputs may be particular to California, many such as projected bus prices are likely to be applicable nationwide.

3.1.2 Vehicle technologies for analysis

This analysis takes into account commercially available, economically feasible bus technologies, including diesel, compressed natural gas (CNG), diesel hybrid, and battery electric buses (BEB). Battery electric buses are currently available in two generalized models: a short range bus with a smaller on-board battery that requires more frequent, on-route charging (on-route BEB), and an extended range bus with a larger on-board battery that is designed to charge more slowly overnight (depot charge BEB). While many of the early buses deployed were on-route charge buses, conversations with Proterra and transit agencies suggest that most recent orders are for depot charge buses, given their more similar operational characteristics to a diesel bus, so this analysis primarily considers depot charge buses.

The current generation of electric buses have been on the market for almost five years, with key specifications included in Figure 3-1. Data sources are referenced in the chart, as some are from manufacturers, while others have been verified by Altoona testing. While this analysis primarily accounts for 40' transit buses, which make up approximately 62% of the current U.S. fleet used for fixed-route service according to 2015 NTD data, data for 60' transit buses were reviewed where available. The first 60' electric bus manufactured by BYD was put into service by the Antelope Valley Transit Authority in 2017, and five 60' electric buses will be delivered to the MBTA in 2018. As battery technology improves, so do depot charge bus ranges, enabling coverage of a greater share of transit agency bus assignments. In fall of 2017, Proterra announced its 660 kWh bus had driven over 1,100 miles on a single charge (Munio, 2017). Still, some agencies are considering smaller supplementary on-route chargers to top up longer assignments.

In general, this analysis does not consider the differences between manufacturers, though available models vary in ways that impact cost and operations in important ways, including battery type, range, and charging configuration. For example, some electric bus manufacturers anticipate longer lifetimes than the typical expected life of a bus, with Proterra claiming a lifetime of 18 years due to its advanced carbon composite body (which also reduces weight), as well as a simpler drive train, though anticipates needed battery replacements every six years ("Proterra | Durability," n.d.). BYD on the other hand claims a longer battery life and offers a 12-year battery warranty, eliminating the need for a costly mid-life battery replacement, and also includes a depot charger in its base pricing.

Trolleybuses are another form of electric bus that have been available and in use in cities for decades. While having the advantage of much in-use experience and a longer vehicle lifetime than diesel buses, downsides include community resistance to expansion of overhead wire systems, the high installation and maintenance costs of those wires, the decrease in U.S. suppliers, and the lack of flexibility of routes. Additionally, FTA has traditionally considered trolleybus routes as fixed-route transit, meaning that expansions are considered under the competitive New Starts and Small Starts programs. As a result of these downsides, combined with the increasing cost effectiveness of battery electric buses, this analysis does not consider expansion of trolleybuses. While FTA and other federal agencies have focused significant efforts in the past decade in research, development, and pilot deployments of fuel cell buses in transit agencies around the country, substantially higher capital costs of the vehicles and infrastructure compared with other alternative fuel buses continue to pose a barrier for widespread deployment. As a result, this analysis also excludes fuel cell buses.

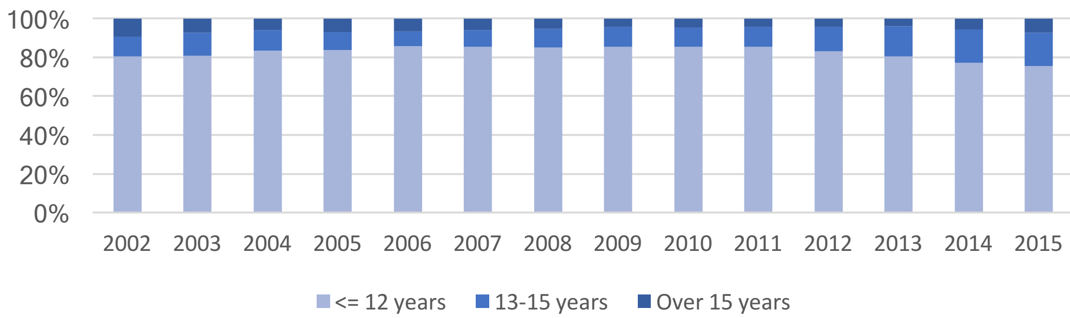
Figure 3-1: Available battery electric bus models

Make	Model	Size	Curb weight (lbs)	Battery capacity (kwh)	Charging type(s)	Type of battery	Charging capacity (kw)	Charging time	Range (miles)
BYD Motors, Inc.	K9, K9S[1]	40'	31,890	324	Depot charge	Iron phosphate	80	3-4 hrs; 6.9 hrs	126.8
	K7[2]	30'	21,381	197	Depot charge	Iron phosphate	80	2-3 hr.	144
	K11[3]	60'	47,620	591	Depot charge	Iron phosphate	200	3 hrs.	200
	C9[4] (Coach/commuter bus, also 23', 45')	40'	30,836	365	Depot charge	Iron phosphate	Up to 300	1-1.5hrs	155
Proterra, Inc.	BE-35[5]	35'	27,680	54-72	On-route charge	Lithium Titanate	500	<10 min	40
	BE-35[6]	35'	28,180	"	On-route charge	Lithium Titanate	"	"	30.99
	BE-40[7]	42'	27,370	53-131	On-route charge	Lithium Titanate	"	"	38.64
	Catalyst FC[8]	40'	26,446-27,500	79-105	On-route /depot	Lithium Titanate	350(OR) /60(D)	10-13 min	49-62
	Catalyst XR[9]	40'	26,637-28,243	220-330	On-route/depot	Lithium Titanate	175(OR)/ 60(D)	< 3 hrs	136-193
	Catalyst E2[10]	40'	29,849-33,061	440-660	Depot charge	Lithium Titanate	120(D)	< 3.5 - 5 hrs	156-204
New Flyer[11]	XE35	35'	29,300	150-400	On route/depot	Lithium ion	200-300kw	1-6 hours (depot); 16-32 min (on-route)	200
	XE40	40'	30,500	100-480	On route/depot	Lithium ion	200-300kw	1-6 hours (depot); 16-32 min (on-route)	200
	XE60	60'	45,500	250-600	On route/depot	Lithium ion	200-300kw	1-6 hours (depot); 16-32 min (on-route)	200
Complete Coach Works	ZEPS remanufactured bus[12]	30-40'	39,600	311	Depot	Lithium ion	40kw	4 hours	150+
Gillig	Standard LF[13]	29'	Limited details available						200

3.1.3 Vehicle mileage and lifetime

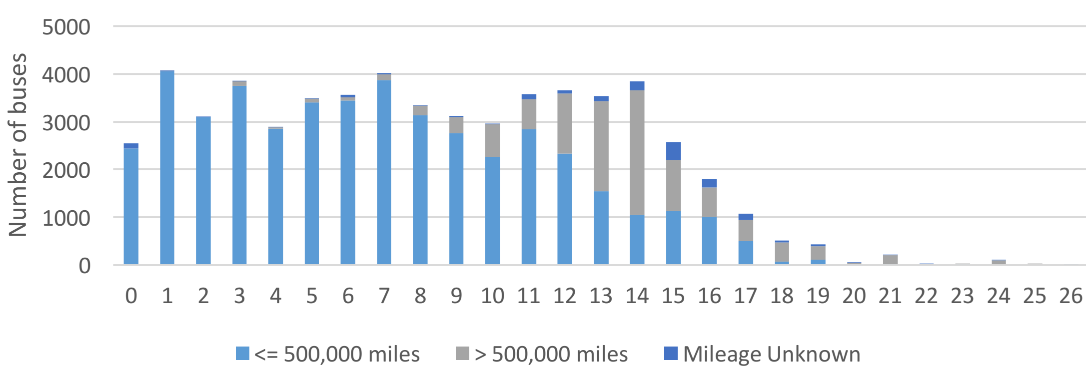
A bus's lifetime mileage and retirement age are key inputs to any lifecycle cost model. FTA has minimum retirement requirements for grant-funded buses of 12 years or 500,000 miles (whichever is reached first) for heavy duty 30-60 foot transit buses, which make up 78% of U.S. transit buses and vans (Richard Laver, Donald Schneck, Douglas Skorupski, Stephen Brady, Laura Cham, 2007). A 2007 FTA study found agencies don't tend to be bound by FTA's minimum life requirements, as they tend to keep vehicles in service 1-3 years beyond the minimum requirements, with the national average retirement age being 15 years (Richard Laver, Donald Schneck, Douglas Skorupski, Stephen Brady, Laura Cham, 2007).

Figure 3-2: Percent of U.S. transit fleet beyond retirement age by year (NTD data, 2002-2015 for agencies with 20 or more buses that are 30' and larger)



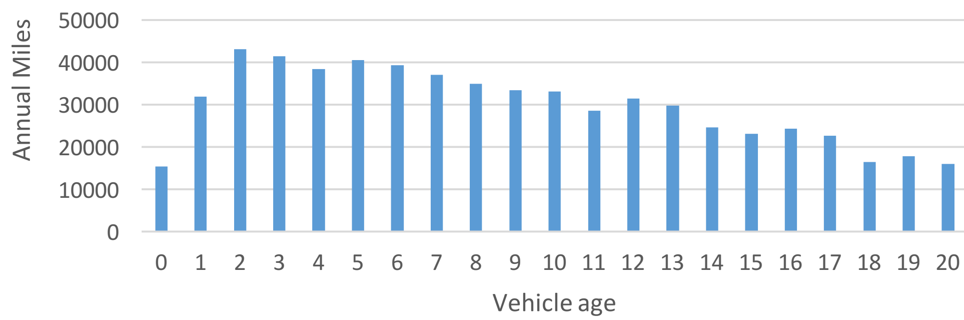
The share of vehicles beyond the FTA's retirement age of 12 years decreased around the late 2000s when there was an influx of ARRA funding for new buses, though has been growing in recent years to about 25% of the 2015 bus fleet as can be seen in Figure 3-2. For the U.S. transit fleet in 2015, Figure 3-3 highlights that vehicles over 12 years old also tend to have been driven over 500,000 miles, and that buses aged 14-15 years are common, tapering off beyond that.

Figure 3-3: Vehicle age and lifetime mileage of U.S. transit bus fleet (2015 NTD data for agencies with 20 or more buses that are 30' and larger)



It appears many buses ramp up to their highest annual mileage in their earlier years, tapering off in their later years (see Figure 3-4), and that within agencies, different sub-fleets can have very different annual mileage figures. Important tradeoffs exist in terms of deploying electric buses for optimal operational and emissions savings between low and high mileage route assignments. On shorter routes that are more congested and slower speed, electric buses do best compared with fossil fuel-powered buses from a fuel economy perspective. On the other hand, higher mileage routes may more than make up for a smaller fuel economy differential by accumulating greater operating savings from fuel and maintenance faster. At this relatively early point in technological development, range may hamper deployment on longer assignments that would achieve operating savings more rapidly, though ongoing improvements to range and battery cost indicate that this issue may be resolved in a matter of years.

Figure 3-4: Age and average annual miles of the U.S. transit bus fleet, 2015 NTD



The model developed for this analysis assumes a bus lifetime of 14 years, and considers the mileage per peak vehicle measured by NTD for each fleet, as well as an average utilization of 40,000 miles per year to compare across contexts. While agencies typically drive buses longer distances in their earlier years, this model does not take into account that distribution due to a lack of data for individual agencies.

3.1.4 Fuel economy and speed

Fuel economy is a critical input with impacts upon both costs and emissions. Lifecycle cost models reviewed analyzed fuel economy's relationship with speed and "hotel loads" (i.e. A/C and heaters). Buses have traditionally been some of the lowest fuel economy vehicles on the road, in large part due to their stop-and-go duty cycles in congested urban environments where the most transit riders are. According to data reported to the National Transit Database, approximately 75% of U.S. transit agencies, and 90% of U.S. transit buses operate in slow- and medium-speed duty cycles, with an average speed, weighted by miles driven, of 13.3mph (see Figure 3-5) (MJB&A, 2013, NTD 2015).

Figure 3-5: Average speed distribution of U.S. transit buses (2015 NTD data for buses 30' and over)

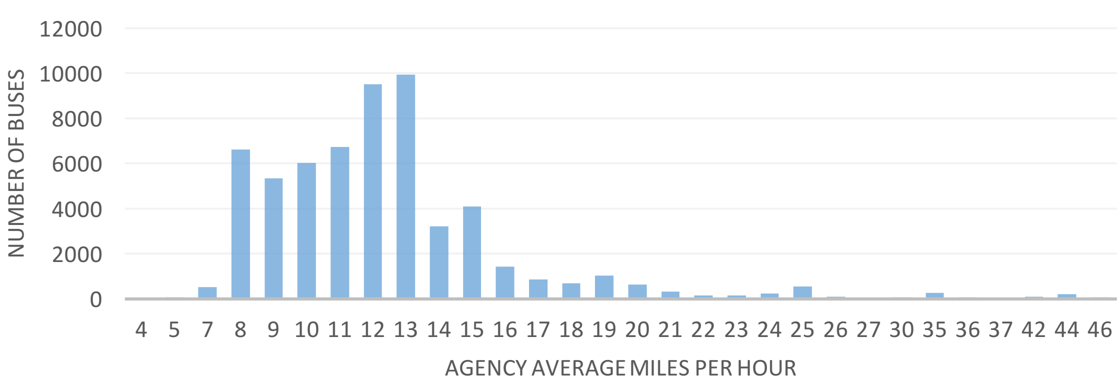
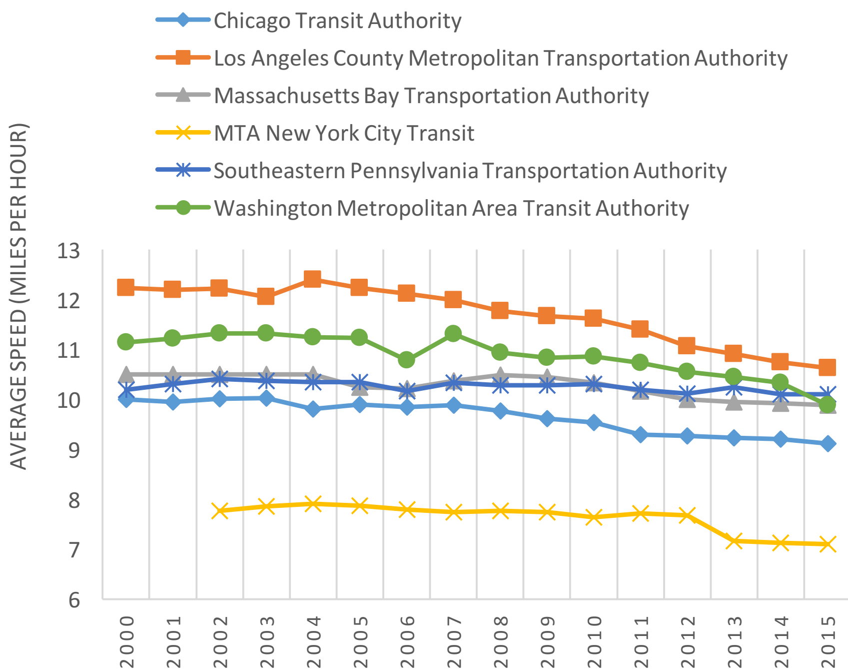


Figure 3-6 highlights that average bus speeds from the nation's largest bus fleets reported to NTD have declined for nearly all of them in the last 15 years, perhaps due to rising congestion.

Figure 3-6: Average speed over time of largest U.S. transit bus fleets (NTD)



The 2009 TCRP WVU and Post 2010 TCRP lifecycle cost models use field and dynamometer test data of fuel economy measures paired with average speeds of the routes those vehicles were deployed on to estimate a relationship between speed and fuel economy for each bus type, and then used that relationship equation in their model (see Figure 3-7). The researchers generally found a very similar speed-fuel economy curve between the field and test data, with the field data approximately 26% lower than the test data.

Figure 3-7: Diesel bus fuel economy data and fitted trend lines (Clark et al., 2009)

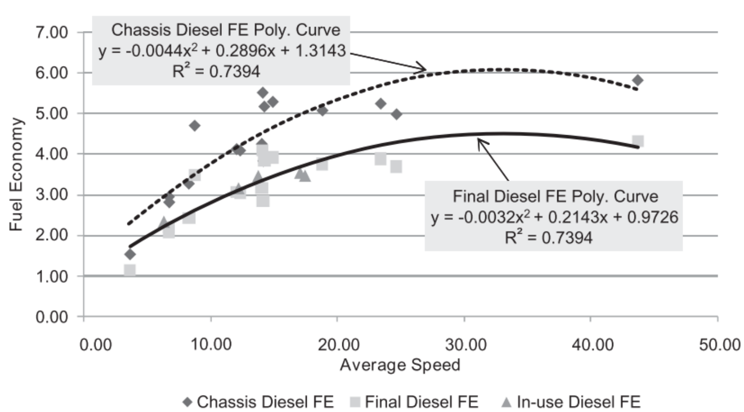


Figure 2.2. Diesel bus fuel economy data and parabolic trend lines.

Using vehicle simulation software, researchers estimate that fuel economy for electric buses varies less by speed than conventionally-fueled buses, while auxiliary loads have a relatively greater impact, as is depicted in graphs in Figure 3-8, which show the range of fuel economy for different drive cycles for diesel buses on the left, hybrid buses in the four middle bars, and electric buses on the far right. The graph on the left shows the variation by drive cycle in raw energy consumption figures, while the graph on the right shows the percent variation by auxiliary loads of total energy consumption across different bus types. While the impact of auxiliary loads is greater for battery electric buses, their energy consumption still varies less than other technology types.

Figure 3-8: Variation in energy consumption over different drive cycles and auxiliary loads (Lajunen, 2014)

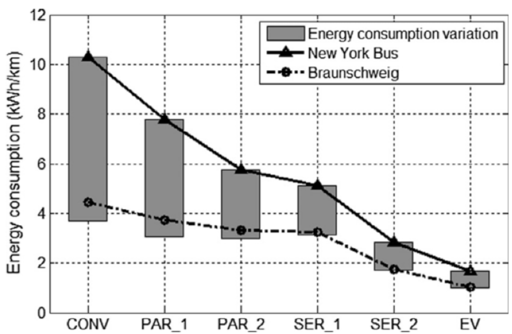


Fig. 3. Variation of the energy consumption.

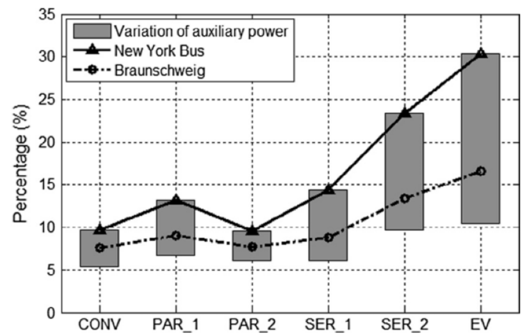
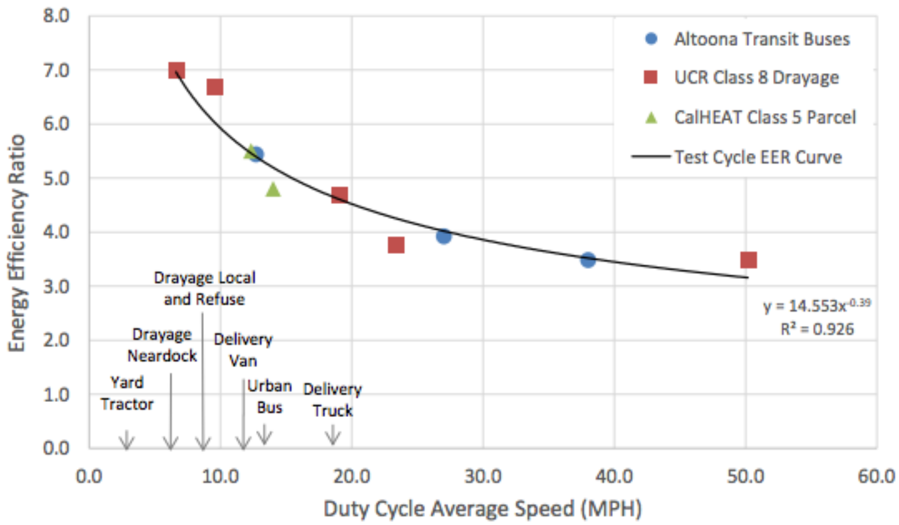


Fig. 6. The auxiliary energy consumption as percentage of the total energy consumption.

For this analysis, the equation established for the 2009 TCRP WVU model and used in the TCRP post-2010 bus procurements model is used for diesel, diesel hybrid, and CNG buses. The equations for conventional fueled vehicles were improved by 15% to account for advances in fuel economy since that model was developed, which corresponds to EIA's projections for heavy duty fuel economy increases of 5% every 5 years (Hao Cai, Andrew Burnham, Michael Wang, Wen Hang, 2015). When setting the speed to 13.3 mph, and adjusting the equations developed by WVU by 15%, the base values better approximate the in-use fuel economy estimated by the California Air Resources Board in 2017.

For battery electric buses, this research relies on a CARB analysis of battery electric bus and truck energy efficiency ratio, or the fuel economy ratio to a comparable conventional diesel vehicle operated in the same duty cycle. The CARB analysis found a robust relationship, shown in Figure 3-9, between average speed and energy efficiency ratio across multiple heavy duty vehicles that is used to estimate battery electric bus fuel economy relative to diesel buses at each speed for this analysis.

Figure 3-9: Battery electric bus and truck energy efficiency ratio at different average speeds (California Air Resources Board, 2017)



In addition, the TCRP WVU model adjusts the speed-based fuel economy to account for A/C or heater use, based on user-inputs ranging from 0-10 for A/C (0 being cold climates with no A/C use, 5 for temperate zones, and 10 for tropical zones where A/C always on), and 5-10 for heat (5 for no heaters used to 10 for cold climates where heaters are used more than 6 months a year). Researchers analyzed the seasonal deviance from the average fuel economy to estimate how to adjust the base fuel economy for different seasons. Using seasonal fuel economy data from manufacturer Proterra for buses in different cities, these buses had on average an 8% increase over their average fuel economy in their best fuel economy month (typically spring), and on average a 10% decrease in their worst month (summer or winter depending on the location), resulting in the range shown in Figure 3-10, which is greater than the other bus types. This analysis adjusts the base fuel economy with the A/C and heater load adjustment factors in Figure 3-11.

Figure 3-10: Battery electric bus fuel economy seasonal range (data from Proterra) (figures in MPDGE)

Location	Full Year	Winter	Summer	Best Period	Best FE period	Max increase	Max decrease
Stockton, CA	19.7	17.7	18.9	20.8	Spring	6%	10%
Seneca, SC	18.6	19	17.4	19.8	Spring	6%	6%
Springfield, MA	14.9	13.6	-	15.7	Spring	5%	9%
Seattle, WA	15	12.7	15.2	17	Spring	13%	15%
Average						**8%**	**10%**

Figure 3-11: A/C and Heater Load Adjustment Factors Table (TCRP WVU model, Clark 2009 except battery electric bus values)

Scale	Diesel	Diesel Hybrid	CNG	BEB
0	104%	106%	106%	108%
1	103%	105%	105%	106%
2	102%	104%	104%	105%
3	102%	102%	103%	103%
4	101%	101%	101%	102%
5	100%	100%	100%	100%
6	99%	98%	99%	98%
7	97%	97%	98%	96%
8	96%	95%	97%	94%
9	95%	94%	95%	92%
10	93%	92%	94%	90%

Based on the adjusted equations developed by the TCRP WVU model, and the one estimated using CARB's data, the base fuel economy for the four fuel technologies are included in Figure 3-12, without any adjustment for A/C or heat.

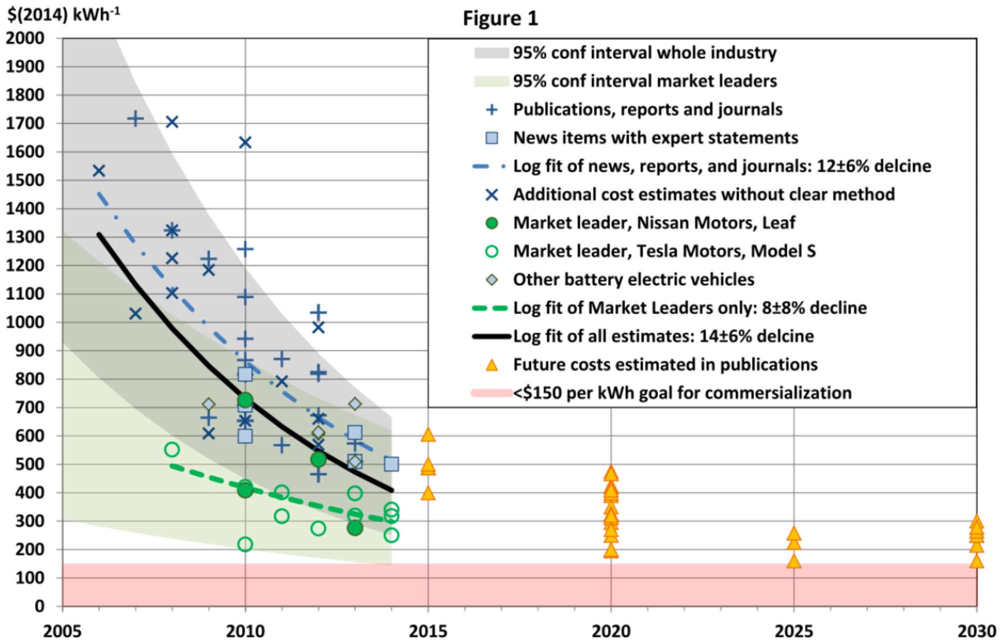
Figure 3-12: Base fuel economy for four speed categories

Duty cycle	Average Speed	Diesel	Diesel Hybrid	CNG	BEB
Slow city	6 mph	2.5	3.3	1.9	16.9
Fast City	11.5 mph	3.5	4.2	2.8	18.5
Suburban	20.5 mph	4.6	5.2	4.0	19.7

3.1.5 Bus purchase cost

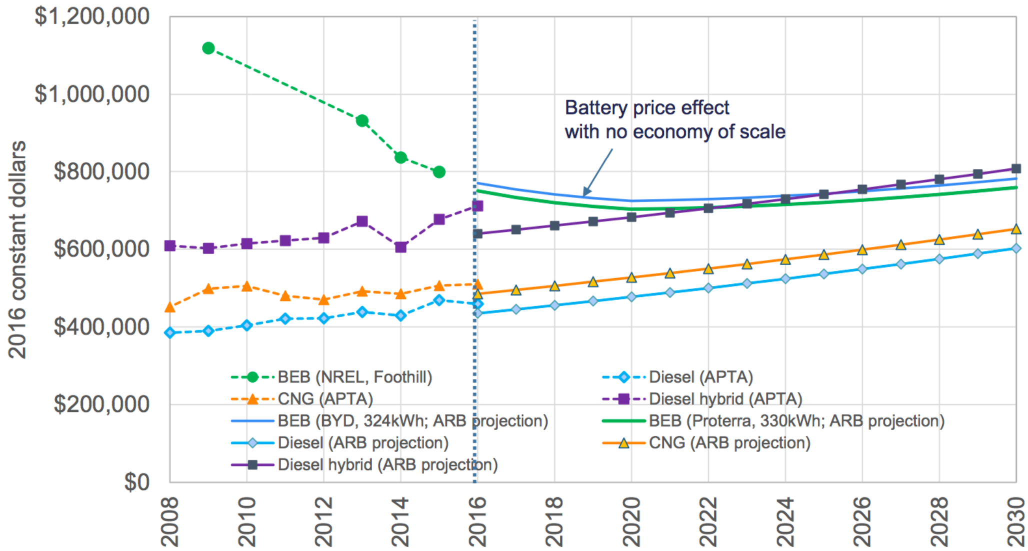
The primary difference in cost between conventional and electric vehicles is the power train, particularly the battery, which has been declining in cost consistently as production has increased. In a 2015 article for Nature, Nykvist and Nilsson undertook a comprehensive review of battery cost literature, finding that the cost of battery packs for leading EV manufacturers have declined faster than anticipated, due perhaps to learning rates amongst manufacturers and increasing production volumes, with battery costs per kWh in 2014 already below those projected for 2020 (see Figure 3-13) (Nykvist & Nilsson, 2015). The authors estimate costs have declined approximately 8% annually from around $1,000 per kWh to around $300 per kWh, with $150 per kWh being the commonly understood threshold at which EVs would become cost competitive with conventional vehicles (Nykvist & Nilsson, 2015). Between 2011 and 2015, cumulative battery capacity grew 100% annually, after which Tesla's new gigafactory and other major production facilities have likely increased that rate.

Figure 3-13: Historical and projected battery cost curves (Nykvist & Nilsson, 2015)



While battery costs for heavy duty electric vehicles is currently higher than light duty vehicles due to lower production volumes, analysts predict heavy duty vehicle batteries will experience similar trends. The California Air Resources Board's (CARB) Advanced Clean Transit Workgroup undertook a comprehensive battery cost analysis for heavy duty electric vehicles in 2016, predicting battery costs would fall from $720/kWh in 2016 to $230/kWh by 2030 (California Air Resources Board Advanced Clean Transit Program, 2016). Using the Consumer Price Index (CPI) to adjust historical APTA data (2006-2015), CARB's analysts found bus prices generally increased faster than inflation, increasing annually by 2.35%. Using base diesel and CNG bus prices reported by transit agencies participating in CARB's Advanced Clean Transit Working Group, and diesel hybrid bus prices based on a Washington state bus contract, analysts found the median incremental cost from diesel to diesel hybrid bus in 2016 to be $210,000 ("Washington State Contract: Heavy-duty Mass Transit Vehicles," 2015). Through discussions with electric bus manufacturers BYD and Proterra, battery cost reduction trends, and assumed non-battery cost bus price increases of 2.35% annually, CARB projects the premium for battery electric bus prices will fall by approximately $100,000 between 2016 and 2020, and that the battery portion of bus costs will continue to decline 3% through 2030, narrowing the premium between battery electric depot charge buses and diesel buses from $288,000 in 2017 to $157,000 in 2030, as can be seen in Figure 3-14. Academic research has similarly predicted a 2% annual cost decrease for electric buses (Lajunen & Lipman, 2016). CARB's projections for battery electric bus prices might be considered conservative, as they assume no price decrease for potential gains from economies of scale. Already, some agencies are seeing pricing below $700,00 per bus as they make larger procurements, far lower than CARB's projections, with BYD winning a bid with LA Metro for a base pre-tax cost of approximately $686,000 per bus for 60 electric buses in 2017; in comparison, bids for 295 low NOx CNG buses came in at an estimated $620,000 per bus pre-tax (LA Metro, 2017a, 2017b).

Figure 3-14: Historical and projected cost curves for bus technologies (California Air Resources Board Innovative Clean Transit Working Group, 2017b)



While considerable uncertainty remains regarding future battery cost decreases, the projections produced by CARB are used for this lifecycle analysis (California Air Resources Board Innovative Clean Transit Working Group, 2017b). These costs are for the "base" bus which includes ADA and other standard equipment, but not elements like fare boxes or automatic data collection systems. The analysis for this research assumes a 330 kWh battery for 40' buses, which CARB estimates can handle a 150-mile daily range, though can be adjusted to up to a 660 kWh battery pack (California Air Resources Board Innovative Clean Transit Working Group, 2017c).

3.1.6 Charging infrastructure and other capital costs

To estimate charging infrastructure and other capital costs, figures from CARB's Innovative Clean Transit cost assumptions for battery electric bus equipment and installation costs are used (see Figure 3-15). Actual installation costs and other depot upgrade needs will likely be highly variable due to different needs for electric capacity upgrades. At this point, no cost savings are assumed for chargers over time. The model assumes one depot charger per depot charge bus, and assumes 6 buses per on-route charger, within the feasible range of 4-8 identified by the FTA (Bloch-Rubin, Ted; Gallo, Jean-Baptiste, Tomic, 2014). The model does not assume any costs for CNG or diesel fueling infrastructure, due to the wide variability in capital cost estimates for these facilities, and assumes an agency already has these if procuring that technology.

Figure 3-15: Electric bus charging infrastructure cost estimates (California Air Resources Board Innovative Clean Transit Working Group, 2017e)

	Depot charge	On-route charge
Equipment	$50,000	$349,000
Installation	$55,000	$250,000

In addition to charging infrastructure, CARB also estimates "soft costs" for training, administration, professional services, contract spare, and other costs to be 2.5% of the bus price; this same assumption is used in the model.

3.1.7 Midlife costs

Transit agencies vary substantially in their approach to midlife rehabilitation of their buses. A 2007 FTA study found only the largest agencies operating in "severe" urban environments perform midlife overhauls, such as the MBTA, NYCT, WMATA, while no other agencies interviewed they did so (Richard Laver, Donald Schneck, Douglas Skorupski, Stephen Brady, Laura Cham, 2007).

This analysis uses figures from CARB's 2017 Advanced Clean Transit cost assumptions and LA Metro's Zero Emission Bus Options report to create a range of mid-life cost values for each technology (see Figure 3-16). The low range indicates no mid-life overhaul, which is the practice of many agencies, and could be true for battery electric buses as well, as BYD offers a 12-year battery warranty. The default values represent a mid-range that for the internal combustion engine buses are for engine overhauls and for battery electric buses, battery replacement. The higher values are for engine replacements, or in the case of battery electric buses, drive motor and inverter replacement. LA Metro, through discussions with manufacturers, determined the drive motor and inverter may need a midlife overhaul.

Figure 3-16: Estimated mid-life costs by bus fuel type (California Air Resources Board Innovative Clean Transit Working Group, 2017e; Ramboll Environ; M.J. Bradley & Associates, 2016)

	Low	Default	High
Diesel	$-	$35,000	$100,000
CNG	$-	$35,000	$100,000
Diesel hybrid	$-	$35,000	$100,000
Battery electric bus	$-	$75,000	$84,600

3.1.8 Maintenance cost

Manufacturers of electric buses have claimed substantial maintenance savings due to having a simpler drive train, fewer moving parts for technicians to maintain, and less brake wear due to regenerative breaking (which is the same for diesel hybrids). While these claims have been difficult to substantiate given that no current electric bus model has been on the road for its full useful life, there are now beginning to be empirical studies documenting electric bus maintenance savings. To determine maintenance savings used in this model, manufacturers' claims, academic and agency projections, and empirical studies were reviewed in order to select low and upper bounds for relative maintenance savings for different bus technologies (see Figure 3-18, Figure 3-19, and Figure 3-20). Researchers have found transit bus maintenance costs to be highly variable between and within agencies, due to a variety of reasons besides bus technology such as agency size and average speed, so there remains uncertainty regarding the actual savings a particular agency would experience (Little et al., 2016). Figure 3-17 illustrates this variability through the average maintenance cost per mile and standard deviation for transit agencies of different sizes.

Figure 3-17: Average maintenance cost per mile by bus fleet size (2015 NTD for buses 30' and over)

Bus Fleet Size	Average maintenance cost per mile	Standard deviation	N
Large (500 vehicles and over)	$2.91	1.46	27
Medium (100-499 vehicles)	$1.67	0.61	91
Small (0-99 vehicles)	$1.24	0.92	322

In addition to potential maintenance savings from cleaner technologies, the rising cost of diesel bus maintenance is another important consideration. Many agencies reported that maintenance costs have risen and reliability has worsened with the introduction of diesel particulate filters (DPFs), SCRs, and other technologies in post-2007 diesel buses that have improved emissions, but complicated maintenance for agencies. DPFs are designed to reduce particulate emissions by 90%, though need to be regenerated as soot accumulates. The accumulated soot can be burned off when exhaust temperature is high enough, though this only occurs at sufficiently high, sustained speeds, which some transit agencies' routes never reach. In 2009, Clark and his team at West Virginia University estimated post-2007 diesel buses would have 5% higher unscheduled maintenance costs (Clark et al., 2009). While nearly all agencies interviewed who run diesel buses discussed this issue unprompted, it is nevertheless difficult to quantify cost increases in the data due to the many factors that impact agency maintenance costs.

Figure 3-18: Manufacturers' maintenance savings claims

Manufacturer	Year	% Reduction in maintenance costs per mile, battery electric bus compared with a diesel bus
Proterra[14]	2017	38%
Complete Coach Works[15]	2017	80%
BYD[16]	2016	77%

Figure 3-19: Academic and government agency maintenance savings projections

Source	Source type	Year	Unit	Diesel Bus	CNG Bus	Hybrid Diesel	BEB
CARB Advanced Clean Transit	Environmental agency	2016	$/mile	$0.85	$0.85	$0.74	$0.60
		2016	- % difference (diesel to BEB)	-	0%	13%	29%
LACMTA[17]	Transit agency	2016	$/mile	-	$0.85	-	$0.808
		2016	- % difference (CNG to BEB)	-	-	-	5%
Electric Bus Analysis for New York City Transit (2016).[18]	Academic	2016	- % difference (diesel to BEB)	-	-	-	40%
Electric buses: A review of alternative powertrains (2016).[19]	Academic	2016	$/km	$0.38	-	$0.26	$0.2
		2016	- % difference	-	-	32%	47%
Life Cycle Assessment of Diesel and Electric Public Transportation Buses (2016)[20]	Academic	2011	- % difference (diesel to hybrid, BEB)			25%	25%

Figure 3-20: Empirical maintenance savings estimates

Source	Year	Unit	Diesel	CNG	Hybrid Diesel	BEB
Clemson CatBus[21]	2016	$/mile	$1.53	-	-	$0.55
		- % difference (diesel to BEB)	-	-	-	64%
Foothill NREL study[22]	2016	$/mile	-	$0.28	-	$0.22
		- % difference (CNG to BEB)	-	-	-	21%
King County NREL Study[23]	2017	$/mile	$0.44	-	$0.32	$0.18
		- % difference (Diesel to Hybrid, BEB)	-	-	27%	59%

CARB's Advanced Clean Transit workgroup conducted a review of maintenance costs for electric buses and concluded that the expected savings would primarily be from brake and propulsion-related costs (as opposed to body, accessories, heating and cooling, tires, etc.) (Guo, 2016). CARB's review also studied conventional bus maintenance costs, and concluded that propulsion and brake costs at mid-life typically represent 45-50% of maintenance costs. As a result, CARB sets 45% as an upper bound of maintenance costs savings, with a more conservative 29% estimated savings in its total cost of ownership model assumptions. Due to higher documented savings for battery electric bus maintenance, this analysis uses 21% as a lower bound, which is the savings documented in the Foothill NREL study (Eudy et al., 2016), while 59%, what was documented by the King County NREL study, is used as an upper bound, with 40% as a midpoint. Multiple transit agencies interviewed also reported an approximate maintenance savings of 40% for their electric buses. CARB's assumed cost per mile for hybrid buses is 13% less than for diesel, which is used as the mid-range; 27% less is used as the upper bound, which was the savings documented by the recent King County NREL study (Eudy & Jeffers, 2017).

Figure 3-21: Range of relative maintenance costs per mile to a diesel bus by fuel type

-% Difference $/mile relative to diesel			
	Low	Mid	High
CNG	-10%[24]	0%[25]	12%[26]
Diesel hybrid	4%[27]	13%[28]	27%[29]
Battery electric	21%[30]	40%	59%[31]

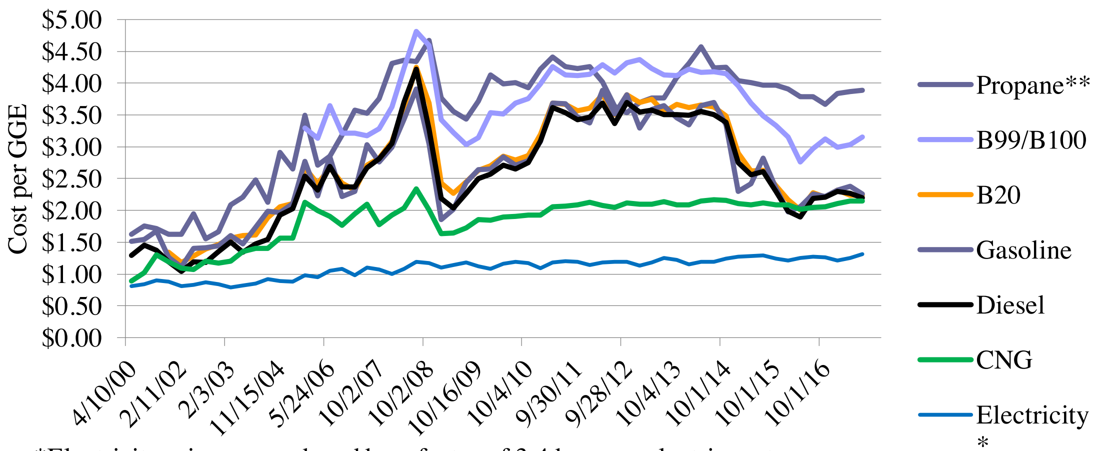
This analysis uses the average maintenance cost from 2015 NTD data of $1.43 per mile for a diesel bus, and then applies the low, mid, or high relative values for the other technologies in Figure 3-21. This analysis also then applies the same speed correction cost factor as the TCRP WVU 2009 model, included below, which corrected maintenance costs by average speed, based on much higher maintenance costs found for agencies operating in slow speeds (Clark et al., 2009). Their review of empirical data found maintenance costs were twice as high for buses operated at 6 mph as at 15 mph. Additionally, the TCRP WVU model discounts maintenance costs in first five years of the buses' life by half based on costs being less during warranty years, which is also applied in this analysis.

$$Correction\ cost = Original\ cost * (0.5 + \frac{7.5}{average\ speed})$$

3.1.9 Fuel prices

Fossil fuel prices have tended to be far more variable over time than electricity costs as seen in Figure 3-22, which can expose agencies to risk, though agencies tend to execute long term fuel contracts to help stabilize costs.

Figure 3-22: Cost per gallon equivalent by fuel type, 2000-2016 ("Alternative Fuels Data Center: Fuel Prices," n.d.)



*Electricity prices are reduced by a factor of 3.4 because electric motors are approximately 3.4 times as efficient as internal combustion engines (AFDC.gov)

This analysis uses EIA's Annual Energy Outlook 2017 projections for diesel, natural gas, and commercial electricity prices in real 2016 dollars through 2050 by region, and utilizes the EIA reference case, as well as high and low oil price scenarios. In the EIA reference case, diesel prices are projected to grow six times as fast as electricity prices, while natural gas prices are expected to decline. Price projections for diesel fuel also have the greatest differential between the low oil price and high oil price scenarios, introducing additional uncertainty for agencies (see Figure 3-23).

Figure 3-23: Projected annual growth rates in price (EIA Annual Energy Outlook 2017, 2015-2050)

FUEL	SCENARIO	GROWTH RATE (REAL 2016 $)
DIESEL	Low oil price	0.20%
	Reference case	1.80%
	High oil price	3.50%
NATURAL GAS	Low oil price	0.10%
	Reference case	-0.20%
	High oil price	0.40%
ELECTRICITY	High oil price	0.50%
	Reference case	0.30%
	Low oil price	0.30%

FOSSIL FUEL PRICES

This analysis uses a moving average fuel price over the lifetime of the bus, as is done in the TCRP WVU model, based on EIA's projections, and looks at three different EIA scenarios, Low Oil Price, Reference

Case, and High Oil Price. $2.00 per gallon was used as the current fuel price, based on numerous conversations with transit agencies who mostly had fuel contracts for slightly less or slightly more than $2.00 per gallon, which is then scaled based on the different EIA scenarios. CARB's assumption of a total $1.12 per diesel gallon equivalent for CNG in 2016 is used as the base assumption, yielding $0.76 when estimated operating and maintenance costs are subtracted (see Fueling Infrastructure Operations and Maintenance section).

ELECTRICITY PRICES

While electricity prices are generally more stable over time than fossil fuels due to the way in which they're regulated, they vary widely by geography and by particular tariff, making careful analysis prior to procurement important for agencies to understand their true cost of fuel for electric buses. Additionally, some agencies, particularly those without light or heavy rail, may be unfamiliar with procuring electricity to power their transportation systems and possible ways to introduce savings, especially if they are in states with deregulated electricity markets. Early deployments of electric buses have led to some key lessons learned about electricity costs, particularly demand charges as a key barrier to electric bus deployment, the importance for agencies to manage electric bus charging and practices to minimize costs, and the potential importance of introducing electricity tariff designs that are favorable to electric buses.

Many commercial and industrial electricity tariffs applicable to electric bus charging include demand charges, which levy a per kilowatt charge on the peak 15-minute demand over the course of a month, and are designed to recover a utility's fixed costs for transmission and distribution infrastructure. A survey of 26 major electric utilities by the FTA found that a majority levied demand charges on commercial customers, and that they ranged from $0 to $23.65 per kw (Bloch-Rubin, Ted; Gallo, Jean-Baptiste, Tomic, 2014). Some demand charges vary by time-of-use, and/or seasonally, particularly in California. The researchers found that demand charges "have been a surprise to some commercial electric vehicle users", and in some cases have been quite high, particularly for on-route charge buses using high capacity 500kw chargers during on-peak times, eroding some of the potential operating savings anticipated (Bloch-Rubin, Ted; Gallo, Jean-Baptiste, Tomic, 2014). Demand charges may still be an issue for depot charge buses as agencies undertake larger deployments and have many buses charging simultaneously.

Some agencies interviewed for this research discussed managing their fast charging schedules to keep the peak 15-minute draw from their fast chargers below about 10 minutes to minimize costs, and maximizing the number of buses utilizing the same charger to spread the demand charges over more buses. This of course introduces more operational constraints to manage, yet can help maximize fuel savings from electric buses. For depot charge buses, it is likely possible to stagger charging overnight such that the entire fleet isn't charging at once. With most agencies having heavily peaked service during the evening rush hour, early pull-ins could likely begin charging by 8pm, as is discussed further in Section 5.2.

CARB's Innovative Clean Transit initiative has developed a charging cost calculator to estimate the actual anticipated electricity costs of different charging strategies. This analysis expands upon CARB's charging cost calculator to include tariffs for agencies in Kentucky and Massachusetts, as well as for the MBTA, which has a unique situation in which it purchases electricity on the wholesale market. Additionally, electricity prices are scaled over time using EIA projections for commercial electricity. The model also enables different assumptions about the number of buses to use a single charger, the peak draw in different time periods, and the percent of charging that takes place during each time period.

3.1.10 Fueling infrastructure operations and maintenance costs

CNG fueling stations, for example, can incur substantial electricity costs from their operations, and battery electric bus chargers may require annual maintenance. CARB has made estimates of fueling operations and maintenance costs for different technologies that are used in this model (see Figure 3-24). CNG operations and maintenance costs are included in the default cost for CNG.

Figure 3-24: Fueling and charging infrastructure operation and maintenance costs

Diesel	$0.02	per DGE
CNG	$0.36	per DGE
Battery electric - depot charge	$500	per depot charger per year
Battery electric - on-route charge	$2,200	per bus per year

3.1.11 Bus retirement costs

This analysis does not account for end-of-life costs and emissions, given the difficulty of obtaining data as well as research suggesting minimal differences between bus technologies (McKenzie & Durango-Cohen, 2012). The main difference with electric buses is their large battery packs, which could either require additional costs to recycle, or as some analysts predict, could be worth $20-$120 per kWh to be reused to support the electric grid (Elkind, 2014; J. S. Neubauer, Pesaran, Williams, Ferry, & Eyer, 2012). When batteries have reached the end of their useful life for the vehicle, studies have found they still are useful to the electricity grid, particularly for frequency regulation ("PG&E Issues Findings on Battery Storage in Wholesale Markets," 2016). As of now, there is yet to be a standard second-life battery market, so potential value is still prospective and dependent on the comparative cost per kWh of new batteries which continues to fall. But the value of second-life batteries to the grid, whether for energy storage or other ancillary services like frequency regulation, has been demonstrated in pilots, and would have multiple environmental benefits including deferring battery recycling and supporting additions of intermittent renewable energy to the grid (J. Neubauer, Smith, Wood, & Pesaran, 2015). As the cumulative amount of battery capacity in electric vehicles on the road increases by orders of magnitude beyond the amount of installed stationary storage capacity, policymakers are analyzing how to encourage repurposing those batteries when they reach the end of their useful life as mobile storage, to enable much more additions of stationary storage capacity to the grid in the future (J. Neubauer et al., 2015).

3.1.12 Finance

This analysis looks at all cost parameters in constant 2016 dollars. Other lifecycle cost models have used a range of discount rates, with LA Metro using 4% to reflect their typical cost of capital, King County using 4.5%, and CARB using 3% (King County Metro, 2016; Ramboll Environ; M.J. Bradley & Associates, 2016). This analysis uses a 3% discount rate reflective of the current estimated cost of capital for a 30-year bond issue, based on the Thomson Municipal Market (MMD) AAA curve, as was recommended by one of the fleets interviewed for this analysis. The analysis then discounts costs to their appropriate year, with midlife costs being assigned to year 7 of the assumed 14-year lifetime of a bus. It is assumed that the 80% FTA formula funds typically available for bus replacements are fixed, and do not increase to match the increased first cost of a battery electric bus; in other words, it is assumed that local agencies will need to be able to afford the full incremental cost of a battery electric bus compared with their baseline vehicle.

3.2 Battery electric bus total cost of ownership analysis

3.2.1 Base case total cost of ownership analysis

The parameters summarized in Figure 3-25 are used to create a base case analysis of lifecycle cost by bus technology intended to represent an average case, and are summarized and referenced in the previous sections. This case is then used to develop a sensitivity analysis to understand the relative importance of different parameters affecting potential total cost of ownership savings for battery electric buses compared to other bus technologies. Only depot charge bus costs are modeled in these sections, due to the apparent movement of the industry towards these models.

The base case analysis and sensitivity analysis was conducted for a procurement of depot charge buses in 2020, with parameter ranges for the sensitivity analysis selected based on available data and forecasts within a maximum of 80% in each direction of the midpoint used in the base case analysis (some expected ranges varied less than that). Mileage range was selected based on the distribution of annual mileage per vehicle by agency in the U.S. according to NTD data. Other modeling efforts often use 41,667 as a midpoint as that would be the yearly mileage for a vehicle run 500,000 miles over 12 years, the FTA definition of the useful life of a bus. Speed ranges were selected based on the national average weighted speed of 13.3 mph according to NTD data, ranging from 7.5 mph (San Francisco MUNI) to 23.9 mph, though some agencies have higher average speeds than that. Some parameters, including speed, grow in opposite directions, and were ordered based on the direction that is more favorable to electric buses for the sensitivity analysis, to be able to better compare the influence of each parameter. While typically slower speeds are not an advantage, battery electric buses are likely to have a relative advantage compared to conventional buses at lower speeds, which is reflected by bus speeds' influence on the fuel economy and maintenance costs of the vehicles within the model.

The fuel price range was based upon what the diesel price would be in 2020 based on the EIA's Low Oil price case, Reference Case, and High Oil Price case scenarios, starting with $2.00/gallon diesel in 2017. The maintenance cost difference utilizes the cost differential recorded in the two NREL studies thus far that found a 21% difference relative to CNG at Foothill Transit for electric buses, and a 59% difference relative to diesel buses at King County Metro (Eudy & Jeffers, 2017), with 40% used as the midpoint.

Determining an "average" case is somewhat difficult, particularly for modeling electricity rates, given the wide variance in rate structures and prices for demand charges and per kWh fees. The average per kWh fee was selected based on a national average for commercial rates, and the range was based upon rates in the tariffs applicable to the fleets studied in the case study states. The average demand charge was selected based on the midpoint of the range identified by the FTA's survey of demand charges (0 to $23.65/kw), though they can range even more substantially (Bloch-Rubin, Ted; Gallo, Jean-Baptiste, Tomic, 2014). The sensitivity analysis only varies one off-peak demand charge in order to provide some insight into the influence of demand charges relative to other cost parameters, and does not explore the interplay between different peak period demand charges that exist for many utility tariffs, though this is explored further in Section 5.1. In practice, demand charges can range even more than the range reflected here, with some utilities having no demand charges, and some having up to a combined $30-$40 per kw across all time periods. The degree of managed charging was selected based on the range used in CARB's Innovative Clean Transit electricity cost modeling, with 75% of the maximum potential draw (or of vehicles charging simultaneously) as a midpoint, ranging from 50% to 100%.

Certain values were held constant, including a value of 8 for both heating and A/C loads, a charger rating of 80 kw per charger, an assumption of a single depot charger per bus, and the middle value for mid-life costs of about $35,000 for conventional fuel buses and $75,000 for battery electric. In reality, these values will vary based on weather, and for midlife costs, based on an agency's individual practices and selection of bus makes, models, and warranties. While some agencies interviewed for this analysis suggested a potential need for a greater than 1:1 bus replacement ratio, this analysis assumes that electric buses can be deployed strategically in the coming years on routes and assignments that can handle their more limited range, and assumes ranges will improve to be able to handle all assignments between 2025 and 2030.

Figure 3-25: Summary of assumptions for base total cost of ownership analysis in 2020

CAPITAL COSTS	Diesel	CNG	Diesel hybrid	Battery electric – depot (330 kwh)
Base bus cost (2020)	$477,000	$527,000	$682,000	$703,000
Charger equipment	-	-	-	$50,000 (assumed one bus per charger)
Charger installation	-	-	-	$55,000
Mid-life costs	$35,000	$35,000	$38,000	$75,000
OPERATING COSTS	**Diesel**	**CNG**	**Diesel hybrid**	**Battery electric – depot (330 kwh)**
Annual miles driven	40,000			
Speed	13.3 mph			
Fuel costs in 2017 (scaled with Reference Case)	$2.00/gallon	$1.12/DGE	$2.00/gallon	Per kw - $12.00 Per kWh - $0.10 Meter fee - $150; no time-of-use variance
Maintenance costs ($/mile)	$1.25	$1.25	$1.09	$0.75 (40% less than diesel)
Fuel economy (MPDGE)	3.5	2.9	4.1	17.3
Charging assumptions				80 kw per charger; 75% buses charging simultaneously

Following the above assumptions for the base case analysis, the sensitivity analysis uses the ranges in Figure 3-26 to test the impact of each parameter, varying each parameter 80% (or less based on expected reasonable ranges) in each direction of the midpoint. Parameters to vary were chosen based on those that clearly vary substantially by agency, or that literature or agency interviews indicated uncertainty about.

Figure 3-26: Sensitivity analysis ranges

Parameter	Unfavorable	Midpoint	Favorable
Miles per year	24,000	40,000	56,000
EIA fossil fuel price scenario (2020)	Low oil price ($2.16/gal)	Reference case ($2.63/gal)	High oil price ($3.30/gal)
Maintenance cost differential (BEB to diesel)	-21%	-40%	-59%
Speed (impacts fuel economy, maintenance cost) (mph)	23.9	13.3	7.5
Managed charging (% of maximum power draw)	100%	75%	50%
Demand charge rate (per kw)	$21.60	$12.00	$2.40
Per kWh fees	$0.18	$0.10	$0.03

Under the referenced midpoint parameters, CNG buses have the lowest total cost of ownership in 2018, followed by diesel buses, depot charge battery electric buses, and diesel hybrid buses. In 2019, under CARB's projected bus purchases costs, battery electric buses would become more cost effective than diesel buses, as can be seen in Figure 3-27. This indicates that under "average" parameters, battery electric buses are already or soon will be cost effective on a total cost of ownership basis compared to diesel and diesel hybrid buses without any additional subsidies. With less of a capital cost premium and cheap fuel that is projected to remain cheap, the total cost of CNG vehicles is projected to remain lower than battery electric buses through 2032 under the EIA Reference Case. This however is only true for fleets currently with CNG buses, as this analysis does not take into account the cost of depot retrofits or CNG fueling infrastructure investments, which can be substantial and vary widely between agencies. However, total cost of ownership will vary substantially by agency, due to different operating contexts, available electricity tariffs, and each agencies' strategic approach to electrification.

Figure 3-27: Discounted total cost of ownership per bus technology, 2018-2032

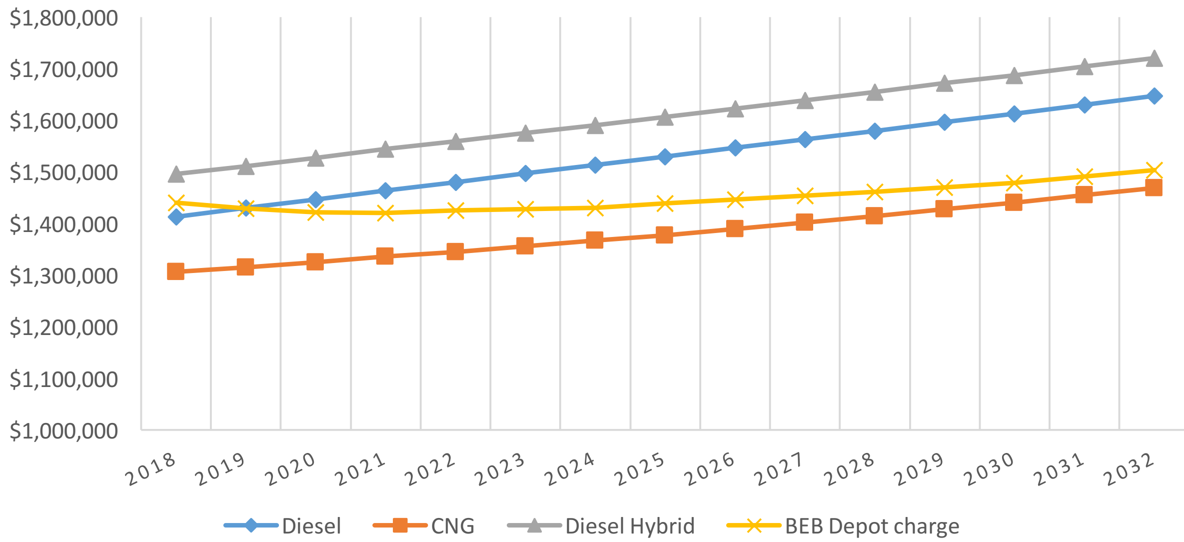
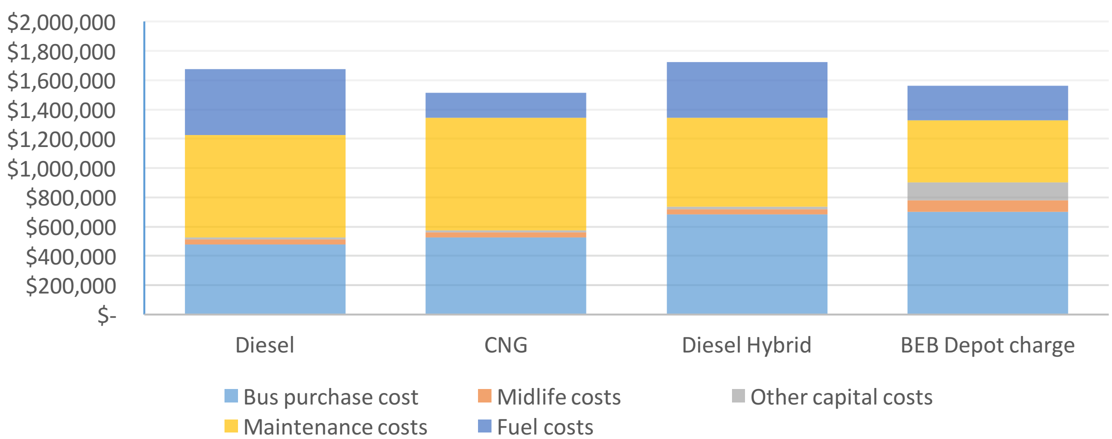


Figure 3-28: Discounted total cost of ownership by bus technology and cost category, 2020



This analysis does not take into account any depot expansion needs or greater than 1:1 replacement needs for electric buses, which would impact total cost of ownership savings if needed. Ambrose et al estimate depot expansion costs could range from $15,000-$40,000 amortized over the life of an electric bus, which could be needed to accommodate charging infrastructure, though this will vary by agency and their current depot capacity, and their charging infrastructure strategy (Ambrose et al., 2017). LA Metro, the California Transit Association, and Ambrose et al also assume that a greater than 1:1 replacement ratio may be needed to accommodate range limitations, though some agencies interviewed planning for full electrification expressed being able to sequence bus assignments for electric buses to electrify longer assignments last when bus range will likely have increased to be able to accommodate all assignments.

3.2.2 Sensitivity Analysis

While an initial analysis with somewhat average parameters indicates that battery electric buses will soon be cost effective on a total cost of ownership basis in comparison with diesel buses, several of these parameters vary widely regionally or by transit agency, while others are still estimates and lack a depth of empirical evidence. To understand the relative importance of some of these factors, this section includes a sensitivity analysis to understand which factors have the greatest impact on total cost of ownership in comparison with a diesel bus.

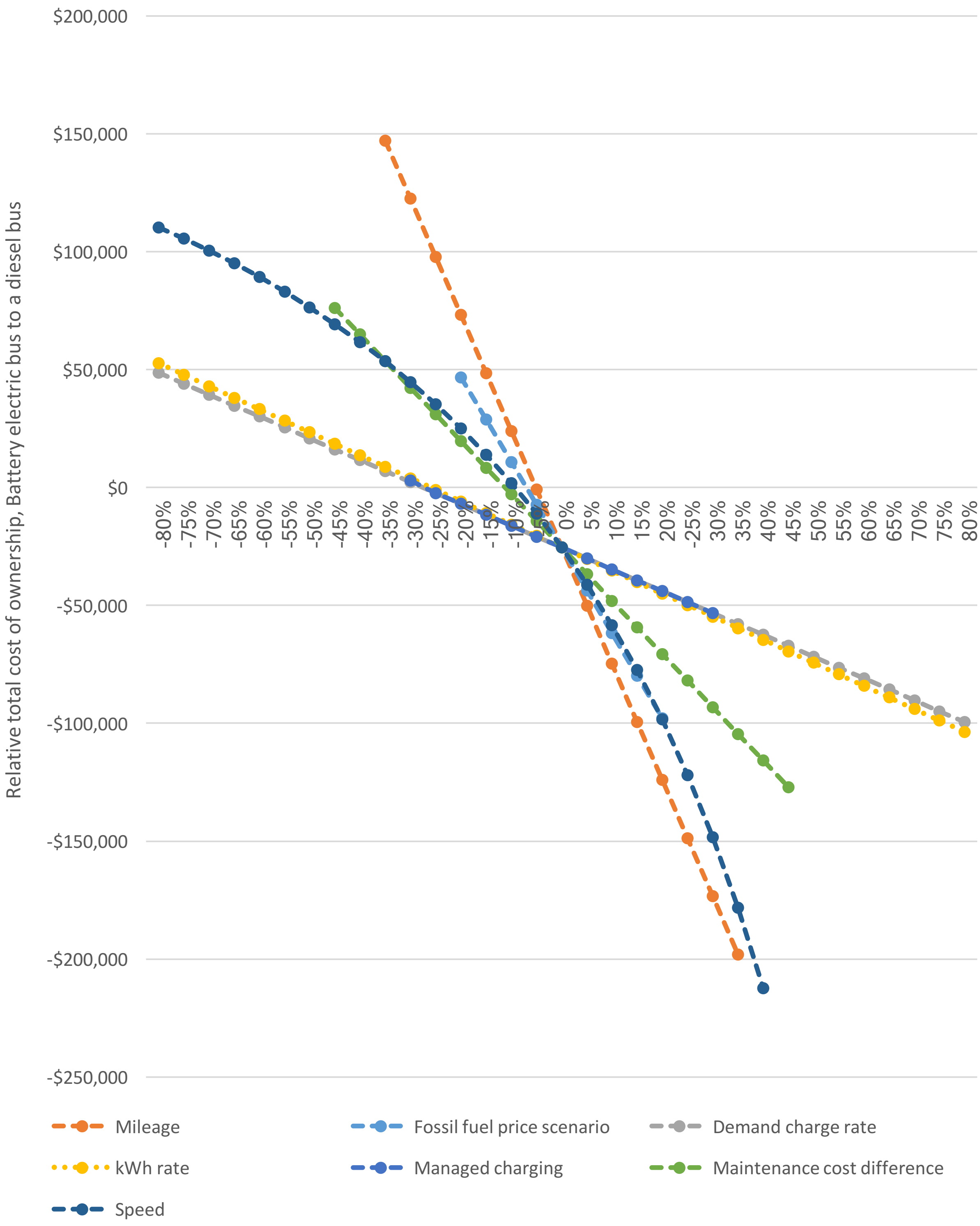
One approach to conducting sensitivity analyses is to set all parameters to an average or moderate value, and change one parameter at a time. Parameters are changed within a reasonable range 5% at a time up to a maximum of 80% in each direction, and the corresponding change in the discounted lifecycle cost differential between a battery electric depot charge bus and a diesel bus is recorded. Those values are then plotted on the same graph (Figure 3-30), known as a spider plot, in which the steepest line represents the most influential parameters that effect the greatest change in lifecycle cost.

Figure 3-29: Sensitivity analysis results

Sensitivity rank	Parameter	Unfavorable	Moderate	Favorable
1	Miles per year	24,000	40,000	56,000
2	EIA fossil fuel price scenario (2020)	Low oil price ($2.16/gal)	Reference case ($2.63/gal)	High oil price ($3.30/gal)
3	Speed (impacts fuel economy, maintenance cost) (mph)	23.9	13.3	7.5
4	Maintenance cost differential (BEB to diesel)	-21%	-40%	-59%
5	Per kWh fees	$0.18	$0.10	$0.03
6	Managed charging (% of maximum power draw)	100%	75%	50%
7	Demand charge rate (per kw)	$21.60	$12.00	$2.40

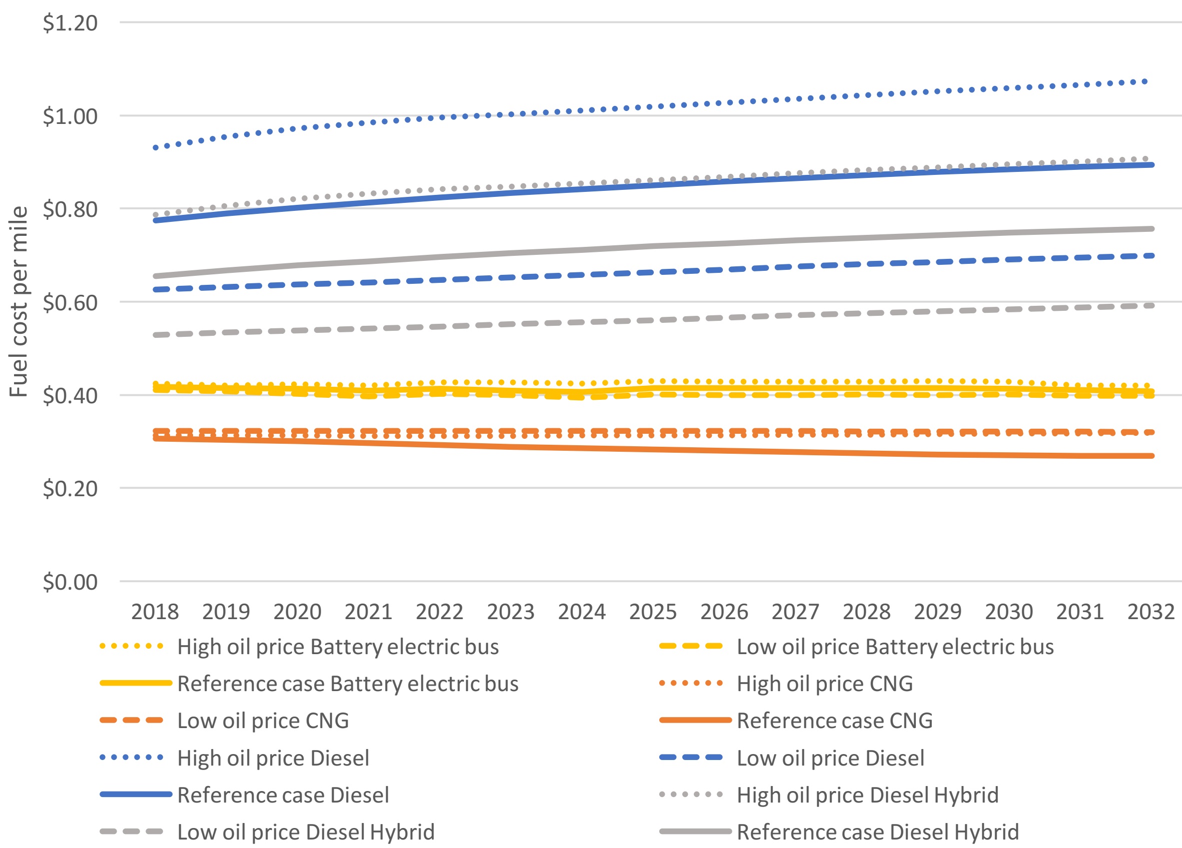
According to this preliminary analysis, cost savings from a battery electric bus relative to a diesel bus is most sensitive to the annual miles a bus is driven, followed by fossil fuel price scenario, the average speed of the bus, the maintenance savings of an electric bus compared with a diesel bus, the per kWh rate, the degree of charging management, and finally the demand charge rate, as is summarized in Figure 3-29. This analysis suggests that increasing electric bus utilization, which can vary widely between agencies, and for buses within a single agency, is essential for realizing cost savings. While range limitations may limit agency's ability to deploy buses on long enough bus blocks initially, manufacturers' newest models should be able to cover the approximately 130-mile daily range needed for an annual utilization of 40,000 miles per year, and larger available battery packs could cover even longer assignments.

Figure 3-30: Sensitivity analysis spider graph: Relative total cost of ownership of a battery electric to a diesel bus in 2020



Other important parameters, such as relative fossil fuel prices and the actual maintenance savings of battery electric buses, are less under the control of transit agencies considering deploying electric buses, which creates uncertainty for the potential to realize cost savings over time. By switching to electric, agencies have the opportunity to shield themselves from future oil price volatility, as seen by the much narrower range of estimated fuel costs per mile between EIA fuel price scenarios for electricity than for diesel (though CNG costs also vary far less) in Figure 3-31. Similarly, while empirical evidence suggest that agencies will experience maintenance savings, the research on actual maintenance cost savings from battery electric buses is still relatively limited, driving some uncertainty for transit fleets.

Figure 3-31: Fuel cost per mile by bus technology and EIA fuel price scenario, 2018-2032



Due to the speed correction factor applied to maintenance costs and fuel economy, speed's influence on lifecycle cost savings is greater for buses operating in slower speeds, indicating that electric buses have an even greater advantage over conventional fueled buses operating on congested, urban routes. This suggests that another way agencies may want to prioritize deployment would be based on slower speed routes where cost savings and emissions reductions would be greater.

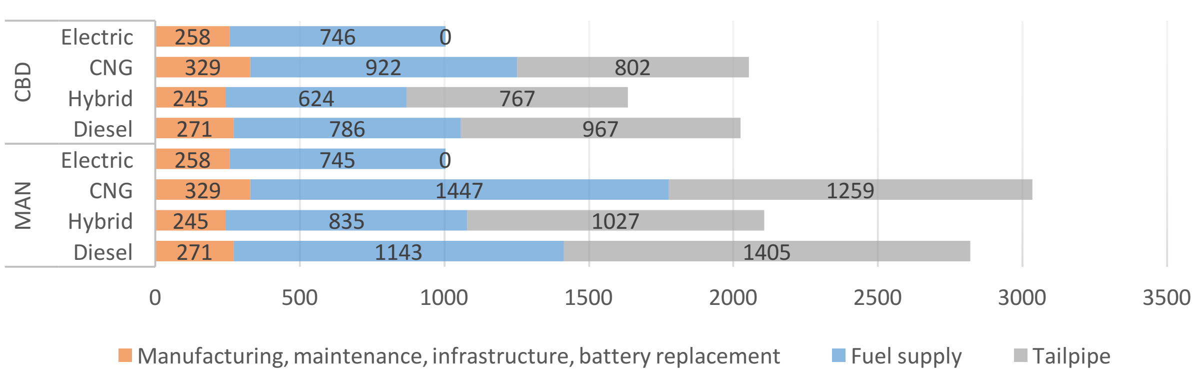
Interestingly, all three parameters associated with electricity costs had a very similar impact on lifecycle cost savings, with per kWh fees having a slightly greater impact than managed charging and demand charges, though the degree of managed charging suggests a much smaller potential range of impact. This analysis suggests that while demand charges have been a big hurdle for on-route charge buses, they may be less of an issue for depot charge buses that will likely have a better load factor; however, this analysis did not take into account the full range of demand charges which can be even higher across all time periods than is accounted for here. Overall, this suggests that agencies can make an important impact on lifecycle cost savings by proactively managing their charging, but that seeking more advantageous tariffs will also be important.

Overall, this sensitivity analysis suggests that if agencies proactively plan, they can improve the likelihood of realizing cost savings for electric buses by assigning them on longer blocks, in slower speeds, and by managing charging. Given the importance of electricity costs, agencies should model the available tariffs in their area prior to procuring electric buses, and if possible, should work with other agencies to advocate for more advantageous tariffs. Other important factors are less in the control of agencies, such as future oil prices and maintenance costs; still, investing in electric buses is likely to reduce maintenance costs regardless, and shifting away from fossil fuels has a benefit of avoiding future oil price volatility. The insights from this analysis are investigated in greater detail in Chapter 5 to form recommendations for better electricity tariffs and other interventions to support electric bus deployment.

3.3 Lifecycle emissions model inputs, assumption, and approach

Vehicle emission analyses often take a "well-to-wheels" approach, which accounts for both emissions produced in the "well-to-tank" phase, or emissions produced in fuel mining, processing, and transportation, as well as the "tank-to-wheels" phase that accounts for emissions from the actual operation of the vehicle. This analysis takes into account well-to-wheels emissions, but does not take into account the lifecycle impacts of vehicle manufacturing and salvage. Even under a likely too conservative assumption of four battery replacements over the life of a battery electric bus, Ercan et al estimate minimal differences compared with other bus technologies for the manufacturing, maintenance, infrastructure, and battery replacement portions of a buses' lifecycle (Ercan et al., 2015). Using the GREET model, they do estimate that manufacturing and battery emissions from electric buses will constitute a relatively larger share (26% compared to 10%) of lifecycle emissions than a diesel bus, but that overall battery electric buses are likely to have far lower lifecycle emissions. Additionally, researchers expect emissions from this portion of electric vehicles to improve over time as grid emissions intensity declines and battery manufacturing technology improves (Nealer, Reichmuth, & Anair, 2015). Figure 3-32 displays Ercan et al's results for lifecycle CO_2 emissions from different transit bus technologies in the Central Business District and Manhattan drive cycles.

Figure 3-32: Lifecycle CO_2 emissions (tons) by lifecycle phase, technology, and drive cycle



3.3.1 Greenhouse gas emissions

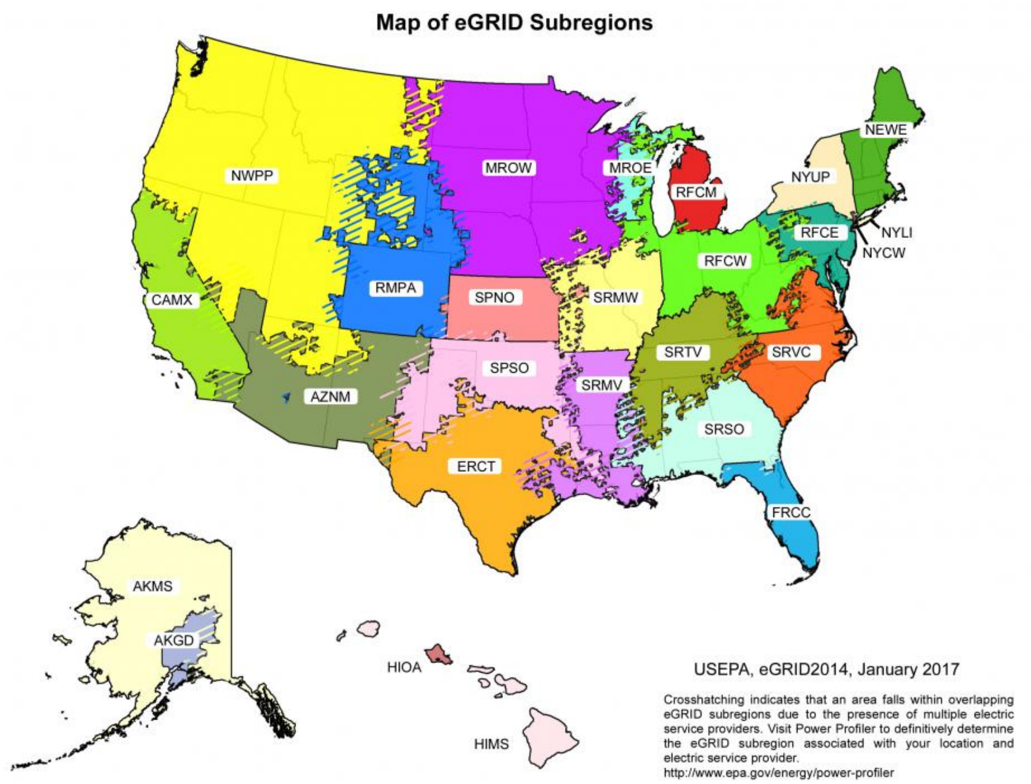
TAILPIPE EMISSIONS

Greenhouse gas tailpipe emissions, or those produced through vehicle operation, are calculated for this analysis using EPA emissions factors to convert diesel gallons and CNG diesel gallon equivalents consumed to CO_2 and greenhouse gas equivalents of CH_4 and N_20, as is recommended by the APTA Transit Emissions Quantifier tool (American Public Transportation Association, n.d.).

ELECTRICITY EMISSIONS

Emissions from the electric grid depend greatly on when and where vehicles are connected to the grid, as emissions rates, or the greenhouse gas emissions produced per unit of electricity produced (kg/MWh), vary substantially by region due to different fuel mixes used. For this analysis, EPA eGrid subregions shown in Figure 3-33 are used to estimate electricity emissions, future electricity generation mixes, and electricity price projections.

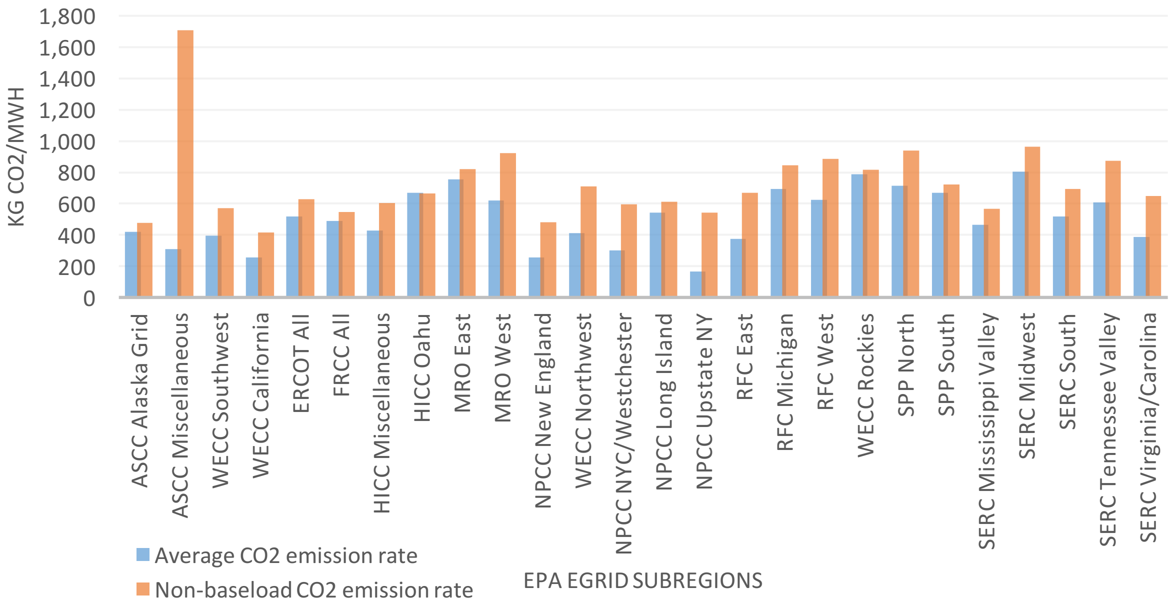
Figure 3-33: EPA eGrid Subregions



EPA's Emissions & Generation Resource Integrated Database (eGrid) provides data on emissions from power plants grouped into regions based on North American Reliability regions which reasonably reflect the electricity generation mix that serves households and businesses in each region. eGrid provides both average and non-baseload emissions factors for the power plants in each subregion; non-baseload emissions factors are calculated from plants which have low utilization factors, and can serve as a proxy for a marginal emissions factor.

Some studies of electric vehicles and buses use marginal emissions factors, which attempt to take into account the emissions from the marginal plant required to meet additional electricity demand on the grid at a particular time. Traditionally, these plants have been among the most polluting, such as small-scale oil power plants known as "peakers", and are operated to meet peak demand, typically in the early evening. Today those patterns are changing somewhat, particularly in places with a lot of solar power, which may require more natural gas or fossil fuel power overnight than during peak hours. The difference between marginal and average emissions factors can be substantial, as is clear from Figure 3-34.

Figure 3-34: Average vs. Non-baseload electricity emissions rates by EPA eGrid subregion (2014)



While important to consider, determining what future marginal emissions factors, and what electrons an electric bus will utilize is very complex, and depends greatly on the region and charging strategy that an agency employs. As a result, this analysis follows the methodology used by the Union of Concerned Scientists in their reports on electric vehicle and bus emissions to use the average emissions factor (Nealer et al., 2015). Assuming that electric buses will incur the marginal emissions factors from today's grid is probably unlikely, as different power sources such as natural gas, stationary storage, and renewables are increasingly playing the role that the dirtiest peaker plants once occupied, and depot charge buses will likely primarily charge overnight when grid emissions tend to be lower.

This analysis uses the average eGrid emissions factors, last updated in 2014, as is used by APTA, the FTA, the Union of Concerned Scientists, and others (Federal Transit Administration, 2016b). Future year electricity emissions are estimated using eGrid's emissions factors for oil, coal, and natural gas plants in each subregion and EIA's estimated electricity generation by power source through 2050 by region to produce estimated emissions factors for future years. These emissions factors are then multiplied by the projected electricity use in kWh based on the estimated fuel economy for electric buses. Emissions factors for CO_2, CH_4, and N_2O are estimated and converted to CO_2 equivalents using EPA's emissions factors. Emissions from line losses from transporting electricity over long distances are also not included, as EPA suggests that in standard carbon accounting methodologies, those losses would be considered the responsibility of the entity who owns the wires (Diem, Quiroz, & Pechan, 2012).

UPSTREAM GREENHOUSE GAS EMISSIONS

Upstream emissions for this analysis include emissions related to the mining, processing, and transportation of fuels used either for direct combustion or electricity generation. TCRP estimated in 2010 that so-called "well-to-tank" emissions for CNG and diesel are about 20-30% of their lifecycle emissions, and that well-to-tank emissions are approximately 12% higher for CNG than diesel (Blaylock et al., 2010). This analysis uses GREET factors of CO_2 equivalent emitted for each gallon of diesel and MMBTU of CNG multiplied by the quantity of fuel used over the life of the bus, and for electricity, uses the GREET per BTU feedstock figures for each electricity generation fuel multiplied by the electric grid mix over time in each region.

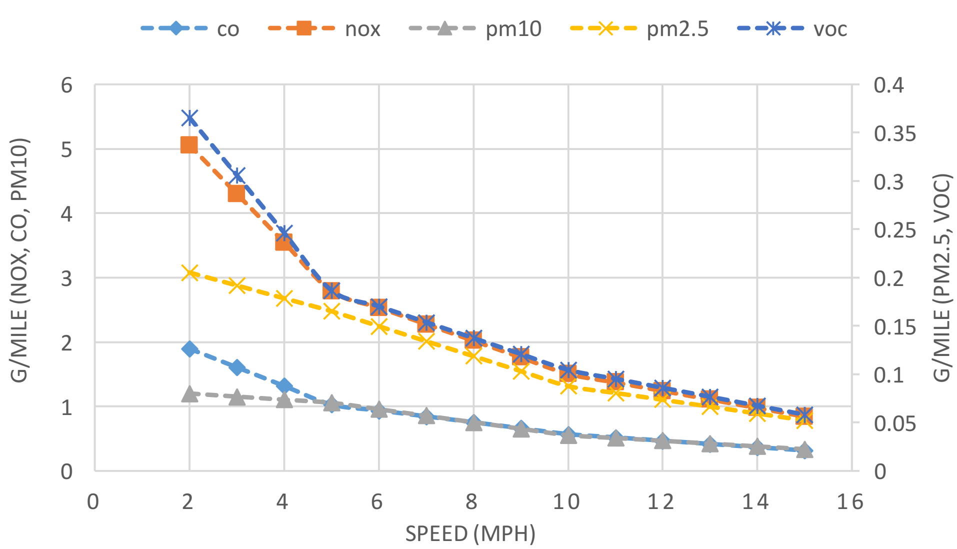
3.3.2 Criteria pollutant emissions

Argonne Labs' Argonne National Laboratory's Alternative Fuel Lifecycle Environmental and Economic Transportation (AFLEET) model, which is recommended for use for CMAQ applications, was utilized to estimate criteria pollutant emissions. This model combines a per mile emissions factor for transit buses for each criteria pollutant by model year generated by EPA MOVES, with data about how those emissions factors degrade over a vehicles' lifetime, and a multiplier to account for alternative fuel vehicles (CNG, hybrid, and battery electric buses). For example, to find the estimated NOx emissions for a model year 2015 diesel hybrid bus in 2020, the equation would be:

NOx emissions in year 5 (g) =
emissions factor (g/mi) for MY 2015 vehicle x *deterioration factor for year 5* x *alternative fuel vehicle emissions factor multiplier for a hybrid* x *annual miles traveled*

Criteria pollutant emissions, as well as greenhouse gas emissions, are also highly impacted by vehicle speeds and duty cycles, which AFLEET does not account for; however, EPA MOVES produces emissions rates for different speed bins, which are displayed for Eastern Massachusetts in Figure 3-35. The impact of slow speeds on criteria pollutant emissions is explored further in Section 5.2.

Figure 3-35: Emission rates by speed for a new diesel bus in Eastern Massachusetts (EPA MOVES)



3.3.3 Externalities

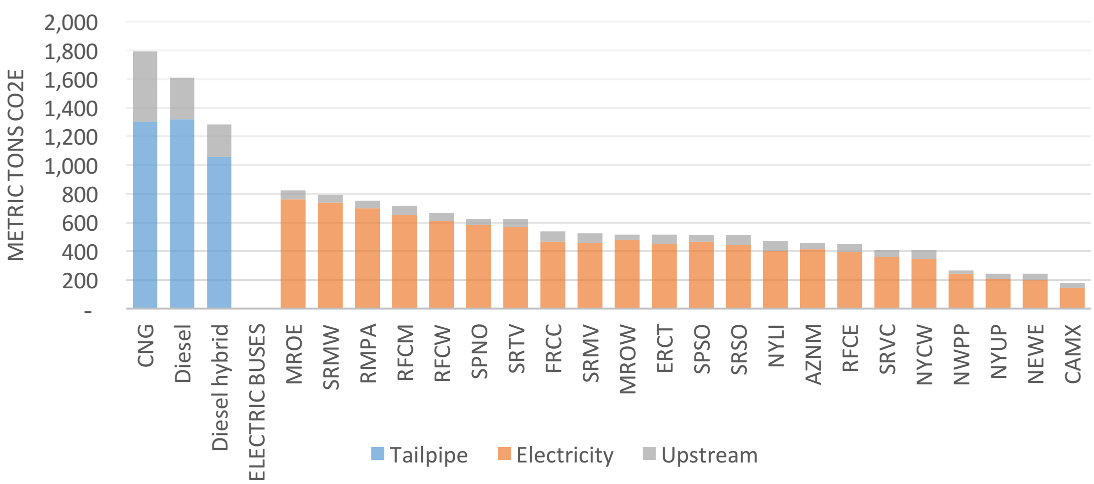
Externality costs were also estimated using AFLEET, which utilizes social cost of carbon estimates from the federal Interagency Working Group on the Social Cost of Carbon and includes "changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change" (Argonne National Laboratory, n.d.). To estimate the impact of criteria pollutant emissions, AFLEET utilizes externality estimates for VOC, NOx, PM2.5 and PM10 from the Air Pollution Emission Experiments and Policy Analysis (AP2) model, which calculates marginal criteria pollutant damages at the county level.

3.4 Battery electric bus lifecycle emissions comparison

3.4.1 Greenhouse gases

For this greenhouse gas emissions analysis, a bus driven 500,000 miles over a 12-year lifetime was assumed, along with average fuel economy figures for each bus technology used by CARB (3.9 mpg diesel, 2.9 mpg CNG, 4.8 mpg hybrids, and 2.17 kwh/mile for battery electric). Using these common assumptions, greenhouse gas emissions were then compared across the eGrid subregions by emissions category in Figure 3-36.

Figure 3-36: Lifetime lifecycle greenhouse gas emissions per bus by technology and eGRID subregion for buses procured in 2018



While a large variance in electricity emissions exists across subregions, all would have substantially less total well-to-wheels greenhouse gas emissions over an electric buses' lifetime than conventionally fueled vehicles, due in part to their greater efficiency, and in part to ongoing shifts in the electric grid to cleaner generating technologies. Total well-to-wheels GHG emissions are generally slightly higher from CNG buses than from diesel buses for example, due to their worse fuel economy and greater upstream impact of methane emissions from natural gas production and processing (MJB&A, 2013). Parts of the country in the Midwest, Rocky Mountain West, and South are projected to have the highest electricity emissions per electric bus, while parts of the Northeast and West Coast are projected to have much lower lifetime electricity emissions per bus. From an environmental perspective, battery electric buses have a substantial advantage over conventionally fueled buses throughout the country, particularly in parts of the country where the grid is more reliant on renewable resources, and less on coal and oil plants.

3.4.2 Criteria pollutant emissions

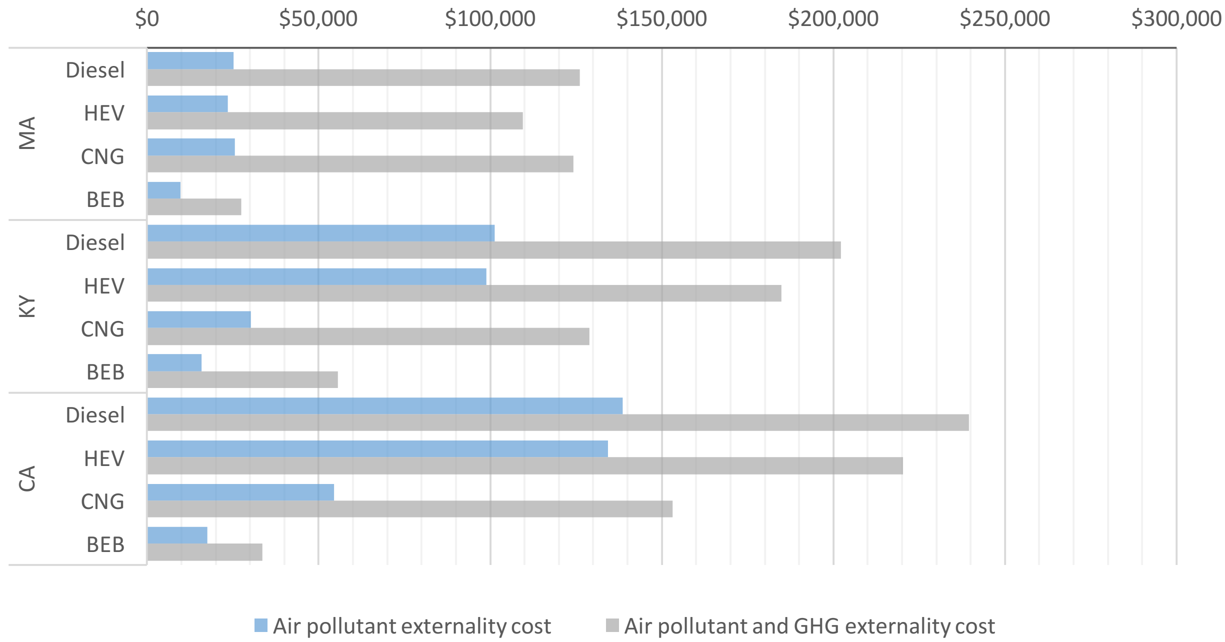
The well-to-wheels criteria pollutant emissions for different bus technologies were estimated for each state in Figure 3-37, taking into account tailpipe emissions rates that vary somewhat due to differences in local weather conditions and electricity grid emissions intensity in 2020 in each state.

Figure 3-37: Estimated well-to-wheels lifetime air pollutants per bus (lbs.) (AFLEET)

		CO	NOx	PM10	PM2.5	VOC	SOx
MA	Diesel	1,311	7,698	272	126	480	994
	BEB	636	693	219	56	120	240
	Hybrid	1,213	7,478	258	114	425	849
	CNG	30,462	2,570	227	81	673	995
KY	Diesel	1,272	7,423	250	122	475	994
	BEB	283	966	406	126	155	3,964
	Hybrid	1,175	7,202	235	110	421	849
	CNG	28,766	2,567	204	77	667	995
CA	Diesel	1,319	7,580	278	126	477	994
	BEB	394	543	203	47	94	557
	Hybrid	1,222	7,360	264	114	422	849
	CNG	30,854	2,569	233	81	668	995

For criteria pollutants, battery electric buses are anticipated to have the greatest reductions of NOx, with 87-93% less emissions than diesel buses in each state. For carbon monoxide (CO), battery electric buses are anticipated to have 51% (MA) to 78% (KY) less emissions compared with a diesel bus (99% less than a CNG bus). Massachusetts' CO emissions from battery electric buses are somewhat higher than the other states due to the northeast's heavy reliance on natural gas power plants. PM10 is estimated to be lower in CA and MA, but somewhat higher in Kentucky, likely due to a greater reliance on coal power plants. Additionally, PM emissions from this model account for significant tire and brakewear, which researchers believe is likely to be lower for regenerative braking vehicles, though there isn't yet sufficient research to account for this difference. PM2.5 is also anticipated to be lower in CA and MA than diesel buses, but not in Kentucky. VOCs are estimated to be 42-91% lower for battery electric buses, and SOx is estimated to be much lower in CA and MA, but much higher in Kentucky due to the more coal-reliant electricity mix there. Overall, externality costs estimated using the AFLEET model for greenhouse gases, VOC, PM10, PM2.5, and NOx estimate battery electric buses will have far lower air pollutant and greenhouse gas impacts on human health and natural systems than other bus technologies in all three states (see Figure 3-38). This analysis does not capture the benefits of reduced ultrafine particles, which are not yet regulated, but which may have much more serious impacts on human health. Over time, the emissions intensity for the electric grid in each region modeled is expected to improve, with Massachusetts and California anticipating additions of renewable energy to the grid to meet state renewable portfolio standards, and Kentucky anticipating a reduced reliance on coal power over time, which will improve battery electric buses' air quality impacts.

Figure 3-38: Lifetime well-to-wheels criteria pollutant and greenhouse gas externalities (AFLEET)



SECTION END NOTES

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4. Qualitative analysis of bus electrification case studies

Through literature review and qualitative stakeholder interview analysis, this chapter introduces each case study state, explores how their contexts relevant to electric bus deployment differ, and analyzes reported barriers and drivers to widespread electric bus deployment. The case study locations for this thesis were selected based on places where electric buses had already been deployed, so that agencies may be beyond simply testing the technology and may be ready for more substantial deployment. Importantly, these locations also differ along important dimensions such as climate and energy policy, politics, and electricity sector structure and pricing, providing insight into relevant policies for different contexts.

4.1 Introduction to case study state contexts: California, Kentucky, and Massachusetts

California, often the nation's leader in environmental policy, similarly in the case of electric bus deployment has been leading in developing a wide variety of complementary policies and programs to accelerate transportation electrification broadly and electric bus deployment specifically. Massachusetts, often a close-behind leader on the east coast, has some similar climate policies, but generally far fewer incentives, programs, and other initiatives designed to accelerate electric bus deployment specifically, offering a counter-example to California. Finally, Kentucky represents a very different political and policy context, one in which many of the nation's small to medium sized bus fleets likely find themselves in, in which very little state or local incentives or policies exist, and bus fleets must rely on federal supports or other pathways to support deployment.

4.1.1 Overarching federal context

In addition to the fuel economy and air pollution standards for heavy duty vehicles described in Section 2.3.1, the following grants, incentives, and other programs are also relevant for electric bus deployment.

GRANTS, SUBSIDIES, AND INCENTIVES

The FTA has formula funding programs totaling over $5 billion annually nationwide that cover about 80% of capital funds for bus replacements (20% required local match), though the subsidy per state or metro area doesn't increase when capital costs increase for new technologies or service expansion. There are many requirements for procurements to be eligible for capital funds; for example, each bus must be kept either for 12 years of 500,000 miles, must comply with Buy America regulations (60% American materials and assembled in the U.S.), and the bus model must have undergone testing in Altoona. FTA also stipulates the types of procurement methods that can be used. While the FTA still provides a substantial subsidy for bus capital purchases, operating subsidies have diminished over time, though many operating costs can still be covered with FTA capital funds, particularly some maintenance costs.

Figure 4-1: FTA formula funding programs for buses (FTA Statistical Summaries)

Program	Appropriation in 2015 (national)
Urbanized Area Formula Program	$4.5 billion
Non-urbanized Area Formula Program	$607 million
Bus and Bus Facilities (within Capital Investment Program - $2.1 billion total)	$428 million

Besides formula funds, other much smaller, discretionary grant programs come and go. The FAST Act made available $55 million a year through 2020 for a competitive grant process to fund the purchase or lease of “low or no emission buses”, and has been a key source of funding for many of the first battery electric bus deployments. In FY16, the program was very oversubscribed, with 101 projects totaling $446 million requested, and just 20 projects worth $55 million awarded (Federal Register, 2017). Low No grants require a 15% local match for vehicles, and a 10% local match for charging infrastructure.

The FAST Act also extended Congestion Mitigation and Air Quality Improvement Program (CMAQ) funding through 2020, with about $2.4 billion allocated per year nationally through state governments to projects that improve air quality and traffic congestion. Many states have used CMAQ funds for cleaner vehicles, though many other types of transportation investments also compete for these funds. The Volkswagen settlement mitigation trust will disburse $2.7 billion to states to spend on cleaner vehicles. States are now in the process of preparing plans for how to spend their share over the next 10 years, as this represents a major increase in the amount of funds available for these types of investments.

OTHER PROGRAMS

The Energy Policy Act of 1992 created the Clean Cities program which established coalitions around the country that work to provide technical assistance and support fleet transitions to alternative fuel vehicles; several Clean Cities coalitions were active collaborators with fleets looking to procure electric buses in the case study states. Most recently, the Clean Cities program is working on multiple bulk purchasing program for public fleets to attempt to bring down the cost of electric vehicles.

4.1.2 State and local policy context by case study state

This section introduces the policy and institutional contexts relevant to electric bus deployment in each case study state, including policy related to climate change, energy, electricity, and clean vehicles, informed by a literature review, relevant public data sources, and interviews with stakeholders. The relevant contextual factors for each state are summarized in Figure 4-2.

Figure 4-2: Case study policy and institutional context comparison summary

	CA	MA	KY
Political context	Very liberal, first-in-the-nation climate leadership. Strong environmental justice movements	Liberal, strong climate leadership. Current Republican leadership focused on transit agency austerity.	Conservative, coal and heavy manufacturing state
Air quality context	Major air quality issues in southern CA and Central Valley	Just one county in non-attainment in 2017	Moderate air quality problems
Goals, standards, and targets	AB32 (80by50) SB 350 (Renewable Portfolio Standard (RPS)) Zero Emission Vehicle Mandate (ZEV)	Global Warming Solutions Act (GWSA) (80by50) RPS ZEV Mandate	Voluntary local level goals and plans only
Climate policy mechanisms	Cap and trade Low Carbon Fuel Standard (LCFS)	Regional Greenhouse Gas Initiative (RGGI)	-
Bus fleet regulation	Transit fleet rule	CMR 310 60.05	-
Grants, subsidies, incentives for electric buses	HVIP LCFS	-	-
Programs	Innovative Clean Transit Washington State Contract	Clean Cities	Clean Cities Partnership for a Green City
Energy policy and context	SB 350 transportation electrification proceedings Partially deregulated Decoupled Expensive energy prices Low emissions rate Commercial EV tariffs	IOU proposals for light duty EV investments only Deregulated wholesale and retail Decoupled Expensive energy prices Low emissions rate No commercial EV tariff	Not deregulated Lost Revenue Adjustment Mechanism (like decoupling) Cheap energy prices High emissions rate No commercial EV tariff
Clean energy finance and deployment policies and programs	PACE ESPC Tariffed on-bill financing CalCap loan program for vehicles, EVSE	Green Communities Act CEIP	ESPC Tariffed on-bill financing

POLITICAL CONTEXT

California: California often leads the nation in environmental policy, and the same has been true with respect to climate change, transportation electrification, and electric bus deployment. In addition to setting precedent for most state environmental policies, California also has the distinction of being the only state with the authority under the Clean Air Act to issue its own vehicle emissions and fuel economy standards, which other states can opt into (known as the Section 177 states). Their size and strength of their economy, in addition to their relative isolation to other major economic centers, has minimized the perceived risk of losing business from more stringent regulations. Additionally, their air quality and resulting public health issues in the South Coast basin and Central Valley are far worse than any other part of the country, adding increased urgency to address vehicle emissions, particularly from heavy duty vehicles that represent a disproportionate share of air pollutants. California provides an example of a state with multiple complementary policies that drive emissions reductions, raise revenue, and invest that revenue in further reducing emissions. Their strong environmental and economic justice coalitions have been instrumental in driving climate policy forward in the state, and have also won important victories in steering revenues to mitigate pollution in disadvantaged communities, as well as ensuring those communities can benefit from electric vehicle manufacturing that is beginning to take off in the state.

Massachusetts: Massachusetts, a socially and environmentally progressive state, often follows close behind California on environmental issues. While a very liberal state with both chambers of the state legislature democratically controlled, Massachusetts currently has a Republican governor who has been focused on fiscal austerity, particularly for the state's transit agencies. Massachusetts collaborates very closely with many of its neighboring northeast states on different environmental policy issues, including the Regional Greenhouse Gas Initiative cap and trade program (RGGI) and joining California's Zero Emission Vehicle mandate program. At present, air quality is not a major driver of electric vehicle deployment in Massachusetts, as the entire state except for Martha's Vineyard is in attainment for criteria pollutants, though particulate matter remains a concern for public health officials. Massachusetts' efforts on electric vehicle deployment thus far have primarily been focused on light duty vehicles, and the state provides very little of the program and policy support California has in place that make electrification more feasible for transit fleets. Environmental justice advocates were instrumental in winning cleaner bus investments for the MBTA several years ago, though are currently more focused on averting fare hikes for low income riders. Today, the Sierra Club, MASSPIRG, and other traditional environmental advocates are organizing for electric bus investments in the state.

Kentucky: Kentucky is a much more politically conservative state than either Massachusetts or California, though the urban areas tend to be more liberal. Their state economy has traditionally depended on coal extraction and, due to its low electricity prices, heavy manufacturing. There is little environmental policy at the state level, though the urban areas have taken some steps on climate change and other environmental issues. Air quality issues were historically a major issue in Louisville due to manufacturing and coal plants, and it remains a non-attainment area for some criteria pollutants. Kentucky has some strong community organizing and advocacy groups, notably Kentuckians for the Commonwealth, which has fought mountaintop removal coal mining, amongst a wide variety of social and environmental issues. Having organized historically around air quality issues in low income neighborhoods, local teams for the organization are now pressing for more electric buses in both Louisville and Lexington.

GOALS, STANDARDS, AND TARGETS

California: California has multiple policies that set goals and targets relevant to bus electrification, including California's AB32, which sets a goal of 80% reductions in greenhouse gas emissions below 1990 levels. Their legislation was the first in the nation to set this goal, a precedent many other states have followed. California also has a Renewable Portfolio Standard (RPS), which requires utilities to procure an increasing share of renewable energy over time, which it just strengthened with its passage of SB 350 from a 33% share of renewable electricity in 2030 to 50%. California also initiated the Zero Emission Vehicle mandate, which requires manufacturers to achieve a certain percentage of sales as zero emission vehicles, for which they earn credits that are tradeable with other manufacturers.

Massachusetts: The 2008 Massachusetts Global Warming Solutions Act (GWSA) requires greenhouse gas emissions reductions of 25% below 1990 baseline levels by 2020 and at least 80% reductions by 2050. Additionally, Massachusetts enacted its Renewable Portfolio Standard in 1997 which required utilities to increase the amount of renewables from a baseline by one half percent per year between 2003 and 2009, moving to 1% a year after 2009, aiming for 15% by 2020. Currently, a proposal is before the state legislature to increase the percent change per year of the RPS. Massachusetts has joined California's ZEV Mandate to make a commitment to a goal of 300,000 ZEVs on the road by 2025, though the state is currently not on track to meet that goal. Additionally, a recent piece of legislation sets a target of 25% of state fleet purchases to be zero emission vehicles by 2025 ("Bill S.2505: An Act Promoting Zero Emission Vehicle Adoption," 2016).

Kentucky: Kentucky has no statewide climate, renewable energy, or clean vehicle policy, though some cities do have plans and goals. Louisville signed the U.S. Mayor's Climate Protection Agreement in 2005, committing to 7% reductions below 1990 levels by 2012. Sustain Louisville, the city's climate plan, calls for decreasing transportation-related greenhouse gases by 20%, and reducing VMT 20% by 2025.

CLIMATE POLICY MECHANISMS

While California and Massachusetts both have set ambitious greenhouse gas targets, they differ in the policy mechanisms in place to achieve those goals.

California: California has two mechanisms to achieve greenhouse gas reductions from its transportation sector. The first is an economy-wide cap and trade program that targets power plants and, as of 2015, fuel distributors. In 2017, California extended its cap and trade system and tightened the cap. The second mechanism is the Low Carbon Fuel Standard, enacted in 2007, which regulates oil refineries and distributors, requiring that the mix of fuel they sell in California meets a declining carbon intensity target, measured in lifecycle CO_2-e grams per unit of transportation fuel. This declining standard is paired with a market that enables regulated entities to meet the standard in a variety of ways. It also means that transit agencies in California operating alternative fuel vehicles can sell LCFS credits, helping the business case for investing in those vehicles. In 2017, CARB's Innovative Clean Transit working group estimated these credits would be worth $0.06 per diesel gallon equivalent (DGE) for CNG, and $0.11 per kWh for grid electricity in 2020 (California Air Resources Board Innovative Clean Transit Working Group, 2017e).

Massachusetts: Massachusetts is part of the Regional Greenhouse Gas Initiative (RGGI), a regional cap and trade program with other northeast states that covers the electric power sector. The regional cap declines 2.5% per year, and allowances are auctioned for larger power plants in the region, which provides revenue to each state. Since 2008, Massachusetts has invested more than $308 million in RGGI proceeds, most of which have been invested in the states' award-winning energy efficiency programs. Average annual electricity emissions from the 9 states participating in RGGI, the regional cap and trade program in New England and the Mid-Atlantic, fell 37% between 2008 and 2014 due to a combination of market forces and government policies, and the states announced an extension of RGGI and a tightening of the declining cap to drive deeper cuts in emissions in summer of 2017 of an additional 30% (Gustin, 2017). Still, RGGI does not cover the transportation sector, so Massachusetts currently has no mechanism to drive emissions reductions from what is now the state's largest sector of emissions.

BUS FLEET REGULATIONS

California: The California Air Resources Board (CARB) has for some years had a Fleet Rule for Transit Agencies that imposes several clean technology requirements on fleets, and provides different options to comply. One option requires 85% of buses purchased each year to be alternative fuel vehicles, while the other, "diesel option", requires fleets to meet certain NOx fleet average and diesel PM totals. Presently, CARB is working with transit agencies and other key stakeholders to develop a new version of that rule that would likely impose either a requirement of the share of new buses that must be zero emission, or a portion of the fleet that must be zero emission by a certain date.

Massachusetts: In 2016, the Supreme Judicial Court ruled in favor of advocacy groups and four teenagers who sued the MA Department of Environmental Protection (MassDEP) for failing to set binding declining limits on greenhouse gas sources in the state as is required in the Global Warming Solutions Act, leading MassDEP to promulgate several regulations in 2017. One of these regulations, 310 CMR

60.05, requires the MBTA and state transportation agency (MassDOT) to reduce their combined vehicle fuel and building heating CO_2 emissions by 5,000 metric tons annually from an FY15 baseline starting in 2018 and extending through 2020. While regulations have not yet been written beyond 2020, the state is currently developing interim targets for 2030, again following California's lead. This legislation applies only to the MBTA, and not to the rest of the states' Regional Transit Authorities (RTAs).

GRANTS, SUBSIDIES, AND INCENTIVES

California: California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) offers direct incentives for the purchase of eligible clean trucks and buses on a first-come, first-served basis, with no proposals or paperwork required. So far, HVIP has funded the deployment of 2,400 clean trucks and buses in the state, mostly with funds from the cap and trade system. The incentives range based on the carbon reduction potential of the technology and lists grants of $95,000-$115,000 per bus for current battery electric buses ("FAQ - California HVIP," n.d.; HVIP, n.d.). The program is currently oversubscribed, with $21.4 million having been allocated for FY17.

Massachusetts: Massachusetts has incentive programs for electric light duty vehicles, but so far none for buses or heavy duty vehicles more broadly. An incentive program exists for electric fleet vehicles, the Massachusetts Electric Vehicle Incentive Program (EVIP), which provides a $7,500 incentive for light duty vehicles owned by municipalities and other government entities (MassDEP, 2017). At this time, all allocated funds thus far ($2 million) have been committed. The state's MOR-EV program, which incentivizes individual consumers to purchase electric vehicles, was allocated $12 million in 2016, and offers $750-$2,500 per vehicle. In 2017, House Bill 3742, "An Act relative to electric vehicles expansion" was proposed in the Massachusetts legislature that would create a competitive grant program of an unknown size for Massachusetts' regional transit authorities to electrify their vehicle fleets, and was referred to committee (Golden et al., 2017).

Kentucky: Kentucky does not have any state subsidies for electric buses, but does have the Kentucky Clean Diesel Grant Program which provides funding for projects such as diesel particulate filter retrofits.

PROGRAMS

California: Programs offering technical assistance, coordination, and partnerships can be important in supporting technology transitions. California passed legislation establishing what is now called their Innovative Clean Transit initiative, which is run by the California Air Resources Board (CARB) and has been convening transit agencies, utilities, and other stakeholders to support the transition to zero emission buses, conducting research, and determining potential policies to accelerate electrification.

Massachusetts: While Massachusetts doesn't have a particular program for electric bus deployment, its Clean Cities coordinator, who works within the state energy agency, has been working on a pilot electric school bus deployment, and MassDOT has an office that supports the regional transit authorities with funding and technical assistance.

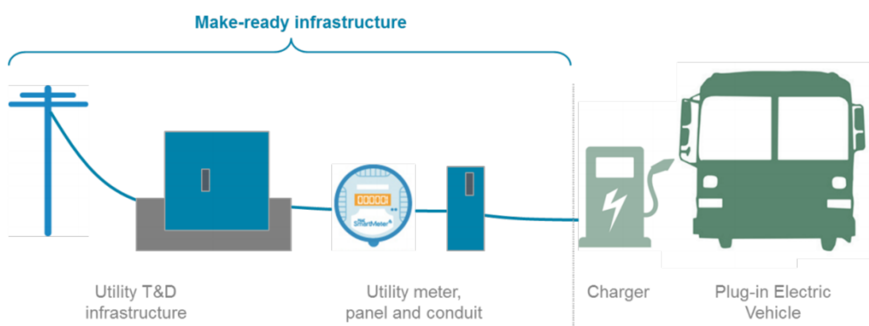
Kentucky: While there are no state-led programs, Kentucky's non-profit Clean Cities coalition is very active, and has played a large role in convening fleets to share best practices, apply for grants, and other collaborations. Additionally, a major partnership in Louisville between major institutions, Partnership for a Green City, has been an important driver of sustainable fleet initiatives in the city.

ENERGY POLICY AND CONTEXT

California: Decoupling is in place for all investor-owned utilities in California, though not for some of the smaller utilities, including LADWP which LA Metro gets most of its electricity from. California has partially deregulated its electricity sector, though only a capped portion of non-residential customers in each utility service area is able to choose their electricity provider. California imports much of its power, though in recent years has been bringing much more renewable energy and natural gas onto the grid. The amount of solar in particular is now beginning to cause challenges for the state's grid operator, causing electricity prices to go negative during some afternoons, and prompting utilities to shift their off-peak hours to include daylight hours to encourage people to use electricity while the sun is shining.

One aspect of California's new state climate policy SB 350 modified the public utilities code to "declare that the principal goals of the electric and natural gas utilities' resource planning and investments, in addition to other ratepayer protections, includes 'widespread transportation electrification'", due to transportation electrification's potential contribution to meeting state climate goals (California Public Utilities Commission, 2016). Subsequently, major investor-owned utilities have submitted plans to invest a total of $1.1 billion in ratepayer funds to promote transportation electrification, with projects such as "make-ready" rebates to cover the cost of electricity upgrades for electric bus charging infrastructure, more advantageous commercial electric vehicle rates, direct heavy duty fleet investments, and more.

Figure 4-3: PG&E illustration of "make-ready" infrastructure for electric bus charging (Sawaya, 2017)



Massachusetts: Massachusetts has decoupled its gas and electric utilities and deregulated its wholesale and retail electricity markets, which has helped slow the growth in costs, though Massachusetts still has some of the highest electricity costs in the country. The New England grid has reduced emissions in recent years due to the retirement of the state's remaining coal plants, and a transition to natural gas and renewables. While natural gas is better from a climate perspective than coal, some experts believe the grid is becoming too reliant on natural gas, threatening to limit the ability of the New England states to meet their climate goals, and subjecting customers to volatile natural gas costs (Hibbard & Aubuchon, 2015). Because of deregulation, the region's electricity markets are not subject to state Renewable Portfolio Standards or other climate policies, but are rather regulated by FERC, which in the current administration is unlikely to favor decarbonization. Currently, the state's two main investor-owned utilities, Eversource and National Grid, have proposals before the Department of Public Utilities to invest in "make-ready" infrastructure for electric vehicle charging ($45M for Eversource). Both proposals are written focused on either residential or *public* charging stations for private vehicles, but no mention of chargers for *publicly-owned* vehicles was mentioned. Neither proposal creates any new rate designs for electric vehicles.

Kentucky: Kentucky gets a majority of its electricity from coal, with a growing share of natural gas, and has some of the cheapest electricity rates in the country. Utilities in Kentucky have not been deregulated, but have in place Lost Revenue Adjustment Mechanism (LRAM) which similarly to decoupling severs the link between electricity sales and revenue so that utilities are no longer incentivized to sell more electricity. The state has two major investor-owned utilities, one that serves Lexington and Louisville, and Duke Energy serving the Cincinnati suburbs. The rest of the state is served by electric cooperates and municipal utilities. The utilities serving Lexington and Louisville, Louisville Gas & Electric/Kentucky Utilities (LG&E-KU), currently offer electric vehicle time-of-use rates designed for residents (not for commercial customers), as well as a tariff designed for light duty public charger deployment.

CLEAN ENERGY DEPLOYMENT

California: California has many different clean energy finance and deployment programs, including some geared towards vehicles. The state has enabled PACE financing and has multiple active programs, has enabled and mandated energy saving performance contracting for some public buildings and provides financing for others, and tariffed on-bill financing through multiple utilities. PACE financing is allowed to be used for electric vehicle charging infrastructure, and the California Capital Access Program is designed to make low-interest loans available to businesses for clean heavy duty vehicles and charging infrastructure by providing a loan loss reserve. So far that program has contributed over $76 million to a loan loss reserve, enabling the deployment of 12,000 new cleaner trucks and 600 exhaust retrofits.

Massachusetts: The American Council for an Energy Efficient Economy ranks MA first in the nation in its energy efficiency programs and policies, some of the most important of which are included in the Green Communities Act, which mandates a per kilowatt hour charge that goes to fund energy efficiency, a per kilowatt hour charge to fund renewable energy development, and mandates meeting electric and gas resource needs first through "all available energy efficiency and demand reduction resources that are cost effective or less expensive than supply" ("MA General Laws Part I, Title II, Chapter 25, Section 21," n.d.). By 2014, IOUs had invested $675 million in ratepayer funds, saving an estimated $3.2 billion for consumers (MA Energy Efficiency Advisory Council, 2014). In addition, Massachusetts directs state agencies to utilize energy saving performance contracting (ESPC), and has seen $470 million in investments in state buildings, and another $240 million in energy saving projects for municipalities. Additionally, Massachusetts has the Clean Energy Investment Program (CEIP), a low-cost financing program that uses project savings to repay capital costs available to state agencies. The program was designed to fund energy efficiency and clean energy projects, and enables state agencies to finance projects "off-cap", i.e. allows access to low cost capital without affecting agency debt capacity. The program has funded $285 million worth of projects, and works similarly to ESPC with less costs for measurement and verification (M&V). Program managers said the program has not been used yet for vehicles and were unsure if it could.

Kentucky: Kentucky has a strong background with policy supporting investment in energy efficiency. Legislation enabling ESPC passed in 1996, and over $1 billion worth of energy efficiency projects primarily in public schools and municipal buildings have been completed since. The Local Government Efficiency Retrofit Program (LGERP) provides no or low cost loans to city and county governments to incentivize ESPC, and leverages funds from the state-funded Green Bank of Kentucky. In eastern Kentucky, MACED, an economic development non-profit, has worked with electric utilities to win approval from the public utilities commission to offer tariffed on-bill financing to residents, enabling low income residents to begin saving from energy efficiency projects immediately as they pay them off through the savings on their electric bill.

TRANSIT BUS FLEETS

Figure 4-4: Summary of transit bus fleets by case study state

	CA	MA	KY
Total buses (FHWA 2014)	93,064: 59,130 (public), 33,934 (private)	13,224: 2,844 (public), 10,380 (private)	9,690: 7,698 (public), 1,992 (private)
Transit fleets (NTD)	150	27	10
Transit buses (NTD)	10,792	1,620	437
% 12 years old or more in 2015 (NTD)	35%	11%	32%
Battery electric transit buses deployed (~ share of state fleet)	350 (3.3%)	14 (0.85%)	13 (3.5%)
Transit fleets w/ electrification commitments	**7** LA Metro Foothill San Joaquin RTD Antelope Valley Transit Authority Porterville Transit LA DOT Santa Cruz Metro	**1** Martha's Vineyard Transit Authority	**0**

For each state, transit buses represent a small fraction of the total number of buses registered, which also includes school buses, charter buses, and other commercial buses. With respect to zero emission bus deployment progress, a similar proportion of the state transit fleet has transitioned to electric buses thus far in Kentucky and California (3.5% and 3.3% respectively), though California has by far the most fleets with commitments to fully electrify their fleet. Outside California, Martha's Vineyard Transit Agency in Massachusetts may be the only agency with such a commitment.

California: California has 130 transit fleets serving urban and rural communities around the state. Due to California's Transit Fleet Rule, much less of the California fleet is diesel than elsewhere in the country, with many fleets making major transitions to natural gas or other fuels. The history of transit funding in California has been varied, with Prop 13 in 1978 capping property taxes, which many transit agencies (and other public services) relied on. Later however, other ballot measures helped restore funding, with Prop 42 bringing 20% of the gas tax to transit, Prop 1B bringing $5B for transit statewide, and metropolitan level ballot initiatives raising sales tax increments for transit in recent years. In addition, numerous state programs provide additional funding, many of which are funded through cap and trade proceeds. The California Transit Association, a statewide association which all the fleets interviewed mentioned being a part of, advocates for the interests of transit agencies in Sacramento.

Massachusetts: In Massachusetts, the largest transit agency in the state, the MBTA, is itself a state agency, as its service area includes much of the eastern portion of the state. There are an additional 15 fleets across the state, known as Regional Transit Authorities (RTAs) serving small to medium sized urban and suburban areas, that receive the majority of their capital and operating funds from MassDOT, the state transportation agency. Many of the state's fleets have invested in some hybrid vehicles, and the MBTA has also made substantial investments in CNG buses. The MBTA is also one of the few fleets in the country that still runs a fleet of trolleybuses. Two agencies are already operating battery electric buses, Worcester Regional Transit Authority and Pioneer Valley Transit Authority, and two more, the MBTA and Martha's Vineyard Transit Authority have won FTA Low No grants for battery electric buses. A series of state policy changes have tightened funding for the MBTA and RTAs alike in recent years, which has led to service cuts for multiple agencies.

Kentucky: Kentucky has three medium-sized transit agencies, serving the cities of Louisville, Lexington, and the suburban portions of Cincinnati in Kentucky, and multiple small transit agencies serving other parts of the state, some of which have a few full size buses for fixed route service. Mostly the three midsize agencies continue to run diesel buses, though have some hybrid vehicles from when grant funding has been available. Both TARC in Louisville and Lextran in Lexington are now operating electric buses that they received FTA Low No grants for. Kentucky state legislation prevents gas tax revenue from being spent on transit, so transit agencies in the state continually struggle to cover their costs, with TARC having to make service cuts in the last several years.

4.2 Qualitative interview analysis

4.2.1 Qualitative analysis approach

This section includes a qualitative analysis of stakeholder interviews, publicly available documents, and public statements in board meetings and other events to identify reported drivers and barriers to electric bus deployment, as well as intentions for future deployment. Semi-structured interviews were conducted with transit agency representatives with open-ended questions addressing what agencies perceived as the barriers and drivers motivating or inhibiting future procurements of electric buses, their stated intention to procure electric buses in the future, and what policy and program solutions they felt necessary to enable them and other agencies to transition their fleet to electric. Figure 4-5 lists the individuals interviewed at each transit agency.

Figure 4-5: List of transit agencies and representatives interviewed

State	Agency	Name	Title
KY	Transit Authority of River City (TARC)	Barry Barker Geoff Hobin	Executive Director Capital Projects Administrator
	Transit Authority of Northern Kentucky (TANK)	Andrew Aiello	General Manager
	Transit Authority of Lexington, KY (Lextran)	Carrie Butler	General Manager
MA	Massachusetts Bay Transportation Authority (MBTA)	Bill Griffiths	Senior Director Vehicle Fleet Maintenance & Strategy
	Vineyard Transit Authority (VTA)	Angie Grant	Administrator
	Pioneer Valley Transit Authority (PVTA)	Sandra Sheehan	Administrator
	Worcester Regional Transit Authority (WRTA)	Jonathan Church	Administrator
CA	Foothill Transit	Andrew Papson	Electric Bus Program Manager
	LA Metro	Steve Schupak Philip Rabottini	Electric Bus Program Manager Senior Engineer
	Antelope Valley Transit Authority (AVTA)	Mark Perry	Director of Fleet & Facilities
	Golden Gate Transit	Steve Miller	Director of Maintenance
	San Joaquin Regional Transit District (SJRTD)	Donna DeMartino	Chief Executive Officer

Rather than prime interviewees with a particular set of pre-determined barriers and drivers, participants were asked to list "top-of-mind" the factors they perceived to influence their agency's electric bus investment decisions. Responses were then coded to be able to identify and summarize key barriers and drivers. Not all interviews were directly quoted either due to duplicative information with other interviews, or participants requesting to have their information or quotes withheld.

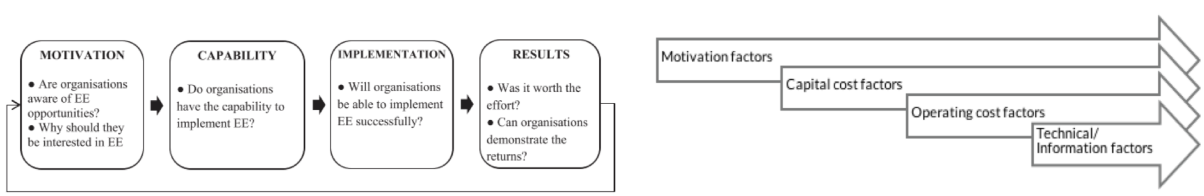
First the analysis summarizes the primary top-of-mind barriers and drivers described by transit agencies and key stakeholders in interviews and public documents, then it explores through more in-depth textual analysis the nuances of how agencies and stakeholders perceive each barrier and driver, and concludes with a discussion of each agencies' stated intention to procure electric buses in the future, to provide a set of examples of how these barriers and drivers differ across geographic and agency leadership contexts and combine in particular ways to drive agency decision-making.

4.2.2 Summary of factors influencing electric bus procurement decisions

Figure 4-7 summarizes the top factors (barriers or drivers) mentioned by interviewees or in public decision documents or meetings, with factors categorized by type, perceived level of impact, and the share of agencies that mentioned that factor. Factors were categorized by their perceived level of impact as major (***), moderate (**), or minor (*) based on how and when the interviewee or public documentation described that factor. Major factors were typically listed early in the interview or described as having a major impact on agency decision-making. Minor factors were typically listed later, and were described as having a more minimal effect.

Factors were also categorized by type, based on one energy efficiency gap study which took a systems approach to understand how barriers interact sequentially, highlighting that "the overall effectiveness of energy efficiency policies is only as strong as the weakest link" (Chai & Yeo, 2012). The authors propose a sequential framework to understand barriers and solutions, including motivation, capability, implementation, and results. This analysis adopts a similar approach, separating out Motivational factors, as agencies must first be interested in electric bus adoption before any technical or policy solutions might make a difference. Capability is then considered to largely include economic considerations for agencies, and is divided into Capital cost factors and Operating cost factors, and Implementation and Results is captured by the Information and Technical factors categories (see Figure 4-6).

Figure 4-6: Motivation-Capability-Implementation-Results framework (Chai & Yeo, 2012) (left) and adaptation (right)



Factors were classified as having been mentioned by "some" if 1-5 agencies reported the factor, "most" if 6-11 reported it, and "all" if all 12 of the agencies reported the factor. Robert Weiss in *Learning from Strangers* recommends avoiding precise quantification in qualitative interview analysis when samples are not representative of a broader population (Weiss, 1995). Each factor is described with greater nuance in the sections that follow to better illustrate how agencies and stakeholders considered each factor.

Figure 4-7: Factors influencing electric bus procurement decisions (*Chart sorted by perceived level of impact followed by share of agencies reporting)*

Top of mind barriers/drivers	Category	Barrier or driver	Perceived level of impact	Share of agencies
High first cost	Capital cost	▼ Barrier	* * *	All
Infrastructure cost	Capital cost	▼ Barrier	* * *	All
Availability of capital subsidies	Capital cost	◀ ▶ Barrier/Driver	* * *	All
Environmental benefits	Motivation	▲ Driver	* * *	All
Electricity costs	Operating cost	◀ ▶ Barrier/Driver	* * *	All
Lifecycle cost	Capital/ Operating cost	◀ ▶ Barrier/Driver	* * *	Most
Maintenance cost savings	Operating cost	▲ Driver	* * *	Most
Board or executive leadership	Motivation	▲ Driver	* * *	Most
External political pressure	Motivation	◀ ▶ Barrier/Driver	* * *	Most
Diseconomies of scale	Technical/ Capital cost	▼ Barrier	* * *	Some
Tradeoffs with providing more service and other budget needs	Capital cost	▼ Barrier	* * *	Some
Low fossil fuel costs	Operating cost	▼ Barrier	* *	All
Learning from peers or direct experience	Information	▲ Driver	* *	All
Battery performance	Technical	▼ Barrier	* *	Most
Added operational complexity	Technical	▼ Barrier	* *	Most
Rising cost of diesel maintenance	Operating cost	▲ Driver	* *	Some
Equity benefits	Motivation	▲ Driver	* *	Some
Economic development benefits	Motivation	▲ Driver	* *	Some
Fleet diversification	Technical	◀ ▶ Barrier/Driver	* *	Some
Uncertainty and risk	Information	▼ Barrier	* *	Some
Data and analysis capacity	Information	▼ Barrier	* *	Some
Noise	Motivation	▲ Driver	*	Most
Manufacturer limitations	Technical	▼ Barrier	*	Some

An analysis of the reported factors influencing electric bus procurement amongst early adopting agencies through interview texts and notes suggests the following findings:

1) Certain factors were consistently listed as primary barriers or drivers for all or nearly all agencies. Key barriers reported by most agencies were high first cost and infrastructure cost (and complexity), while nearly universal drivers included availability of capital subsidies, maintenance cost savings, environmental benefits, and agency leadership.
2) Some major factors were listed by some agencies as drivers and by others as barriers, particularly electricity costs, lifecycle costs, and external political pressure, suggesting the important role of understanding the diversity of contexts in crafting solutions to accelerate electric bus deployment. Capital subsidies have been a key driver thus far, but their limited availability is likely to be a barrier to more widespread, accelerated deployment.
3) In addition to a core set of major barriers that were listed first or second in top-of-mind questions about barriers and drivers, agencies and stakeholders identified a number of moderate and minor barriers and drivers that were more differentiated across agencies. Drivers identified included learning from peers and direct experience, the rising cost of diesel maintenance, equity benefits, economic development benefits, and noise, while barriers included low fossil fuel costs, battery performance limitations, added operational complexity, uncertainty and risk, data availability and analysis capacity, and manufacturer limitations. Fleet diversification of bus technologies was seen by some agencies as a benefit while others saw it as a challenge.
4) Rather than being seen as discrete factors, these barriers and drivers interact in complex ways for different transit agencies, which is explained further through textual analysis of interview notes, transcriptions, and publicly available documents below, and through agencies' stated intentions to procure additional buses. This indicates a need for solutions that can address the multiple compounding factors that influence agency adoption of electric vehicles.

The following sections explore the nuances and complexities in greater detail of how each of these factors manifested in reporting agencies.

4.2.3 Motivation factors

This section describes factors that were cited as key rationales for agencies pursuing electric buses.

DRIVER: ENVIRONMENTAL BENEFITS

Environmental benefits were a key driver for all interviewees, particularly in areas where air quality is an issue, but also in places with ambitious greenhouse gas reduction targets. Southern California and the Central Valley's particularly acute air quality issues are a key driver in the state's focus on criteria pollutant reduction from heavy duty vehicles, which drives an awareness as well as grant funding to support investment in clean vehicles. Louisville, Kentucky is also a non-attainment area for certain pollutants, which TARC described as being an inspiration for their push to achieve a "diesel free downtown". While a top priority for agencies in California and Massachusetts where the states' ambitious emissions reductions goals were top of mind, agencies in Kentucky acknowledged environmental concerns weren't the top issue in their part of the country. As one agency described it, "environmental concerns are part of our mission, but the driving force behind the decisions that are made are more about mobility and connecting people to jobs and participating in the economy".

Some agencies however were uncertain of just how great the environmental benefits were. Some agencies felt that the reduction in criteria pollutants is not as significant given how much bus emissions standards have minimized emissions from diesel and CNG buses: "The diesel buses are getting cleaner and cleaner, and we use ultra-low sulfur diesel as well, so the environmental impacts are not nearly what they used to be." Agencies in Kentucky were also unsure of how much of a benefit electric buses would have given the reliance on coal for electric power in their state, though modeling suggests that the increased efficiency of electric buses produces benefits even in areas reliant on coal-fired power. As one agency said, "I don't know how much on a kWh basis how much pollution is generated at a coal plant… I just don't know if in Kentucky you get the same air quality benefits."

DRIVER: EQUITY BENEFITS

Equity and environmental justice was a key driver for stakeholders in multiple cases, though was not mentioned explicitly by transit agency interviewees. A core focus of the LA Electric Bus Coalition Campaign, as well as the Union of Concerned Scientists (UCS) and Greenlining Institute's statewide efforts, has been to ensure electric bus deployment advances equity (Martinez, 2017):

> It's also vital that these electric buses operate first in the communities already disproportionately burdened by pollution, and that they provide quality union jobs for the people who build the electrical infrastructure and the buses themselves.

LA Metro's July board decision affirmed an environmental justice approach to electric bus deployment, committing to "develop an equity threshold consistent with Title VI regulations for priority deployment of electric buses in underserved communities" (LA Metro Board, 2017). While some agencies briefly mentioned the benefits of electric bus investment to low income communities in their service territory, interviewees generally did not focus on this benefit.

DRIVER: ECONOMIC DEVELOPMENT BENEFITS

In addition to environmental justice being an important value driving electric bus investments, economic development potential and economic justice have also been important issues in California driving the involvement of some stakeholders. With California agencies being first movers in investing in electric buses, multiple manufacturers including BYD, Proterra, and eBus have already set up factories in southern California, often with the support of state funds. BYD set up a factory in Lancaster, in AVTA's service area, which was one of the first agencies to commit to going 100% electric. Having seen the benefits in southern California, another California agency stressed the potential economic benefits as part of their agency's decision to go all-electric. Describing one manufacturer, they said:

> "They'd just opened one assembly plant, and they talked about also opening another. Of course, if we're the ones going all-electric, it's likely to bring that economic investment to our region."

In addition to playing a core role in the LA Electric Bus Coalition Campaign, Jobs to Move America, a national coalition of unions, economic and environmental justice organizations, and community organizing groups, has also been focused on ensuring that job creation from the city's electric bus commitments benefits local, marginalized communities (Patterson & Gillespie, 2017):

> Beyond creating environmental benefits, Metro can craft a comprehensive policy that uses our transit investments in new clean buses to cultivate a more just economy. With robust policies, Metro can attract thousands of good jobs in electric-bus manufacturing and charging-unit installation, especially for people who have been left out of the emerging tech economy, such as women, people of color and low-income residents.

Jobs to Move America has succeeded in doing so previously, having originally intervened in a $1B light rail car purchase by LA Metro to win contract language that incented manufacturers to create good-paying, local jobs for disadvantaged communities. In their words (Ibid):

> In 2011, the [LA Metro] piloted a now nationally heralded policy known as the U.S. Employment Plan for its purchase of 235 light-rail cars. The plan encourages companies seeking lucrative rail and bus contracts to create or sustain more manufacturing jobs and hire workers who face significant barriers to gainful employment, including experiencing homelessness, being custodial single parents, receiving public

> assistance and suffering chronic unemployment barriers that tend to disproportionately impact women and people of color. This policy played a significant role in bringing Japan-based Kinkisharyo's car-shell manufacturing facility to Palmdale. Kinkisharyo committed to create 250 jobs in an area suffering from years of economic distress. With support from Jobs to Move America coalition partners Kinkisharyo has exceeded its original commitment, recruiting and hiring a diverse workforce to fill 404 jobs, with workers earning an average wage of $21 per hour.

Now Jobs to Move America is focused on achieving similar commitments for LA Metro's electric bus investments (Ibid):

> Metro can win more victories like this as it replaces its bus fleet if it incorporates the U.S. Employment Plan on all future electric bus purchases. This will consistently encourage electric-bus makers seeking new contracts with Metro to create and sustain more jobs for Los Angeles County and the greater U.S.

Manufacturer BYD, which had been paying relatively low wages for the industry and struggling to fill the 500 jobs currently at its Lancaster plant, recently signed a community benefits agreement with the SMART union with the support of Jobs to Move America. The agreement includes paying workers a living wage and hiring 40% from disadvantaged communities, which JMA supports by creating a jobs pipeline (SMART, n.d.). Now they are working with Proterra on a community benefits agreement. Interviewees and advocates in other case study states didn't focus on the economic development potential of electric bus investments, though the successful coalition efforts in California suggest that doing so could increase political support and improve economic justice outcomes.

BARRIER/DRIVER: EXTERNAL POLITICAL PRESSURE

The presence or absence of political pressure to invest in electric buses was an important factor for many agencies interviewed. Agencies in California described the overall political context supporting climate action and electrification as creating supportive conditions and giving them the confidence to make the investment. As one summarized, "California's going to be a leader in this because our governor is so committed to electrification, so I think with cap and trade and other programs that have come out, especially recently, there'll be more opportunities for agencies to receive help with the delta in the cost of vehicles as well as some of those infrastructure investments we need for electric charging." Another put it even more succinctly: "The good news is in California, the governor is committed to it, the legislature is committed to it, and we suspect that they will pony up the money to make it happen."

Conversely, some agencies in Kentucky expressed how they felt a lack of external pressure and interest in electric vehicles given the surrounding conservative political environment somewhat undermined the arguments they could make for the investment. One agency expressed the skepticism they experienced: "But it was just kind of, well why are you spending all that money on those buses? And I thought, well because they're good for the air, and potentially they're going to cost less, but people were sort of suspicious and questioning their benefit a lot more than I would have thought." Another described, "Some agencies get pressure, they feel like their community tells them that they need to be on the edge of trying to solve some of these issues. That's just not a pressure that we feel… I mean the environment is part of our mission, but it's not something our stakeholders are pushing hard on us."

In each state, advocacy efforts have come together to lead a push for more electric bus investment at different scales, with leadership from traditional environmental groups as well as environmental and economic justice, labor, and community organizing groups. In the past, urban bus fleets have frequently been a focus of environmental justice advocates, with major campaigns winning previous commitments to cleaner bus fleets in Boston (led by Alternatives for Community and Environment) and Los Angeles (led by the Bus Riders Union).

Today in California, advocacy groups like the Union of Concerned Scientists and Greenlining have been active at the state level, particularly in the SB 350 proceedings to try and ensure utility funds are spent to support environmental justice communities, and in a way that can help spur the deployment of electric buses. In Los Angeles, the LA County Electric Bus Coalition, a coalition spanning traditional environmental groups, environmental justice groups, unions, and came together to advocate for LA Metro to commit to a 100% electric fleet. An organizer with the Sierra Club writes that the campaign was inspired in part by a resistance to the Trump administration, with goals that transcended emissions reduction goals to include economic and environmental justice values (Gillespie, 2017):

> The campaign that emerged over the coming months has a few straightforward goals starting with shifting the Los Angeles Metropolitan Transit Authority (Metro) to 100 percent electric buses by 2030. From there, we seek to ensure those buses are built and powered with union labor, fueled with clean energy, and hit the streets first in environmental justice communities most impacted by fossil fuel pollution today. In laying out these goals, the campaign is as much persisting with policies and programs that fulfill a set of values Angelenos hold as it is about resisting the dumpster fire in Washington D.C.

Following months of organizing work to collect petitions and mobilize around LA Metro board meetings, the coalition secured the support of the LA Times, LA's mayor, and in July, won a commitment to fully electrify Metro's fleet pending a technical and cost feasibility assessment to be completed in 2019.

In Massachusetts, advocates have also been coming together to advocate for electric buses, with the Sierra Club chapter leading a letter to the state transportation secretary in 2016 from representatives of traditional environmental groups, unions, and community organizing groups calling for a commitment to electric buses, citing the state's climate commitments, disproportionate impacts of air pollution on low income residents, and cost savings as primary reasons to do so (Sierra Club, 2016). In 2017, the Sierra Club organized a letter from 19 mayors pressing for a statewide mandate for electric bus commitments, including the mayors of Worcester, Boston, and multiple cities in the Pioneer Valley (Sierra Club, 2017).

Kentuckians for the Commonwealth (KFTC), a statewide community organizing group that has historically focused primarily on economic and environmental justice issues affecting coal communities, also has focused on air quality issues from industry in Louisville. There and in Lexington, member leaders from KFTC are now helping to lead local campaigns for electric buses, and together with the transit agencies, they have been collaborating to press their local utility for more advantageous electricity rates, and potentially an on-bill financing program to help with the up-front costs of electric buses.

DRIVER: BOARD OR EXECUTIVE LEADERSHIP

While some fleets chose to invest in electric buses due to some external pressure, many described having internal leadership drive those decisions and see the vision through. For one agency, their board first made a commitment to full electrification, but then the interviewee expressed it was also critical that their executive leader had a "got-to-believe" attitude towards being able to solve the many technical and financial challenges they faced along the way.

In some instances, external political pressure and board member and elected official leadership driven by environmental consciousness has been essential. As representatives from LA Metro described, "recently we've gotten this real push through Mayor Garcetti for environmental consciousness for zero emission buses, and other board members have jumped on that to continue our push for better health for the overall area and emissions reductions." From their perspective, this support from the board is essential: "So the board is very enthusiastic for converting to zero emission. What I liken it to is a piece of string. You try to push it and it's really hard to get there; but if you pull it through it'll go just fine. And our board is pulling this through, so that's great."

DRIVER: NOISE

While not a primary driver, many interviewees cited reduced noise as an ancillary benefit of electric buses. Multiple interviewees cited that the quieter buses had been received well amongst riders and neighbors, with some describing that engine after treatment systems had made diesel and hybrid buses louder, and that they had received more noise complaints in recent years.

4.2.4 Capital cost factors

BARRIER: HIGH FIRST COST

High first cost was the most cited obstacles to procuring electric fleet vehicles by interviewees, though agencies acknowledged that this barrier would lessen over time as battery costs continue to decline and manufacturers achieve economies of scale. LA Metro had just witnessed falling prices, citing the "hyper aggressive" pricing below $700,000 per 40' bus that they received from manufacturer BYD on their latest procurement of 60 buses, to the point that it was "within spitting distance of a CNG bus". Still, when agencies' budgets are as strained as they are in many parts of the country, "even a small increment would be a big burden" as one California agency described it. One agency in Kentucky described:

> "The tension is, everyone's saying that the return on investment is so good, you won't need to buy as many parts, and the lifecycle cost is going to be so much lower over time. But, I can't trade that for a bus, noone is going to take return on investment as payment in advance. It doesn't matter if we save over time, we don't have that cash to pay up front."

Given that transit agencies almost always purchase buses outright, rather than lease or finance them, this view that it would be difficult to overcome the first cost hurdle was common amongst interviewees.

BARRIER: INFRASTRUCTURE COST

Infrastructure costs were a major barrier cited by all agencies interviewed, which can vary substantially based on a set of factors both within and outside an agencies' control, such as an agency's utility, the existing infrastructure near them, and the charging strategy agencies pursue. One agency described infrastructure costs as the top barrier they faced:

> "But number one is how do we finance the infrastructure and get it in place? It's going to depend a lot on what utility service area you're in, and your infrastructure buildout. Is there sufficient electrical capacity available close enough to where it's not going to cost some inordinate amount of money to build out your charging stations? Because if you're on the end of a distribution line where there's not enough power available and the utility has to come build a bunch of infrastructure, it could get ugly."

The agencies interviewed have primarily deployed on-route charge buses, for which the charger and installation costs have been substantial:

> "On rough order of magnitude what we've seen, the cost of installing equipment equals the cost of the equipment. Because you also have to install the power electronics somewhere, you have to run conduit to the transformer at the edge of the property, and all those things can be really expensive, because you're trenching through concrete or running conduit."

While the infrastructure costs for initial deployments of on-route charge buses have already been substantial, some agencies expressed concerns that the cost of electrifying an entire depot would be even greater. One agency described their current outlook this way:

> "I could run six buses. Once I get past that I'd have to invest in major infrastructure upgrades. Once we get to 5, 10, 15, 20, what does that price tag look like? We don't really know that at this point."

BARRIER/DRIVER: AVAILABILITY OF CAPITAL SUBSIDIES

All the agencies interviewed had utilized special federal, state, or local grant programs to fund their first procurements, with most using the FTA's former Clean Fuels program or newer Low No program, as well as some state programs or CMAQ funds. As one agency described their motivation for their first electric bus procurement, "the California Energy Commission was giving us free buses, and who would say no to free buses?" While the availability of grant funding has been a primary driver thus far, its limited availability is likely to be a barrier for more widespread electric bus deployment, with current grant programs heavily oversubscribed. One interviewee described, "anytime there's an open solicitation for zero emission buses, it's way over-subscribed. The first year of the cap and trade money, they had $25 million, but they had $200 million in proposals."

Some agencies expressed needing to wait for grants specifically for low emission buses for future purchases, while others planned to invest regardless. As described earlier, transit agencies typically pay for new buses through FTA formula funds that cover 80% of the capital cost, with 20% coming from a local match. Funds are allocated by formula to metro regions, which then each have different processes to allocate the funds by agency. One agency said their region provided an 80% match even for more expensive buses, meaning agencies there just had to pay 20% of the incremental cost, rather than the full incremental cost. Regardless, agencies would still need to increase the 20% local match per bus, a significant hurdle for some more cash-strapped agencies. However, typically the amount of funds going to a region are capped, and putting formula funds towards electric buses would mean being able to procure fewer buses overall. As one agency said:

> "The formula funds are based on a bunch of factors and then there's a big sum of money that goes to a region, and you have to figure out how to fund everything with that fixed pot of money. So if the buses cost more, then that means less buses, or some other program will have to take a hit to finance that."

Multiple agencies in Kentucky expressed that they would need to wait for special grant funds to be able to procure more buses, rather than rely on formula dollars. One agency expressed the equation this way:

> "We get formula dollars, a specific award from FTA that would allow us to buy one and a half diesel buses per year. So if we just use our formula allocation for bus purchases…we could buy one electric bus every two years, so we kind of have to manage our fleet replacement needs based on the dollars we have. And that's why grant funds when they're available for the electric buses are so attractive."

BARRIER: TRADEOFFS WITH PROVIDING MORE SERVICE AND OTHER BUDGET NEEDS

For most agencies, the high first cost barrier of electric buses is amplified by the intense demand for other budget priorities needed to fulfill their public service mission of providing transportation to their communities. Particularly given the climate benefits of increasing transit ridership, having to curtail service in order to reduce emissions is clearly an undesirable tradeoff. One agency described it this way:

> "Most transit agencies get the job done on a shoe string, meaning we're often scrambling to finance the operation we have. So if it's even 10% more in operational costs, where's that going to come from? At that point you're looking at having to curtail service. And the point you do that to be able to run transit on electricity, have you really gained anything? That becomes sort of the philosophical question."

Multiple agencies interviewed described the ongoing financial stresses they face. Some of the contributors to their financial stress are structural, with some agencies citing increasingly sprawling service territories and growing paratransit needs creating an increasingly unsustainable situation. One agency responded to what was driving their budget challenges this way:

> "It's sprawl, it's having to go further, it's the passenger per mile equation. From 1950 to now, our service area is six times what it was. New companies always locate in green space and localities fight for these jobs, but they're always sure to ask about transit service once they've built their facility. Additionally, paratransit has now grown to 20% of our operating budget, for about 1-3% of our customers."

Competing priorities for capital budgets also represent a substantial barrier for being able to invest in electric buses. For some agencies, the main competing priority was operating costs. The Federal Transit Authority no longer provides operating funds to transit agencies, though they still allow some operating costs to be covered by capital funds. As a result, agencies often use their capital funds where possible to cover maintenance and other allowable expenditures, leaving less for needed bus replacements, even for conventional technologies; one agency said they used 98% of their FTA capital funds to cover operational costs. For others, substantial bus replacement needs outweigh the benefit of getting fewer electric buses. One agency described their significant need to replace old diesel buses:

> "There are still 60 buses today that are an average of 15 years in service and 600,000 miles. So do you replace as many as you can, or do you replace half the number with electric buses? Even though you know the lifecycle cost justification is there or nearly there and that you're going to reduce your maintenance substantially for those buses you can replace, you're just going to replace as many as you can."

For some agencies in California, capital funds have been raised through ballot initiatives that are all earmarked for particular local projects, so getting additional capital funds for electric buses means competing with those already committed priorities. As one agency described:

> "A lot of these projects were advertised as part of the initiatives, so now you have a municipality who thought they were getting a rail line or a station, and now you're saying sorry guys you're getting electric buses instead. So that doesn't go over well. So that's where the real challenges start rolling in is where are you going to find the money for it?"

Some agencies described that they had already had to cut service due to previous financial stresses, and that increasing service again would be a bigger priority if they had the funds available than electric buses.

> "If we can do it, we can do it. What I keep saying to anyone that will listen is that the level of service on the street today is not sustainable or sufficient. So the priority is getting more service on that street."

Agencies in all three states stressed their top priority being to maximize "service on the street", and that if it came to choosing between investing in electric buses or investing in expanding service, they simply couldn't justify investing in electric buses. Given the public service mandate of transit agencies and their extremely strained budgets in most areas of the country, this speaks to the need to provide support for overcoming key barriers to electrify fleets without impacting existing or expanded service.

4.2.5 Operating cost factors

DRIVER: MAINTENANCE COST SAVINGS

Almost all agencies believed they would experience maintenance savings, or said they were experiencing maintenance savings already from electric buses, though many had some uncertainty about how great those savings would be, and some were uncertain about their ability to capture them. One agency in California and another in Kentucky both quoted an approximate maintenance savings of 40% compared with their baseline bus technology. Part of these savings come from improvements to brake life from regenerative braking, which one agency described this way: “They get about four times the brake life. A brake job is equivalent to about 40 person hours from maintenance folks, so that was a pleasant surprise”. Another agency believed that the simpler bus would lead to less midlife replacement costs: "We should see some reductions in maintenance with a lack of reciprocating engine, so you don’t have oil changes, transmission is easier, and the motors last 1 million miles, or the life of the bus."

Still, there was some uncertainty about the maintenance costs over the life of the bus, and whether agencies would be able to fully capture the maintenance savings. No agency has had an electric bus long enough to know what midlife costs and maintenance costs in the later years of a bus’s lifetime will look like. As one agency described, “We’re pretty confident of having lower maintenance costs, even though it’s going to be years before we do any midlife battery replacement.” Some agencies interviewed, one in California and multiple in Massachusetts, contract out their maintenance and other operations, and pay for maintenance costs on a specified per mile, per hour, or some other basis. These agencies were uncertain as to whether they could capture the maintenance savings from electric buses the way their contracts are currently written. Only one agency was skeptical about the potential for maintenance cost savings, at least in the short term, due to reliability concerns, describing, “in the long run in 15 years or so, electric buses will be more reliable and cost less to maintain. But it’s a nascent technology, I think in the short run it’ll be more to maintain.”

BARRIER/DRIVER: ELECTRICITY COST

Electricity cost was a major factor for all agencies interviewed, but was the factor which more than any other diverged in terms of whether agencies expected savings or increased costs. One agency described the variation this way: "This utility issue going to be a problem for every transit agency, but it’s going to be a separate solution because each utility is different. So everyone has the same challenge, but they won’t have the same answer." Another agency felt electricity costs would be the greatest barrier moving forward: “up-front cost of vehicles and infrastructure is a problem, it’s not the biggest problem. I think long term operating cost is going to be a big factor unless we can address rate structures for transit.”

Some agencies reported they’ve been paying more per mile than their diesel buses due primarily to high demand charges, which has been a particularly acute issue for agencies that have deployed on-route charge buses with 500kw chargers and are on a utility tariff with high demand charges. For example, Kentucky agencies have low per kWh fees at around \$0.04/kwh, but “that’s only 12% of the bill. With demand charges it’s been more like \$0.26/kwh. It’s very steadily over 70% of the bill…at this point, especially with diesel so ridiculously inexpensive, we don’t have any cost savings from electricity.”

For some agencies, better utility rates or learning to manage charging and leverage subsidies meant saving on electricity. Antelope Valley, which doesn’t pay demand charges through the municipal contract they’re on for electricity, described anticipating completely covering their electricity costs in 2017 with LCFS credits, while saving about \$2.9 million on what they would have spent on fossil fuels. Other agencies remained optimistic that as they figured out how to manage charging, and utilize their chargers more fully to spread demand charges out, that they would save eventually:

> “In the long run, we’re fairly confident that we will see operating savings on the fuel side, but they won’t be as substantial as we hope until such time as we can find another way to mitigate or even eliminate demand charges.”

Rate complexity was also described as a challenge, particularly in places like California and Massachusetts where a deregulated electricity sector presents agencies with more options for electricity procurement, but greater complexity. Some agencies expressed difficulty in being able to estimate the costs for future deployments, and in being able to determine the optimal electricity procurement solution, with some expressing a desire for a simple, flat rate like they're used to for their fossil fuel contracts.

BARRIER: LOW FOSSIL FUEL COST

While it wasn't expressed as the top barrier for any agency, low fossil fuel costs for diesel or CNG fuel was cited by all agencies as a barrier to realizing cost savings and inhibited their arguments for transitioning their fleet. In Kentucky and Massachusetts, where more fleets still run on diesel, agencies interviewed typically had extremely low fuel contracts, as low as $1.25 per gallon for some respondents. For California fleets, many of which have transitioned to CNG due to CARB regulations and board decisions, the costs for CNG were frequently even lower, with some below $1.00 per diesel gallon equivalent including operations and maintenance costs. One agency described how the low cost of fossil fuel and high cost of electricity in some places combined to inhibit fuel cost savings:

> "Electricity has been a barrier and it will always be. California has very high prices, the Northeast has high prices. And combine that with the rest of our fleet that's natural gas, and that's especially cheap, so as a result our electricity costs are about 40% higher on a cost per mile basis."

While most agencies execute long term fuel prices that give them some certainty for a period of time, multiple agency representatives did express concern over the uncertainty of future fossil fuel costs over the lifetime of a bus, and felt moving to electric buses generally was advantageous given that electricity costs tend to be more stable over time. One agency described:

> "We don't know how the cost of fuel versus the cost of electricity will change, the price of commodities is influenced by so many different things, politics, environmental regulations. We've seen diesel prices in the last 12 years range from $0.99 per gallon to close to $3.50 per gallon."

This uncertainty is particularly acute for some agencies like Martha's Vineyard in Massachusetts where the logistics of transporting fuel to an island places an additional premium on their fuel prices. With the forces influencing fossil fuel costs out of the hands of agencies, being able to predict their relative costs for electric buses becomes more complicated.

DRIVER: RISING COST OF DIESEL MAINTENANCE

Multiple interviewees discussed the problems and expenses associated with post-2007 emission standards diesel engines as a motivation to switch technologies. While less of an issue for California fleets where regulations have driven many agencies towards CNG or other fuels, multiple Massachusetts and Kentucky fleets cited the reliability of the vehicles and expense of cleaning the filters and other after treatment technologies as being major issues motivating them to want to switch technologies. This is particularly problematic for agencies with slow speed routes, as diesel filter "regen" happens only at higher speeds, requiring more expensive and laborious treatment. Quoted in the local paper, Martha's Vineyard's Angie Grant described it this way:

> "We all know that diesel has been, up until about six years ago, extremely reliable. When the engines changed and the emissions standards [changed], things got a little bit more complicated, especially for transit buses, which are stop-and-go-stop-and-go-stop-and-go. We've struggled with reliability with those newer buses, and that's really the driver for us to look at other fuels." (Prescott, 2017)

BARRIER/DRIVER: LIFECYCLE COST

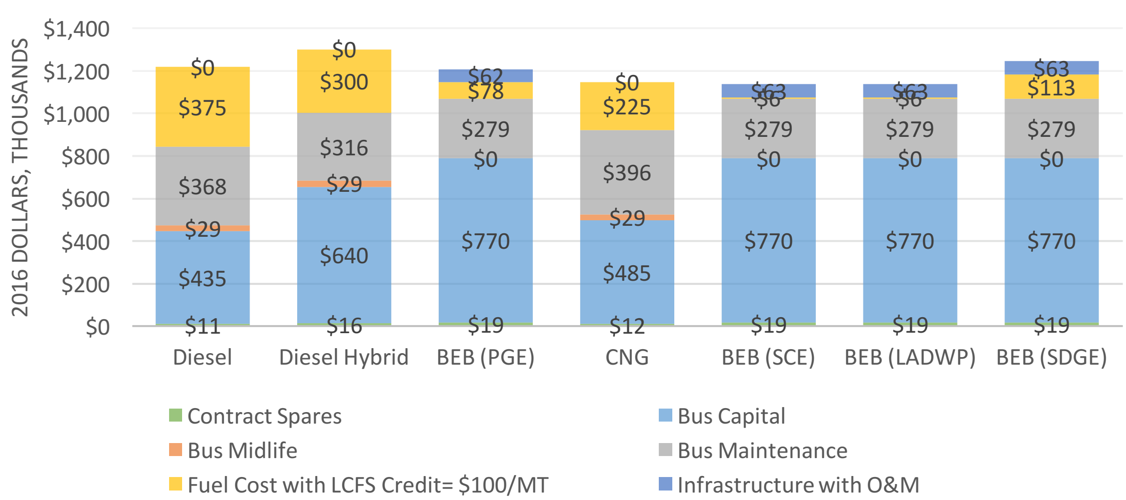
Some interviewees discussed lifecycle cost savings as a key driver motivating their interest in electric buses, while some said it wasn't an analysis they typically undertook. Interviewees also had divergent expectations as to whether electric buses would increase or decrease their total cost of ownership per bus, given the wide variance in costs anticipated as described in the previous sections.

Despite nearly all the California agencies interviewed having committed to going 100% electric, and having numerous policy supports that help improve the business case for electric buses, all except one believed going electric would cost more on a lifecycle cost basis. Some California agencies made a point to push back on what they viewed as manufacturers and CARB having too-optimistic claims about the potential for electric buses to be less expensive on a total cost of ownership basis:

> “Manufacturers are making claims that I don’t think are reliable. They’re saying they know the electric buses cost more, but we’re going to have so much in savings that we can use to pay its delta off. And that’s not panning out."

An important backdrop to this view is the recent modeling released by CARB as part of their efforts to implement a new transit rule that found electric buses to be less expensive on a total cost of ownership (California Air Resources Board Innovative Clean Transit Working Group, 2017a). In June 2017, CARB released new statewide cost modeling (see Figure 4-8) suggesting that if the state’s transit fleets were to transition to 100% battery electric buses, they would save 2.6% on a total cost of ownership basis by 2040. While the modeling suggested that some agencies would experience higher costs in earlier years compared with CNG buses, CARB’s analysis suggests that with LCFS credits and rebates for charging infrastructure installation, costs would be less over time for transit agencies. While their modeling to transition the state fleet by 2040 finds a savings of $0.5 billion statewide, the California Transit Association’s modeling done by transit agency representatives, which used more conservative assumptions, found a range of costing an additional $3.4 to $6.6 billion statewide, depending on the replacement ratio of battery electric buses to conventional buses to account for range limitations.

Figure 4-8: Total cost of ownership for a battery electric bus in 2016 (CARB 2017)



Agencies are concerned that CARB made assumptions that are too optimistic, that being forced into electric could drive up costs for transit agencies whose budgets are already very tight, and that it could have a disparate impact across agencies in different utility service territories. As one agency described with respect to CARB’s optimistic assumptions:

> “The staff at CARB seem to be pretty convinced that electric buses will have a lower total cost of ownership. If that’s what they’re presenting to policymakers, they may make the decision that we’re going to make it a regulatory requirement, and then we find out it costs 10% more to operate. Because what

happens then? Nobody has planned for that. We're trying to say let's not take such an optimistic view, let's take a conservative view and move forward."

Multiple interviewees expressed their opinions that in the long run electric buses may save money, but that the transition period would increase the costs of running transit:

"It will cost more because we're changing our fuel system, we have to bring in power; we have to modify our facilities. CARB keeps saying it's going to be cheaper. We don't quite see eye to eye on that because they make a couple of huge assumptions, number one that vehicle prices are coming down faster than they realistically are, and that range is higher, meaning they're assuming a 1:1 replacement ratio."

"So what we're seeing is basically some increase in operational cost, a capital intensive up-front investment to get infrastructure in place, and finance the buses that are incrementally more expensive. So when you take those three things together, you get an increase in the cost of doing business for transit. Potentially in 10-15 years those costs go away when you have all your charging infrastructure in place. So in the time horizon we're looking at, we're facing some very real increases in the cost of doing business for transit. When you add all those things up and say the total cost of ownership will be less, I think it sort of defies reason considering all those areas of complexity and cost."

With respect to varying impacts across the state, one agency described it,

"And then the fact that the rate structures vary widely from agency to agency means that a regulation would have disparate impact. So I'm in a place with relatively favorable electric rates and a regulation doesn't hurt my constituency. If I'm in a place with expensive rates like PG&E, then a regulation hurts my constituency much differently. So one of the things we'd like to see is some kind of consistency in the electric rates and certainty."

Connected to the agencies' opinions about CARB's modeling were serious concerns that if a regulation were to go through bolstered by CARB's findings, key subsidies such as the HVIP vouchers would go away, making the transition even more difficult. As one agency described it, "if we end up with electrification as a regulatory requirement, then a lot of those funding sources that had been used for these special projects becomes unavailable."

4.2.6 Technical factors

BARRIER: DISECONOMIES OF SCALE

This factor could be considered both a technical issue, as well as a capital cost issue. As agencies looked towards transitioning larger shares of their fleet beyond initial pilots, several were concerned about what more than one described as "diseconomies of scale", or an increase in the marginal cost per electric bus as they deployed more, due in particular to electricity infrastructure costs and the potential needs for more space at depots. Many agencies discussed concern over the amount of power they'd need at their depots if they were to switch their entire fleet. As one agency described,

"The problem is, the expansion of that fleet. When you get to 10 or 20, suddenly you have to refuel 20 buses overnight …and each one is charging at 50kw. Then we don't even have enough service from the utility, we don't have a big enough pipe to provide enough electricity."

Relatedly, agencies weren't clear on how to engineer the charging infrastructure they'd need within the depot space they had. More urban fleets in particular are already very space constrained, which led some to believe they'd need to somehow expand their depots, a considerable expense. One agency described:

> “At full electrification, it becomes more of an impact. Will we need more yards? And then the arrangement of chargers, the geometric design is a big challenge as well. Do you do it gas station style with islands? Or against the wall? Can you mount them overhead with a cord dangling down? Or put it in the ground? I don’t have an answer yet about how we’re going to move forward."

Combined these issues create new challenges for agencies that may amplify at greater levels of deployment if not approached strategically.

BARRIER: BATTERY PERFORMANCE

Interviewees discussed electric buses’ current battery performance, particularly the variability and range limitations, as a barrier. While battery technology and range have been improving, and manufacturers have been incorporating larger batteries into their buses, the buses deployed thus far have largely not been able to cover all “blocks” in agencies’ schedules, meaning the distance a bus is scheduled to travel between when it pulls out of the depot and returns, usually a series of trips chained together. Some agencies have been willing to take on the added complexity of strategically deploying buses on blocks within their current range, while others are accustomed to being able to assign any bus to any block. Variability in range and fuel economy is another factor, with some agencies describing the added stresses of having to monitor how weather, battery age, topography, and individual driver styles are impacting range. One agency described the multiple factors influencing range variability:

> “Battery performance is affected by age, by ambient conditions, by individual operator, so even on day one, two different drivers will get different ranges. So it’s being able to predict what that range is going to be…The first ones were advertised at 150 and averaged about 100. One agency tracked the range and fuel economy of different drivers and found one driver was able to achieve double the range of the other.”

Regarding variability, one agency described, “the other interesting piece you need to take into account is the heat or cold, if you’re running your heat or A/C full tilt, what does that do? So we’re being very cautious about keeping an eye on that, and how we use the bus. Because we don’t want it stuck some place.” This variability has been particularly true for buses deployed in colder climates in Massachusetts where fleets have experienced longer charging times in colder weather, and seen substantial differences in fuel economy between spring and fall “shoulder seasons” and summer and winter.

Multiple agencies said they were accustomed to any bus and driver being able to be assigned to any route, and that needing to manage assignments by bus and potentially driver added complexity to their daily operations: “We have 5,000 operators, we don’t have the luxury of cherry picking one guy to drive every day or super train 50 of them. We need a vehicle that anyone can drive and get comparable results every day.” Similarly, another agency expressed, "In the past we’ve designed the service and then spec’ed the equipment, and now we’re shifting that paradigm." Agencies disagreed over whether this new operating context and the limited range of current electric buses would add to costs, with some believing that the limited range of buses would mean that more than a 1:1 replacement ratio would be needed, driving up vehicle, depot, maintenance, and operator costs. Others seemed to believe that a staggered approach to deploying the vehicles would work:

> "The technology isn’t in place yet for it to work in all of our routes yet, but we don’t need it to right now. We could start by electrifying the easier half of our routes and by the time we get closer to 2030, the buses will have more capability anyway. So I think that’s the approach to going 100% electric, you don’t have to worry about doing the whole thing today."

BARRIER: ADDITIONAL OPERATIONAL COMPLEXITY

Between managing range and battery performance, and scheduling charging times, agencies see electric buses increasing the complexity of their operations. For on-route charge buses, scheduling charging time into each layover and avoiding buses having to wait to charge has been a new layer of operational complexity. Agencies considering depot charge buses also were concerned about the added complexity of managing charging at their depots, with one feeling that it would "upset everything in our yard". If additional complexity adds time, and time is money, one agency described how they felt this investment would drive up operational costs in other ways: "we strongly weight the operational constraints because when you think about the cost to operate a vehicle for an hour, roughly, the way I think about it is, roughly 70-75% of the cost of that hour of operation is in labor."

BARRIER/DRIVER: FLEET DIVERSIFICATION

While some fleets are clearly willing to experiment with new technologies and deal with operating and maintaining multiple different bus technologies, others expressed a strong aversion to the costs and complexities associated with that. Agencies who were accustomed to procuring, maintaining, and operating just one technology saw having to manage multiple bid processes and training mechanics for different technologies as driving up costs. One agency expressed wanting to wait for the technology to improve and then make a bold commitment to fully electrifying their fleet rather than dabbling in pilots:

> "Really, I think we see a lot of fleets that have a few CNG buses, a few electric buses, a few diesels, a few hybrids, and really if you want to be efficient, you want to move towards a technology. To have a process to maintain these vehicles, to have technicians that know how to work on them, all of that overhead associated with it, and then you only have 8 of them. It seems to me that if you're going to make a commitment to that technology, you should do it and squeeze as much efficiency as you can out of it. So we've gone the way of Southwest airlines that buys all the same airplanes to achieve greater efficiencies."

While not indicative of all fleets that haven't piloted electric buses yet, this fleet management approach may be common to other transit agencies, and may require a different approach to encourage deployment.

BARRIER/DRIVER: MANUFACTURER LIMITATIONS

While agencies who had experience with electric buses tended to be happy with their reliability, some interviewees expressed concerned with manufacturers looking forward, both from the perspective of their ability to meet production schedules for larger orders, and maintain reliability. As one said, "there's no manufacturer mass-producing these vehicles yet… they just don't have the capacity for large orders yet." Some interviewees cited reliability issues, particularly as BYD scaled up their first factory in the U.S. and Proterra began building buses for the first time. LA Metro had a particularly difficult time with their first BYD buses, which the company bought back from them: "we got 5 40' electric buses to run as a pilot from BYD, they were the first 5 off their assembly line in Lancaster. Their quality control was non-existent, the consistency was not there, we had five unique individually built buses. They were advertised at 155 miles, never got close. Ultimately because of manufacturing irregularities, reliability, they ended up buying back from us." While these issues will likely get worked out as manufacturers increase the scale of production, this may continue to be a barrier in the short term.

4.2.7 Information factors

BARRIER: DATA AND ANALYSIS CAPACITY

Multiple respondents mentioned a lack of needed data, in-house expertise, or simply time and capacity to be able to do the analysis required to convince their boards or other leadership about the benefits and potential lifecycle cost savings from electric buses. Some agencies don't have accurate data tracking for maintenance costs, making it difficult to compare costs of their electric buses: "it's really difficult to get a handle on cost per vehicle, or cost per sub-fleet. We're just guessing now, … [we don't know] how much a 2000 bus costs compared with a 2012 bus costs." While some had hired consultants to help them strategize how to deploy their buses and track costs over time, others hadn't and seemed not to have the capacity in-house to analyze the value proposition of electric buses in their fleet. As one said when asked about the potential for lifecycle cost savings, "We just haven't gotten there in the analysis, to tell you the truth. It's probably been a couple years since we did an analysis [of electric buses]." Additionally, some respondents felt there wasn't yet enough independent, rigorous data analysis of the performance of electric buses to guide their decision-making:

> "The only true scientific study we have, rigorous data collection, is the Foothill Transit study with NREL. We do have some pilots, but the data collection hasn't been all that rigorous, so we have to infer results."

BARRIER: UNCERTAINTY AND RISK

Uncertainty and risk affect multiple aspects of transitioning bus fleets to electric, including capital and operating cost uncertainty, performance over the life of the bus for the battery and other components, and risk embedded in a new fueling model. As one California agency put it, "So there's all these things we're just starting to understand. I'd be the first to tell you, what is the long term cost, we've made a long term projection, but we don't know what it'll be. If you talk to CARB, they seem darn certain, and I don't think that's the healthiest approach." Another agency described the risks associated with the current on-route charge model: "If one charge head goes down it really impacts our operations, so it's a big risk point." As mentioned previously, the significant variance in fuel economy and range introduces great uncertainty into day to day performance and scheduling, as well as costs. Considering these factors, one California agency stressed, "somebody's gotta help us reduce some of the uncertainty from the equation."

DRIVER: LEARNING FROM PEERS AND DIRECT EXPERIENCE

Similar to passenger electric vehicles, direct experience with electric buses and peer-to-peer information exchange appears to be effective for gaining awareness, familiarity, and trust in new technology. Nearly all interviewees who had deployed electric buses consulted with peers who had experience before them, with multiple Kentucky and Massachusetts agencies citing having spoken with or visited Antelope Valley or Foothill Transit, two of the earliest agencies to invest in electric buses. One agency described how their staff went from skepticism to embracing the new technology through direct experience: "The maintenance staff primarily, they gained trust in it…so combo body fears gone, disc brake issues gone, and so now what they see is this highly reliable bus that they don't have to change fluids on, they don't have to do any engine PM, they don't have to deal with particulate filters, selective catalytic reduction, all of that crap is gone. I mean, it makes so much sense, it's a much simpler bus. Our current director of maintenance has said, if dollars weren't an issue, I would never buy another diesel, every bus would be an electric bus." Another agency described how the "buses performed so well, I couldn't disprove our own data", which contributed to their commitment to procure additional buses. One agency, which received some of the earliest electric buses, was disappointed with their reliability, and is not planning to procure more, though it appears reliability has improved as the manufacturers have scaled their production.

4.2.8 Stated intentions regarding additional procurements of electric buses

As a way to understand the likelihood of more widespread, accelerated procurement, interviewees were asked about their agencies' plans for future electric bus procurements, and public statements and documents were reviewed. This assessment primarily considers early adopters of electric bus technology, and is therefore not representative of all transit fleets in the case study states, but provides an indication for the intention for fleet electrification amongst early adopters. While the factors summarized previously represents the opinion of the individuals interviewed at each agency, the stated intention to procure additional buses more fully captures the intent of organization as a whole, and reveals the complexity of decision-making within bureaucracies with many competing priorities. Still, the explanation behind that intent provided by one or two representatives of each organization, and published in public statements, presents limitations in being considered the comprehensive reasoning behind an agency's decisions, as the interpretation of the main factors driving a decision may vary between internal stakeholders. Figure 4-9 summarizes agencies' stated intentions and rationales for additional procurements of electric buses.

Figure 4-9: Stated intentions regarding additional procurements of electric buses

Agency	State	# BEBs (procured or on order)	Believe electric bus TCO more or less than conventional bus	Stated intention to procure additional battery electric buses	Primary reason(s) stated for procurement plans
AVTA	CA	41	Less	**All-electric**: 100% electric by 2018	Board decision, leadership, environmental benefits, demonstrated cost savings
SJRTD	CA	11	More	**All-electric**: 100% electric by 2025	Board decision, environmental benefits, and economic development
LA Metro	CA	5	More	**All-electric:** 100% electric by 2030, "if technically and financially feasible"	Board decision, political pressure, environmental benefits
Golden Gate Transit	CA	2	More	**None** (beyond receiving 2 pilot buses)	Higher total cost of ownership from infrastructure, electricity, and first costs, as well as diseconomies of scale
Foothill Transit	CA	31	More	**All-electric:** 100% electric by 2030	Board leadership, environmental benefits, opportunity for continued innovation
TARC	KY	16	Less	**None:** Would if grant funding or financing is available.	High first cost, availability of capital subsidies, competing priorities to maximize service, replace old buses
TANK	KY	0	Less	**None**	Waiting to see if technology limitations improve, availability of grant funds
Lextran	KY	6	Less	**None:** Would if grant funding or innovative financing is available.	High first cost, availability of capital subsidies or financing.
VTA	MA	4	More	**All-electric**: 100% electric with energy storage and solar	Leadership, environmental benefits, fossil fuel price uncertainty, rising cost of diesel maintenance
PVTA	MA	3	More	**None:** No plans within five-year capital plan	High first cost, infrastructure costs, waiting to test cold weather performance
WRTA	MA	6	Less	**None**	Waiting to see if technology limitations improve, first cost declines
MBTA	MA	5	Unsure	**None** beyond 5-bus pilot arriving 2018	Waiting for feasibility study and pilot of in-service performance in 2018 to make decisions about larger procurements

Overall, the range of agencies' intentions and rationales to procure additional electric buses reveal that while upfront and lifecycle cost matters, leadership, policy context, external political pressure, and technical considerations often outweigh pure economic decision-making. This was particularly true for

California fleets, for which nearly all of the interviewed fleets had plans to go all-electric, and nearly all of whom also believed doing so would cost them more in the long run. In each case, climate and air quality benefits were driving factors influencing external advocacy and board level decision-making to go all-electric. As mentioned previously, these fleets tended to feel confident that their policy context would support their transition, though had concerns about CARB's potential regulatory activity. In contrast to California, Massachusetts, which has strong climate policy targets but fewer supporting grant programs and other policy mechanisms to support investment in transportation electrification, just one of the fleets interviewed had plans to completely electrify their fleet. For Kentucky fleets interviewed, economic factors did seem to be the primary factor driving their decision-making, with all three agencies expressing that they would need to wait for discretionary grant funds, or potentially financing programs, to be able to procure additional electric buses.

CALIFORNIA

Most California fleets interviewed had plans to go all-electric, which for the most part seemed to have been driven by board-level decision making often supported by external advocacy, though these are most of the fleets in the state at this time who have made such commitments, so this is not a representative group. Boards and advocates alike were driven by the severe air quality issues in California, the impacts of pollution on environmental justice communities, the potential for economic development, as well as helping to meet the state's ambitious climate commitments. As one example of board level decision making, the resolution from SJRTD cited environmental reasons, as well as fuel savings and noise reduction, as primary reasons for committing to all-electric:

> "the urgency caused by the extreme air pollution levels in the California Central Valley and the climate crisis demands that RTD and the city of Stockton pursue transition to zero-emission all electric buses…Hybrid and all electric bus technologies have allowed RTD to reduce its environmental footprint, improve air quality, reduce fuel consumption, reduce expenditures on fuel, and provide passengers with a quieter ride." (San Joaquin Regional Transit District Board of Directors, 2017).

Transit agency representatives were generally supportive of these commitments, and felt confident that the supporting political environment would help ensure grant funding would continue to support them transition their fleets, though nearly all interviewed expressed substantial concern that potential regulations would drive up costs and could affect transit service or end grant funding programs.

MASSACHUSETTS

Despite a similar climate policy context to California, most Massachusetts fleets interviewed are not currently planning to go all-electric, except for one with a unique geographic context and committed leadership, due primarily to cost constraints and concerns over performance in cold weather climates. Martha's Vineyard has been the one agency in Massachusetts planning to convert their fleet to all-electric, with environmental reasons, the rising costs of diesel bus maintenance, the volatility of fuel costs, and the potential to use electric buses for emergency and resilience purposes being key drivers in their decision-making that were compounded by their unique geography. Being on an island, they have to bring in liquid fuels by barge, typically adding 30-40% in cost, and also have no high-speed highways that would enable diesel filters to regenerate automatically. Additionally, they have the worst air quality in the state and are out of attainment for ozone, due mostly to prevailing weather conditions. Administrator Angie Grant's leadership, demonstrated through substantial ridership increases for the agency during her tenure, has also been a key factor. She has proactively studied alternative bus technologies and then put together a unique plan to go all-electric that integrates energy storage and renewable energy systems, for which she has received strong local buy-in and is starting to receive grant funds. While the alternative bus technology study suggested electric buses would cost more, she ultimately felt that while there was no perfect technology solution, electric buses' advantages far outweighed the multiple downsides she saw with diesel engines' lack of reliability, extremely high maintenance costs, and the volatility of fossil fuel costs (Grant, 2017; Vermont Energy Investment Corporation, 2016).

Other agencies interviewed in Massachusetts did not yet have plans to procure additional electric buses. Some were still evaluating electric bus technology performance in their operating context, with Worcester waiting to see if range and charging infrastructure improved since the early buses they procured before investing in more. Additionally, many agencies have been facing major budget challenges and the need for service cuts in recent years, according to news reports, which may also be driving procurement decisions. In 2017, the Pioneer Valley Transit Authority had to cut service on 13 routes due to an increase in operating costs and a decrease in state operating support, which affected regional transit authorities across the state (Rebecca Mullen, 2017). The MBTA has also been struggling to cover operating costs amidst intense pressure from the Governor to cut costs and privatize parts of their operations, and has cut or considered cutting service to weekend commuter rail service, paratransit service, and late night service in recent years (Scharfenberg, 2015). Despite the broader state drive for carbon reduction from the transportation sector, the political context for public transit funding in Massachusetts currently makes the prospect of additional funding for electric buses difficult.

The MBTA has just begun a consultant-led study to be finished in 2018 that will evaluate electric bus technology in its operating conditions, evaluate an initial pilot, and prepare a roadmap for a potential larger procurement. At a board meeting in December 2017, staff and board members indicated the MBTA would likely move towards an electrified fleet eventually, but were cautious about committing to a new technology before testing actual performance on the MBTA's routes and weather conditions, and properly planning for utility upgrade needs and maintenance facilities. The MBTA has been constrained in expanding its bus fleet due to height and space constraints at its maintenance facilities, but is simultaneously planning for all new maintenance facilities, which board members seemed to agree should accommodate electric buses since they will last 40 years and they expect that will be their future technology. Board members and the state transportation secretary Stephanie Pollack also expressed urgency to determine what to replace a large retiring fleet of diesel buses with, and a desire to avoid "stranded assets" of investing in more diesel technology that will last 12-15 years due to current maintenance facility constraints (FMCB meeting Dec. 4, 2017). Additionally, the transportation secretary was very interested in the potential for battery electric buses to enable expanded Silver Line service, which requires zero emission vehicles for the parts of the route that operate in tunnels, and is in need of an expanded fleet to serve increasing capacity issues in the growing Seaport neighborhood of Boston.

KENTUCKY

Kentucky fleets interviewed were not planning to go all electric unless grant funding or financing options were available, and generally expressed being very stretched financially. Both TARC and Lextran were interested in procuring more electric buses, but a lack of funds and low cost financing options, and competing budget priorities meant neither had plans to invest further absent winning a Low No grant or some other means. As TARC said, "We would never buy another diesel bus if we could. But capital funds being as limited as they are, you have to prioritize. It's very hard to justify using general funds, not discretionary funds that are obligated for an electric bus, to purchase one [bus] when you could get two."

Interviewing TANK gave one insight into the perspective of an agency who hasn't yet procured electric buses. Their view was that they would only be able to invest if grant funds were available specifically for electric buses, but seemingly more important was that they wanted to wait to see if the range limitations and complexity of charging infrastructure and management improved before investing to minimized increases in operational costs. However, it seemed that if the technology improved, they may be interested in transitioning their whole fleet eventually, as they tend to like to have just one model and technology in their fleet to make maintenance and operations more efficient.

Kentucky fleets interviewed believed being in a conservative political environment translated to less pressure to invest in environmentally-friendly technologies like electric buses. Without this pressure, and accompanying supportive policies, upfront cost and grant funding availability were more important barriers driving electric bus investment decisions in Kentucky than in the other case study states.

4.2.9 Qualitative analysis summary

Interviews conducted of primarily early adopter transit agencies of electric buses in California, Kentucky, and Massachusetts suggest that some barriers to electric bus adoption are nearly universal, particularly upfront cost (and relatedly the lack of available capital subsidies) and infrastructure cost and complexity, and that helping agencies tackle those barriers through policies and programs will be essential to drive adoption. Some major factors were listed by nearly all agencies, but by some agencies as drivers and by others as barriers, particularly electricity costs and overall lifecycle costs, with a divergence between agencies based on their utility tariffs and a variety of other cost drivers. Motivation factors also impacted most agencies' decision-making but in divergent ways, with some agencies being driven by external pressure or board leadership, while for others a lack of political support and internal leadership posed barriers. In addition to the near-universal barriers mentioned previously, agencies also identified a differentiated set of more moderate and minor factors driving electric bus procurement. In addition to climate and air quality benefits mentioned by most agencies, some agencies identified other key drivers that may be important to highlight in driving further procurement, including noise reduction, equity benefits, the potential for economic development, the rising cost of diesel maintenance, and learning from peers and direct experience. Other barriers mentioned included low fossil fuel costs, battery performance, operational complexity, uncertainty and risk, and data availability and analysis capacity.

The variability of intentions to procure electric buses amongst interviewees suggests that context is also a key factor, with fleets in California where policy supports are numerous and political pressure is strong committing to electrify their fleets regardless of cost considerations. Outside California, upfront and lifecycle cost considerations were more consequential, with just one fleet committing to electrify their fleet while others were mostly waiting to see if grant funds became available. Still, there was variability within contexts, which seemed to be driven by a few factors, namely the level of political pressure felt by agencies, and the enthusiasm amongst agency leadership towards electric buses, with some leaders taking an optimistic, problem-solving view, while others were more risk-averse and took a "wait-and-see" attitude. While public pressure and environmental leadership may be important for transit fleets and possibly other public fleets, these factors may be less applicable to private bus and truck fleets. Overall, the variability and interdependence of factors driving transit agency decision-making suggests policymakers will need to develop a complementary set of context-specific policies and strategies to support accelerated bus fleet electrification.

5. Quantitative analysis of bus electrification case studies

While average parameters explored in the analysis in Section 3.2 suggest a lower total cost of ownership for electric buses than diesel buses, actual cost savings is highly context specific for each fleet. Key factors include those explored in the sensitivity analysis in Section 3.2.2, such as yearly mileage, average speed, fossil fuel prices, and electricity costs, but also include other factors unique to each fleet, such as the electricity upgrade costs and potential expansion costs at their depots, as well as their comparison "baseline" bus technology. This chapter of the analysis presents a high level comparison of total cost of ownership across different fleets and utility service areas in each case study using the model developed in Chapter 3, and seeks to understand the variability across agencies contexts. Additionally, this section includes a more detailed assessment for one fleet, enabled through on-site fellowship work with the MBTA in Boston, which seeks to illustrate total cost of ownership in a more context-specific way.

5.1 Total cost of ownership variability by utility and policy contexts

This analysis presents a high level comparison of total cost of ownership for different bus technologies across agencies with different utilities, baseline technologies, and policy contexts, as summarized in Figure 5-1. To do so, the total cost of ownership model developed for this analysis is applied across utilities in the three case study states, holding key inputs constant to compare a limited set of context-specific variables[1]. Rather than vary agency average annual mileage, speed, and charging strategy, this analysis holds those factors constant both to ease comparison across agencies, as well as due to the wide variability of these factors within agencies and agencies' ability to strategically sequence deployment on assignments that can maximize benefits.

[1] The total cost of ownership analysis by different electricity tariffs in this section holds all of the same variables constant as in the base case analysis in Section 3.2.1. The following charging assumptions are used to model the electricity tariffs, many of which have different prices by time period (which was not modeled in the base case): percent of energy consumed (kWh) on peak (10%), mid-peak (30%), and off-peak (60%), and the percent of potential total draw connected (kw) during on peak (25%), mid-peak (60%), and off-peak (75%). Martha's Vineyard's (VTA) electricity costs are not modeled here, as they are pursuing an energy storage strategy that will enable them to avoid demand charges and reduce electricity costs. The baseline bus for each agency is assessed based on recent large procurements, or by the majority of the bus fleet reported to NTD in 2015.

Figure 5-1: Fleet and policy context summary (2015 NTD data)

State	Capital subsidy	Operating subsidy	Make-ready support	Agency	Number of buses	Current "baseline" bus	Average mileage per year per peak bus	Average speed
CA	HVIP vouchers ($95,000-$110,000 per bus)	LCFS credits ($0.10 kWh, $0.06 DGE CNG)	Proposed	LACMTA	2,811	CNG	47,175	10.9
				SJRTD	170	Diesel	39,843	18.2
				Foothill	52	CNG	54,825	10.8
				Golden Gate	248	Diesel	37,970	17.2
				AVTA	74	Diesel hybrid	53,450	19.6
MA	-	-	Proposed for light duty	MBTA	1,002	50% hybrid/50% CNG	31,200	9.9
				PVTA	185	Diesel	35,516	13.4
				WRTA	327	Diesel	48,184	11.7
				VTA	31	Diesel	41,900	17.7
KY	-	-	-	TARC	235	Diesel	46,211	12.5
				Lextran	57	Diesel	36,332	11.2
				TANK	112	Diesel	43,769	13.8

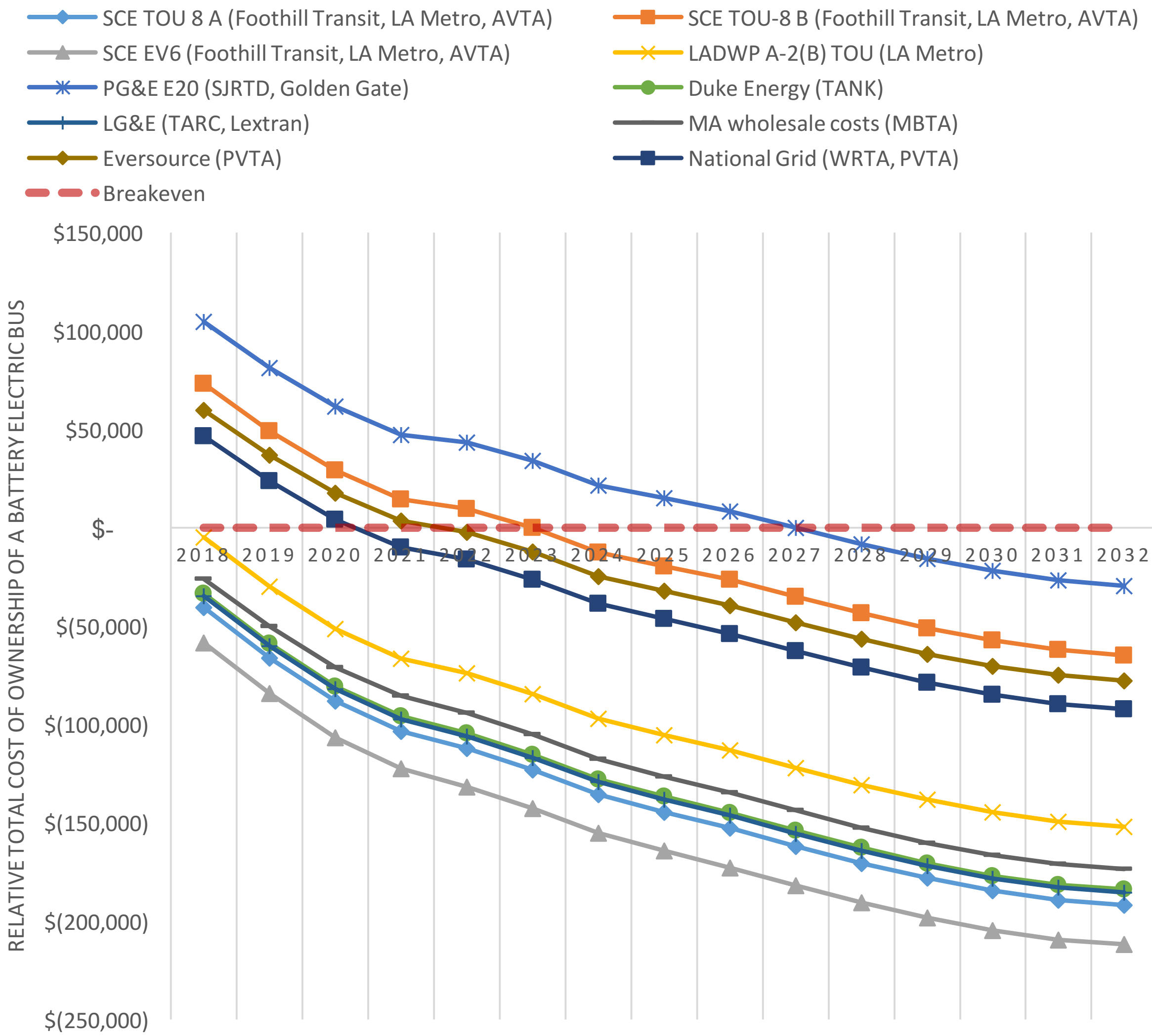
To demonstrate the wide variability of utility tariffs available to transit agencies, key details of the tariffs available to case study fleets are summarized in a simplified form in Figure 5-2, with only typically higher summertime rates shown. California tariffs frequently have multiple demand charges across different periods that vary seasonally, and overall tend to have both higher demand charges and energy charges than the other case study states. Kentucky tariffs also have multiple demand charges, but their cost per kWh tends to be much lower than the California tariffs. The Massachusetts tariffs tend to be simpler with fewer time of use options, though the tariffs presented here are only for distribution service plus "standard offer" service. In other words, Massachusetts agencies have to pay the demand charges and some base per kWh fees for the service of electricity delivery, but otherwise can purchase their electricity from an alternative provider. Those options and potential cost savings are not captured here, though for depot charge buses, Massachusetts agencies can likely save money by charging overnight, when wholesale prices are below $0.03/kWh on average.

Figure 5-2: Summary of available electricity tariffs for case study fleets

State	Utility tariff	Agencies applicable to	Monthly meter fee	Demand charges (summer only) (max / peak / mid / off-peak)				Per kWh charges (summer only) (peak/mid/off-peak)		
CA	SCE TOU 8 Option B (Above 500 kw)	LA Metro Foothill AVTA	$635	$18.55	$18.92	$3.63	-	$0.10	$0.07	$0.06
CA	SCE TOU 8 Option A (EV above 500 kw)	LA Metro Foothill AVTA	$2,051	$8.06	$0.00	$0.00	$0.00	$0.28	$0.09	$0.05
CA	SCE EV6	LA Metro Foothill AVTA	$680	$10.39	-	-	-	$0.41	$0.09	$0.07
CA	LADWP A-2 (B) TOU	LA Metro	$28	$7.45	$10	$3.75	-	$0.12	$0.11	$0.06
CA	PG&E E20	SJRTD Golden Gate	$1,183	$17.44	$18.05	$5.01	-	$0.14	$0.11	$0.08
MA	MA wholesale contract	MBTA	-	$7.75 (coincident)		$1.90 (non-coincident)		$0.05	$0.05	$0.03
MA	Eversource – Time-of-use T-2	PVTA	$2,500	-	-	-	$14.52	$0.10	$0.10	$0.10
MA	National Grid – G3 Time-of-use	WRTA PVTA	$223	-	-	-	$5.76	$0.14	$0.14	$0.13
KY	Duke Energy – Time of Day Rate for Distribution Voltage Service	TANK	$115	-	-	$12.75	$1.15	$0.05	$0.04	$0.04
KY	LG&E – Time of Day Secondary Service	TARC Lextran	$200	-	$6.74	$5.10	$4.60	$0.04	$0.04	$0.04

This high level analysis demonstrates the impact of the wide variability in utility tariffs in the three case study states, indicating the importance for transit agencies to model their electricity costs prior to procurement of electric buses, to determine ways to manage their charging costs, and to potentially advocate for better rates with their utility. While the analysis in Figure 5-3 suggests that many fleets will experience total cost of ownership savings compared with diesel buses by investing in electric buses right away given the common speed, mileage, and charging parameters, fleets in some high cost utility service areas like PG&E and the Massachusetts utilities would not see lifecycle cost savings for several years until the capital cost for electric buses relative diesel will have declined sufficiently. Relative total cost of ownership improves for all agencies over time due primarily to assumed falling bus purchase costs, and because diesel costs grow more quickly than electricity costs in the EIA Reference Case.

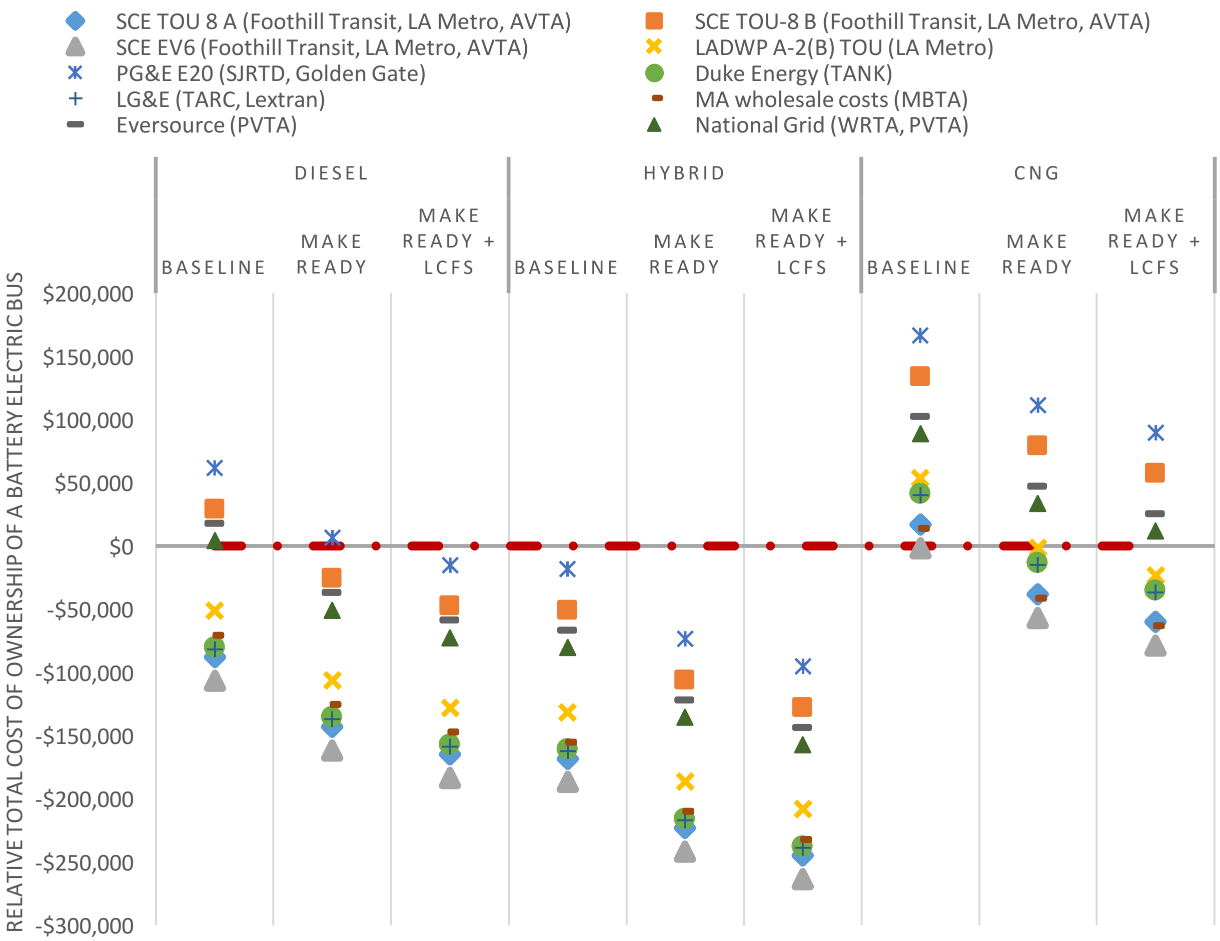
Figure 5-3: Total cost of ownership per electric bus relative to a diesel bus by utility/transit agency



The case of the three SCE tariffs is instructive: SCE TOU-8 B was the tariff available to transit agencies before the utility created commercial EV tariffs, and would increase electric bus total cost of ownership relative to diesel buses in the next several years. Later, SCE implemented its TOU 8 A and EV6 tariffs for commercial EV customers, which perform best and second best in terms of creating lifecycle cost savings relative to a diesel bus. The Southern California Edison (SCE) EV-6 tariff is a relatively recently approved tariff designed to minimize demand charges while increasing per kWh charges to very high rates during summer peak periods ($0.41/kWh from 2-8pm) that particularly depot charge buses may be able to largely avoid. The principles and rationales for creating these tariffs is described further in Chapter 6, and demonstrates the importance of tailoring rates for transit buses.

Baseline bus technology and policy context are also key contextual factors that determine potential lifecycle cost savings. For fleets that are already operating CNG buses, there is much less of a cost advantage with electric buses, with only a few tariffs offering competitive electricity pricing with CNG. Outside of California, Lextran and the MBTA are the only other fleets in this analysis currently operating CNG buses. On the other hand, electric buses appear to be cost effective across the board relative to diesel hybrids, given their similarly high capital costs. Figure 5-4 shows the total cost of ownership of an electric bus relative to different baseline bus technologies, with different electricity tariffs and policies.

Figure 5-4: 2020 Relative total cost of ownership per electric bus with different policy scenarios



This analysis demonstrates that supportive policies, like those available in California, are also critical for improving the chance to achieve total cost of ownership savings. By adding capital and operating cost subsidies in the form of make-ready investments (i.e. assuming the installation cost of a charger is covered) and access to LCFS credits, nearly all agencies would see cost savings from battery electric buses relative to diesel and diesel hybrid buses. These subsidies don't make electric buses immediately cost effective for all agencies in comparison with CNG, though improves the business case for many. Still, the variance between the most and least advantageous electricity tariffs sampled in this analysis is greater than the improvement in the total cost of ownership savings achieved from make-ready and LCFS subsidies, suggesting that a focus on favorable electricity tariffs may be even more important than subsidies for battery electric bus deployment.

5.1.1 Summary

This analysis demonstrates how much relative total cost of ownership varies across the case study states and individual agencies, particularly due to available electricity tariffs, as well as available policy supports and baseline bus technologies. The variance in available electricity tariffs has a major impact on viability for electric buses, and puts agencies in some areas at a major disadvantage, putting the onus on public service commissions to even the playing field for transit agencies, as well as other fleets in the future. Today's tariffs don't reflect the public benefit of electric buses, and aren't designed with their use profile in mind, driving home the unfairness of levying a regulation requiring zero emission buses without harmonization across utility service areas for transit buses and other vehicles that have a public benefit. Aside from addressing electricity rates, infrastructure incentives and other policy supports can help mitigate agencies' risks of investing in this technology, and help improve cost effectiveness for agencies.

5.2 In-depth total cost of ownership and lifecycle emissions case study: MBTA

This section explores in greater detail the financial, greenhouse gas emissions, and air pollution costs and benefits of different technology scenarios for one bus fleet, the MBTA, as well as the tensions between plans to expand service while reducing greenhouse gas emissions, in an analysis that was made possible through fellowship work at the MBTA in the summer of 2017. The results of this analysis do not reflect the opinions of the MBTA about electric bus deployment.

5.2.1 Background

The MBTA historically invested in clean bus technologies, with substantial procurements of CNG buses, diesel hybrids, and specialized vehicles like the Silver Line DMAs after advocacy efforts in the 1990s from environmental justice communities. Pollution from MBTA buses has long been a target of community organizing in Boston, particularly in the Roxbury neighborhood, which has high levels of bus service as well as a bus garage. Alternatives for Community and the Environment, a local environmental justice organization, led a campaign for multiple decades to reduce diesel pollution in neighborhoods in order to reduce the risk of asthma and other health impacts, starting with their Clean Buses for Boston campaign in 1998. High incidences of asthma led organizers to find out that "Suffolk County has the greatest average lifetime cancer risk from diesel soot in the state and region, ranking in the top one percent of counties in the US (41st of 3,109), a risk 309 times greater than what the EPA considers acceptable", which is borne principally by low-income people and people of color (Alternatives for Community & Environment, 2015). Their organizing has led to multiple victories over the years, including an EPA violation notice to the MBTA in 2002 for excessive idling at bus yards and depots, for which the MBTA had to pay millions in fines and led to them procuring 350 natural gas buses.

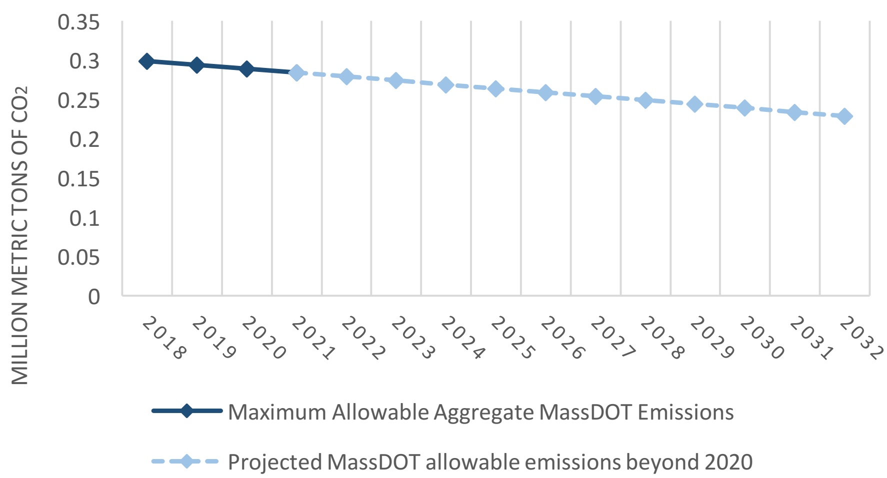
As of July 2017, the majority of the MBTA bus fleet were alternative fuel vehicles, with 44% diesel, 30% CNG, 21% diesel hybrid, and 5% other, which includes the agency's remaining fleet of trolleybuses. In 2018, the MBTA will receive its first battery electric buses, which will be five 60' depot charge electric buses for their Silver Line BRT service. The MBTA is presently in the midst of its fleet and facilities planning process for 2018-2032, which is determining a plan for the timing of future fleet purchases and an entire replacement of current bus garages, as well as a pilot and study analyzing the feasibility of a larger electric bus deployment.

CONFLICTING STRATEGIES TO REDUCE EMISSIONS

Planning efforts and policies that affect the future of the MBTA bus fleet represent the tension between increasing transit service as a strategy to reduce driving and greenhouse gas emissions on the one hand, and reducing direct emissions from transit service on the other. Simultaneous to the fleet planning efforts, the MBTA has been undergoing its 2040 planning process called Focus 40 which has considered a substantial increase to the size of the bus fleet by about 50% to accommodate capacity needs and a goal for increased ridership. Previously, MassDOT set a goal in 2012 of tripling bicycling, walking, and transit modeshare statewide by 2030 as part of its GreenDOT initiative, suggesting a potential need to roughly triple the amount of transit service available to residents ("MassDOT Announces Mode Shift Goal to Triple the Share of Travel in Massachusetts by Bicycling, Transit and Walking," 2012).

After MassDEP was required through a lawsuit to set binding, declining caps for particular sectors of emissions, they enacted regulation 310 CMR 60.05 in August 2017 that sets a non-binding goal for statewide transportation greenhouse gas emissions statewide, but sets a binding declining cap on the much smaller, but more easily regulated, combined MBTA/MassDOT fleet and facilities. The declining cap decreases by 5,000 tons of CO_2 per year from 2018 to 2020, though this analysis anticipates that a similar declining cap will continue as the state moves to set 2030 targets as shown in Figure 5-5.

Figure 5-5: Maximum allowable aggregate MassDOT/MBTA CO_2 emissions under 310 CMR 60.05



According to the MBTA Sustainability Department, the MBTA is the single largest consumer of electricity, and one of the largest consumers of compressed natural gas and diesel in the New England region (MBTA, n.d.). In addition to the local air quality and regional impacts of this fuel use, volatile energy prices for commodities such as diesel fuel can have a substantial impact on the MBTA's budget, with energy costs rising 134% between 2000 and 2014 (Ibid). Under 310 CMR 60.05, MassDOT/MBTA are responsible for direct emissions from their buildings and vehicles, not for electricity emissions, which are regulated separately. For data from the FY15 baseline year, MBTA direct emissions from vehicles and electricity emissions (left-hand column below) were approximately 423,000 metric tons, with commuter rail representing the largest share, followed by electricity emissions to power the rapid transit lines and other uses, and then bus emissions. The CO_2 emissions that are now regulated (right-hand column of Figure 5-6) totaled approximately 298,900 metric tons in FY15, with emissions from MBTA operations representing 91% of the combined MassDOT/MBTA total, of which commuter rail (48%) and bus (28%) accounted for the greatest shares.

Figure 5-6: FY2015 Percent MassDOT/MBTA CO_2 Emissions by source

MBTA EMISSIONS SOURCES **NR = NOT REGULATED*	**% OF MBTA TOTAL**	**% OF TOTAL REGULATED BY MASSDEP**
BUS	19.9%	28.3%
COMMUTER RAIL	34.5%	47.8%
FERRY	2.8%	4.0%
THE RIDE	4.3%	6.0%
NON-REVENUE VEHICLES	1.0%	1.4%
BUILDINGS	2.3%	3.3%
SUBWAY (ALL ELECTRICITY)	33.6%	NR
COMMUTER RAIL NON-REVENUE VEHICLES	1.2%	NR
JET FUEL FOR POWER PLANT	0.4%	NR
MASSDOT EMISSIONS SOURCES		**% of MassDEP Regulated Total**
MASSDOT FLEET		7.5%
MASSDOT BUILDINGS		1.7%
TOTAL	**100%**	**100%**

5.2.2 MBTA fleet total cost of ownership analysis by bus technology

INPUTS AND ASSUMPTIONS

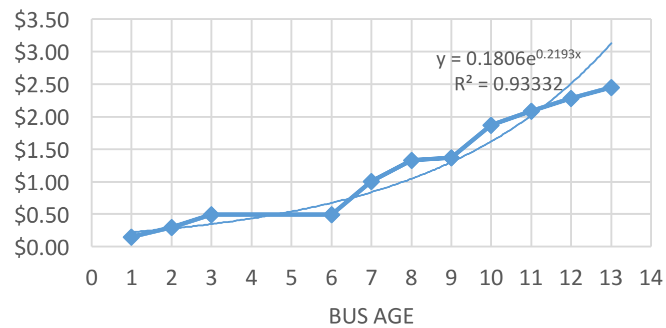
The following section details inputs for a whole fleet total cost of ownership and emissions analysis comparing different bus technologies for future procurements for the MBTA.

Mileage per year: A weighted average annual mileage for 40’ (27,700 miles) and 60’ (19,600 miles) buses is used for projecting emissions for future procurements, using data from the Bus Operations Maintenance Division for FY12-16. However, newer buses tend to be driven much more, so these figures could be higher if electric buses are assigned strategically.

Fuel economy: Aggregate MBTA fuel economy for all diesel (including hybrids) of 3.2 MPDGE and CNG (2.3 MPDGE) buses from actual fuel usage data from Bus Operations in FY16 are utilized. These aggregate figures for the current bus fleet are adjusted to assume a 35% improvement for hybrid buses based on the performance of the MBTA’s newer hybrid vehicles. For the future fleet (including vehicles delivered in 2017 and after), these figures are then improved using an assumption based on MOVES factors from CTPS for diesel and CNG buses, for which there is a 5.6% expected improvement between model years 2003 and 2017 and over (which are all the same). For battery electric buses, 2.53 kWh/mi is assumed, which is the average fuel economy thus far for the buses operated by the Pioneer Valley Transit Authority. This figure is less than the buses observed by the National Renewable Energy Laboratory (NREL) for King County Metro and Foothill Transit, which is to be expected given the harsher climate (Eudy & Jeffers, 2017).

Maintenance costs: Through analyzing MBTA maintenance costs per mile for FY12-17 for each sub-fleet, maintenance costs increase by age by about 20% annually, with buses starting out with very low maintenance costs that rise over the life of the bus (see Figure 5-7).

Figure 5-7: MBTA bus maintenance cost per mile by age

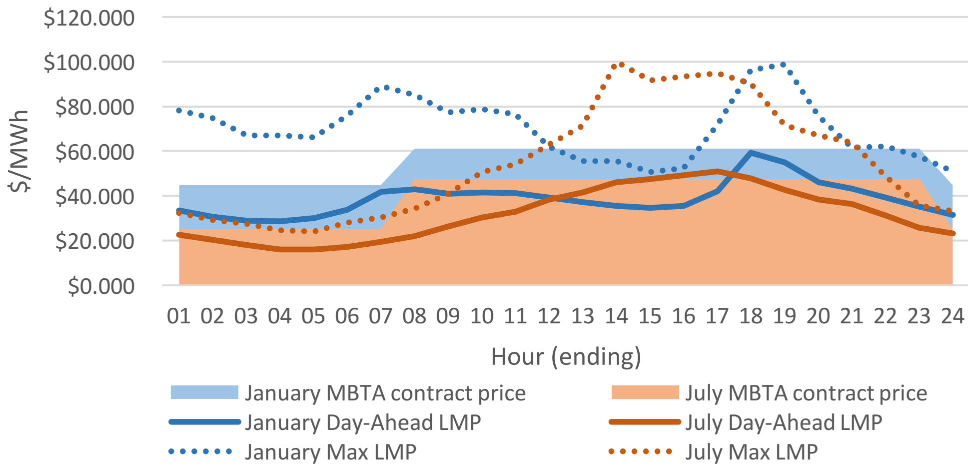


To project future maintenance costs per mile for different fuel types, MBTA maintenance costs for the first 2 million miles in service of their newest buses were analyzed and found to be $0.39/mile for CNG and $0.31/mile for the diesel hybrids. The growth rate by age was then used to project future maintenance costs for the life of the bus, and year 8 is used to reflect an average midlife cost. A more conservative maintenance savings for electric buses of 29% relative to CNG, as used by CARB, was used in this analysis. Together these assumptions generate an estimate of $1.56/mile for CNG, $1.24/mile for diesel hybrids, and $1.11/mile for battery electric buses.

Fossil fuel costs: The MBTA's diesel price per gallon in FY17 was $2.13 and natural gas price was $5.57/therm (or about $1.00 per diesel gallon equivalent (DGE)). While CNG as a commodity is currently very inexpensive, the added operations and maintenance costs are substantial, an additional $4.41/therm, or $0.60/DGE.

Electricity costs: Actual electricity costs are complicated to determine and require a number of assumptions, so this analysis represents just a preliminary estimate. Unique amongst transit agencies, the MBTA is a utility in its founding charter, enabling it to purchase electricity on the regional wholesale markets, and generally access lower electricity costs. The MBTA purchases 70% of its electricity through a contract in fixed blocks based on time period and season, which is set through 2020. Most of the remaining electricity is purchased on the regional spot market for which the MBTA is exposed to variations in the locational marginal price (LMP), the wholesale energy price calculated every 5 minutes at over 1,000 nodes across New England that reflects varying load, generation, and transmission constraints. Figure 5-8 illustrates how on average the current MBTA electricity contract price is slightly greater than the average spot price by hour in a given month, in order to hedge against price spikes as illustrated by the maximum LMP.

Figure 5-8: Comparison of MBTA Wholesale contract and ISO New England spot market prices ("ISO New England - Pricing Reports," n.d., MBTA Wholesale Power Supply Contract)



This analysis uses the 2017 annual average on-peak and off-peak prices per MWh for the MBTA's contract prices (about $0.05/kWh on-peak and $0.03/kWh off-peak in 2017), and applies a 1% yearly increase (the average increase for the 2016-2020 electricity contract) through 2032.

While the MBTA purchases electricity from the wholesale markets, they still pay investor-owned utilities Eversource and National Grid for delivery service. The utilities assess demand charges on wholesale customers like the MBTA for their non-coincident and coincident peak, which varies from month to month based on the MBTA's usage history at each account as well as the overall system peak. Non-coincident peak is defined as the customer's maximum draw from the grid in a given month, while the coincident peak represents whatever the customer's draw from the grid is at the time that coincides with the system peak in a given month. The monthly coincident peak is typically between 3-7pm, a time when the bus fleet will likely be mostly in service, so incurring high coincident peak charges is likely avoidable. Because at this point determining how many electric buses would charge at facilities by utility service area is unknown, a non-coincident demand charge estimate of $7.75/kw per month, an estimate of Eversource's rate, is used across the board, which is higher than National Grid's rate and so can be considered a conservative assumption. An estimate of Eversource's coincident per kw rate of $1.90/kw is also used.

Additionally, the MBTA may be able to minimize electricity demand charges by connecting some portion of electric bus charging equipment to its traction power system, which receives power through a high voltage connection at their South Boston Power Complex (SBPC) that powers the heavy rail, light rail, and trolleybus systems. Because the MBTA paid for the capital costs of the SBPC, as of 2014 no demand charges are assessed, only a flat fee is assessed monthly, though there are still operating costs for the MBTA to maintain that infrastructure ("Re: NSTAR Electric Company and ISO New England Inc. Filing of Local Service Agreement; Docket No. ER14-___-000," 2014). The Southampton maintenance facility is already connected to the SBPC, and other connections exist many places where the heavy rail and light rail system run. However, more detailed study is needed to assess the feasibility of connecting additional load, and the costs associated with doing so.

In addition to the inputs described previously, moderate to conservative ranges of electricity assumptions are tested:

1) **Percent bus charging connected to SBPC (0% to 15%):** 0% was used as a lower bound given the uncertainty of the feasibility of this approach, up to 15%, which would be roughly the equivalent of charging all Southampton buses off the SBPC infrastructure, since that garage is already connected.
2) **Percent of bus charging that could be shifted to off-peak hours (60% to 75%):** Given the bus schedule, this analysis assumes that a majority of bus charging could be scheduled to take place during off-peak times (11pm to 8am), particularly if charging management software can be leveraged to manage charging to take advantage of off-peak rates.
3) **Percent of fleet charging simultaneously (70%-80%):** This assumption assesses to what extent bus charging could be staggered to lessen the peak draw, in order to minimize demand charges. Having analyzed the Spring 2017 MBTA bus schedule, the current schedule suggests it would be possible to stagger charging times to some degree.
4) **Percent of electric bus capacity connected to the system during the coincident peak (50% to 75%):** This analysis assumes at its most positive that the MBTA could manage to ensure bus charging load would be at most 50% of total possible load during the coincident peak, which tends to occur between 3 and 7pm, when most buses are in service.

Facility upgrades costs: This analysis utilizes CARB's general figures for maintenance facility upgrades for different technologies, though the MBTA fleet plan in progress contemplates replacing nearly all bus garages and making each flexible for different technologies, so it's difficult to estimate the actual incremental costs of depot upgrades. Electricity upgrade costs in particular can vary substantially, so more study is needed to determine the feasibility and potential impacts of charging electric buses with the MBTA's current electricity infrastructure.

TOTAL COST OF OWNERSHIP SCENARIO ANALYSIS

This analysis compares preliminary estimated total cost of ownership for buses procured between 2018 and 2032 by bus fleet investment scenario, and discounts those costs using an estimate of the MBTA's cost of capital of 3%. The analysis explores three different bus technology scenarios, which each assume that procurements in 2018 and 2019 would be 50% CNG and 50% diesel hybrids, like the most recent procurement, with investments beginning in 2021 under the following distributions:

1) **Option A (baseline): 50% CNG/50% Diesel hybrid**: This option serves as a baseline, representing the distribution of the most recent large bus procurement.
2) **Option B: 100% Diesel hybrid:** This option represents a realistic option that may be considered by the MBTA board, which continues to feel cautious about committing to larger procurements of battery electric buses.
3) **Option C: 100% Depot charge battery electric:** This option represents a more ambitious scenario pursuing zero emissions bus technology.

Figure 5-9 provides a range of relative costs based on the two sets of electricity cost assumptions described above. Using a moderate to conservative set of assumptions for key parameters as described previously, this analysis suggests that investing in electric buses could be slightly less or slightly more expensive on a total cost of ownership for the MBTA than continuing to invest in CNG and diesel hybrid vehicles. However, both the moderate and conservative charging assumptions indicate that the total cost of ownership for battery electric buses would be less than future investments entirely in diesel hybrid vehicles, as CARB anticipates battery electric buses will have similar purchase costs as diesel hybrids in a few years. Additionally, total cost of ownership estimates are particularly sensitive to vehicle utilization, and this analysis conservatively uses fleet average miles per year, while in reality, the MBTA's relatively high spare ratio means the actual mileage per year for active, newer vehicles can be much higher, enabling the agency to potentially recoup its investment in electric buses sooner. However, considerable uncertainties about actual costs of electric buses in the MBTA context remain, particularly for variables such as electric infrastructure costs, maintenance costs, and fuel economy.

Figure 5-9: Total cost of ownership comparison of MBTA bus fleet investment scenarios, 2018-2032

	Total fleet cost of ownership	Percent difference from baseline
Option A: 50% CNG/50% Diesel hybrid (baseline)	$1.317B	-
Option B: 100% Diesel Hybrid	$1.339B	+1.7%
Option C: 100% Depot charge battery electric	$1.308B - $1.333B	-0.7% - +1.2%

5.2.3 Exploring tradeoffs between service expansion and emissions reductions

This section explores the direct emissions impacts of different service expansion scenarios and bus technology choices, to understand their impacts on the MBTA's ability to meet the MassDEP declining emissions cap, but also to put MBTA bus emissions in perspective relative to other transportation emissions sources. To do so, the analysis first considers the same three bus technology scenarios previously, and three different bus fleet size scenarios, to model the impacts on the MBTA's ability to meet the MassDEP emissions cap. The second analysis seeks to understand the relative emissions impact of the MBTA bus fleet compared with heavy duty trucks in the bus service area. These analyses consider three fleet size scenarios, 1) a baseline scenario that maintains the same fleet of about 1,000 buses, 2) a Focus 40 scenario that imagines a bus fleet that is 1.5 times the current size and scales today's total mileage by 1.5 by 2040, and 3) a GreenDOT scenario that triples the bus fleet and mileage by 2040.

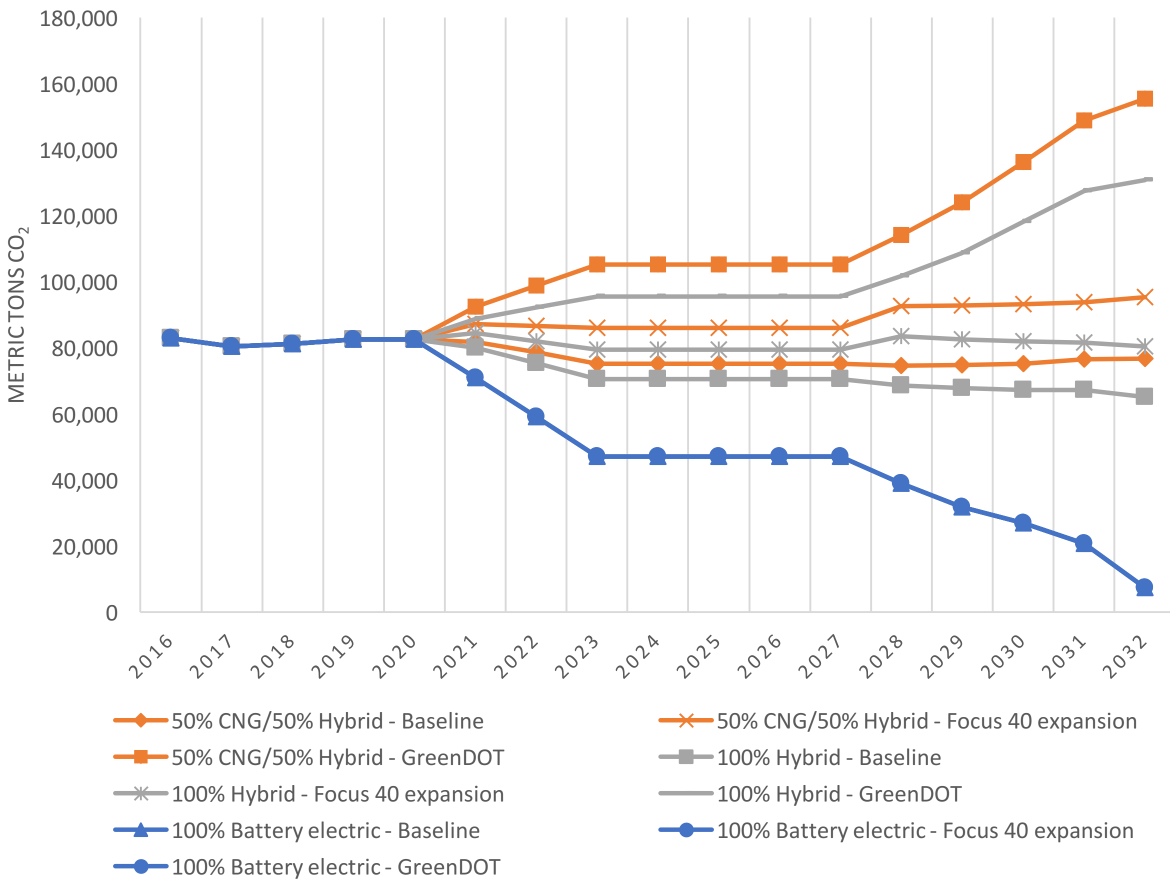
SCENARIO ANALYSIS OF TAILPIPE GREENHOUSE EMISSIONS IN 2032

This analysis considers tailpipe emissions by 2032 under the different fleet investment scenarios, to understand the potential impacts to meeting the MassDEP regulation which applies only to tailpipe emissions. Under these scenarios, change in total bus CO_2 emissions by 2032 would range from a 93% (77,300 tons) reduction to a 16% increase (13,300 tons) from the FY2015 bus baseline of approximately 84,700 metric tons, as summarized in Figure 5-10 and Figure 5-11. For context, if the proposed MassDEP declining emissions cap continues at the same pace beyond 2020, combined MassDOT/MBTA emissions would need to fall by 70,000 metric tons by 2032. Battery electric buses under all three fleet expansion scenarios would meet the anticipated MassDEP tailpipe greenhouse gas reduction trajectory in 2032 for the entire MBTA/MassDOT fleet, which could enable the bus fleet to grow to meet ridership needs while also meeting emissions targets.

Figure 5-10: Change in tailpipe CO_2 emissions by 2032 from 2016 baseline for MBTA bus fleet

		Bus fleet size scenarios		
		Baseline	**Focus 40 expansion**	**GreenDOT expansion**
Bus technology scenarios	**Option A: 50% CNG/50% Diesel hybrid**	-8,000 (-10%) *Metric tons (% change from 2016 baseline)*	10,600 (+13%)	70,700 (+85%)
	Option B: 100% Diesel hybrid	-19,600 (-24%)	-4,300 (-5%)	46,100 (+56%)
	Option C: 100% Battery electric	-77,300 (-93%)	-77,300 (-93%)	-77,300 (-93%)

Figure 5-11: Estimated CO_2 emissions of MBTA bus fleet investment scenarios, 2016-2032



SCENARIO ANALYSIS OF RELATIVE WELL-TO-WHEELS GREENHOUSE GAS AND CRITERIA POLLUTANT EMISSIONS IN 2040

This section explores the relative greenhouse gas and criteria pollutant impact of MBTA bus fleet size scenarios compared with total estimated truck emissions, and compared with state greenhouse gas goals by 2040. Because buses generally contribute relatively little to greenhouse gases, but can have a greater criteria pollutant impact in concentrated areas, this analysis attempts to understand those relative impacts compared with other heavy duty vehicles in the MBTA bus service area.

Truck emissions are estimated using the Boston MPO's modeled truck vehicle miles traveled by town in 2012 and 2040 for the 14 towns in the MBTA inner core service area, where most MBTA bus service runs (CTPS, n.d.). A simplified estimate of well-to-wheels greenhouse gas emissions and criteria pollutants is conducted using the AFLEET model, in which all trucks are assumed to be diesel vehicles with a fuel economy of 6 MPDGE, which is the estimated fuel economy for a regional short-haul truck in AFLEET. The Boston MPO data does not indicate a distribution of different types of trucks, though delivery trucks to regional combination trucks in AFLEET all have similar fuel economy close to 6 MPDGE. Fuel economy is improved for the 2040 year for all vehicles by 10%. EPA MOVES emissions rates for lower speed buses in eastern MA are used to estimate pollutants given low MBTA average speeds of 9.9 mph. In 2040, the comparison MBTA fleet emissions are estimated assuming an all diesel hybrid fleet for simpler comparison than including a mix of hybrid and CNG vehicles, while the actual fleet mix and fuel use is used for the baseline year emissions estimates. MOVES does not have estimates for improved criteria pollutant emissions rates for years beyond 2020, so this analysis does not capture potential gains in diesel technology. Figure 5-12 summarizes the results of this analysis.

Figure 5-12: MBTA bus fleet emissions impacts relative to trucks in MBTA inner core towns

	Baseline (2012-2015)			2040	2040 – Focus 40		2040 - GreenDOT	
	Trucks	MBTA buses	% of trucks	Trucks	MBTA buses	% of trucks	MBTA buses	% of trucks
Annual Vehicle Mileage	983 M	26 M	2.6%	1.1 B	39 M	3.5%	78 M	7.0%
WTW GHGs (metric tons)	2,112,000	105,000	5.0%	2,182,000	117,000	5.4%	234,000	10.7%
CO (lb)	886,000	472,000	53.2%	1,010,000	49,000	4.8%	98,000	9.7%
NOx (lb)	3,404,000	247,000	7.3%	3,877,000	518,000	13.4%	1,037,000	26.7%
PM 10 (lb)	338,000	32,000	9.3%	385,000	48,000	12.4%	96,000	24.9%
PM 2.5 (lb)	80,000	5,000	6.2%	91,000	8,000	8.3%	15,000	16.6%
VOC (lb)	202,000	8,000	4.2%	230,000	13,000	5.5%	25,000	11.1%

Between 2012 and 2040, the Boston MPO anticipates that truck VMT in the MBTA inner core towns will increase by 14%. Criteria pollutant emissions from buses are estimated to be not very significant relative to trucks in the MBTA bus service area as of 2015, except for carbon monoxide due to CNG buses. Increasing the size of the bus fleet and mileage by 2040 would begin to have a more substantial impact for some pollutants (about 25%) relative to trucks for NOx, PM, and VOC in particular, which have a much greater localized impact than greenhouse gas emissions on human health, and may be a more critical concern to mitigate with investments in electric buses.

Investing in diesel hybrid buses and increasing the fleet size would take up a majority of the estimated greenhouse gas emissions cap for the entire MassDOT/MBTA fleet (including commuter rail, buildings, etc.) regulated by MassDEP in 2040 under the Focus 40 scenario, and would exceed the emissions cap in 2040 under the GreenDOT scenario. However, in the grand scheme of the state's transportation greenhouse gas footprint, either fleet expansion scenario would be a very small portion of the aggregate statewide target for transportation in 2040.

Figure 5-13: Contribution of MBTA bus fleet to state transportation greenhouse gas targets

	Baseline 2015 fleet	Focus 40 Diesel hybrid	GreenDOT Diesel hybrid
% of extrapolated 2040 Aggregate State Transportation GHG goal	0.4%	0.7%	1.4%

5.2.4 Considerations for strategic deployment

This section attempts to synthesize initial findings from the total cost of ownership and emissions analysis to recommend a strategic approach for deployment within the MBTA's unique context, starting with a larger scale pilot on the MBTA's specialized services that necessitate zero emission vehicles, and then prioritizing routes that can maximize emissions, equity, and cost benefits.

INITIAL PILOTS

While the previous analysis suggests substantial emissions advantages and potential cost advantages to investing in electric buses, they are still untested in the MBTA context and thus could pose a risk to the agency. A larger pilot beyond the five buses to be delivered in 2018 would help gain needed experience to make a prudent decision about more widespread deployment. These pilots could be undertaken on the MBTA's specialized services that utilize the Silver Line tunnels and the Harvard tunnel. Researchers have found ultrafine particulate matter in an enclosed bus terminal not unlike these facilities to be ten times as high as background levels, posing an additional health risk (Cheng et al., 2011).

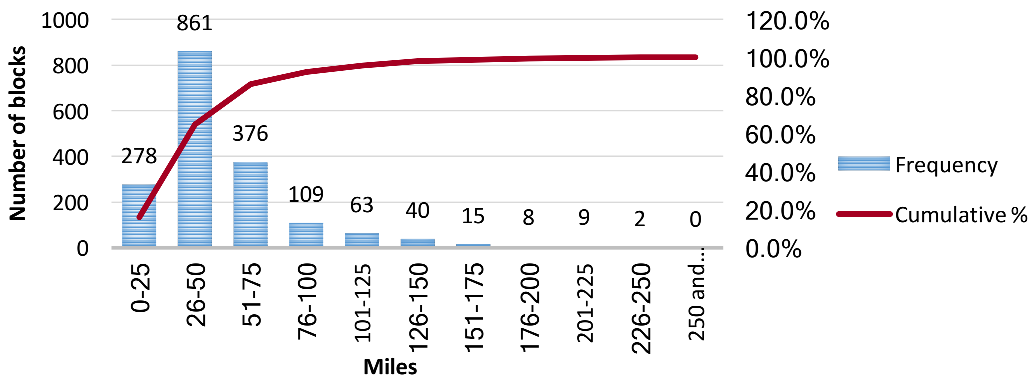
In the Silver Line tunnels, zero emission technology is required, and there is an urgent need to determine the next generation of vehicles, as the manufacturer of the current vehicles that are reaching the end of their useful life has gone out of business. Additionally, growth in the Seaport District and the pending opening of the new Silver Line Gateway service necessitates increasing the size of the existing fleet. Multiple bus lines serve the Harvard tunnel, which is also supposed to only allow zero emission technologies, but currently includes other services in addition to the electric trolleybuses. The non-trolleybus services in the Harvard tunnel could be an important place to pilot electric buses in the short term, while for the trolleybuses themselves battery electric buses will likely be a natural substitution for these services when they are ready for retirement in about five years. Experimentation in 2018 and 2019 with a variety of charging configurations and brands in these different areas, with rigorous data collection, can develop a practical understanding of the advantages and disadvantages of electric buses in the MBTA context, and can provide better capacity to reduce the risks inherent in adopting new technologies.

LARGER DEPLOYMENTS

These initial pilots should take place quickly, as large portions of the MBTA fleet are due for retirement soon, necessitating an urgent decision about future bus technologies. Hesitating to test battery electric bus technology and make a prudent decision about these needed replacements could unnecessarily lock in large new fleets of diesel and CNG buses for 12-15 years. As the MBTA conducts a larger scale pilot, it should begin planning for how to maximize benefits from battery electric buses by prioritizing deployment on routes that can offer the greatest benefits and strategically develop their charging infrastructure plans to take advantage of their low electricity costs and existing infrastructure.

One of the major concerns for many agencies thus far has been assessing electric buses' ability to meet range requirements, though given the MBTA's slower speed operation and dense urban service area, most bus assignments are short comparatively to other agencies. MBTA schedules suggests that today's electric buses could serve a substantial portion of current daily assignments, as 90% of all bus blocks (a single pull out and pull in from a garage, serving one or more trips) from the MBTA's 2017 spring weekday schedule were less than 100 miles long (see Figure 5-14). The California Air Resources Board (CARB) and LA Metro estimate the range for a depot charge battery electric bus today with a 330 kWh battery to be between 93-150 miles (with buses with larger 550 kWh batteries achieving up to 250 miles) (California Air Resources Board Innovative Clean Transit Working Group, 2017c; Ramboll Environ; M.J. Bradley & Associates, 2016). Some vehicles may serve more than one block per day, returning to a garage in between where it may have time to charge before leaving again. This suggests that as the MBTA pursues larger deployments, range issues may be less of a challenge than for agencies like LA Metro that have more routes and assignments that are beyond electric bus range. Additionally, electric bus ranges are expected to improve along with battery technology.

Figure 5-14: MBTA Bus block lengths (Spring 2017 weekdays)



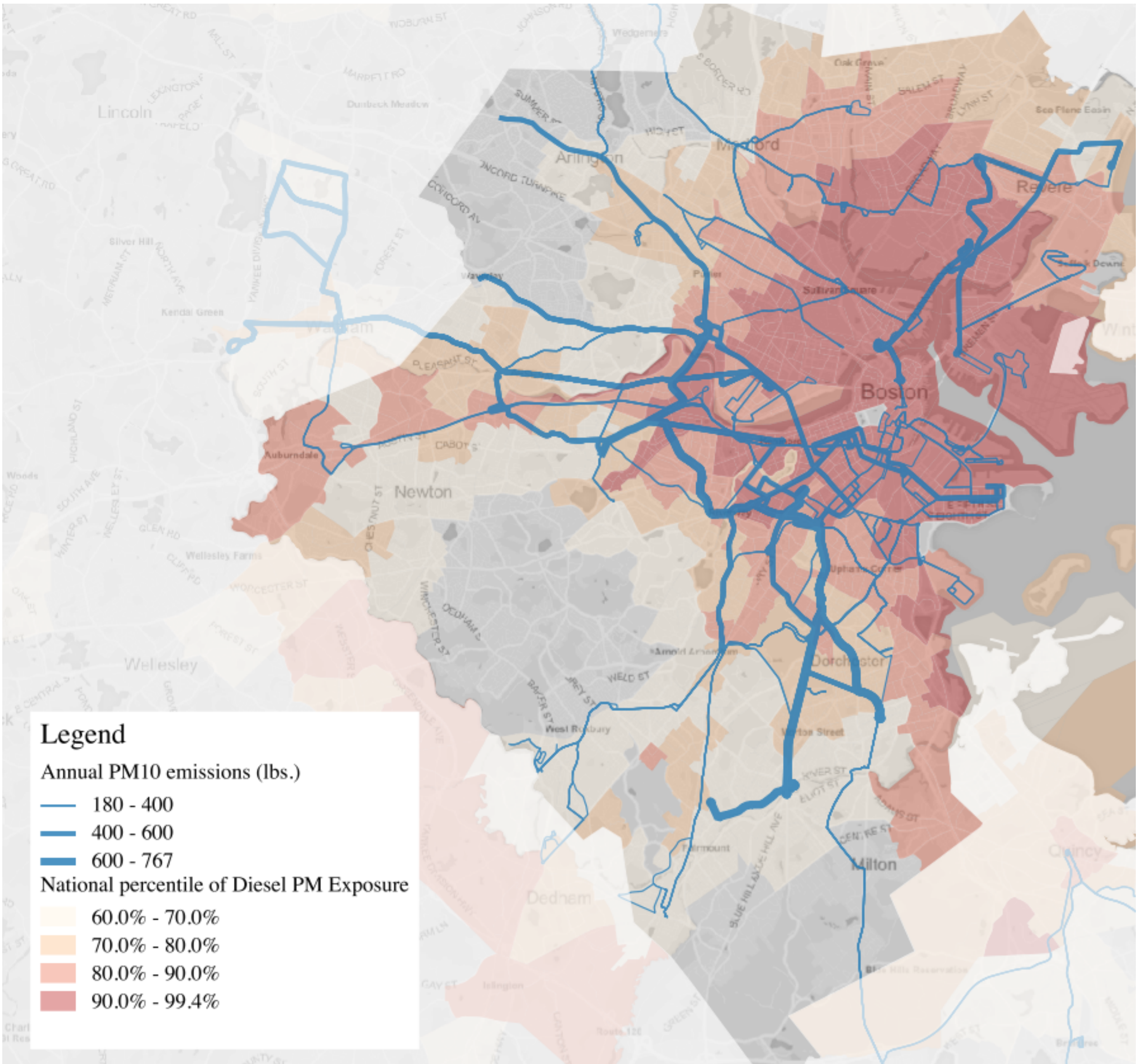
From the perspective of prioritizing equity and maximizing emissions reductions, one way to sequence the next phase of deployments is to consider slower speed routes where the contribution to local air pollution is greatest, as well as where existing exposure to air pollutants is highest, in order to bring the greatest benefits to impacted communities. Figure 5-15 displays the top 20 routes in the MBTA system with the highest annual estimated air pollution emissions if the routes were operated with a 100% diesel hybrid fleet. The analysis utilizes GTFS schedules to estimate frequency, annual mileage by route, and average speeds, and EPA MOVES emissions rates for transit buses for Eastern Massachusetts by speed to estimate route level emissions.

Figure 5-15: Top 20 MBTA routes by estimated pollution levels with a 100% diesel hybrid fleet

Route number	Annual mileage	Avg. scheduled speed	CO (lbs.)	NOx (lbs.)	PM10 (lbs.)	PM2.5 (lbs.)	VOC (lbs.)
23	463,372	8.8	577	1,548	767	115	105
66	421,230	8.2	524	1,407	697	104	96
28	460,863	9.8	504	1,344	661	99	92
39	483,290	10.0	455	1,205	588	88	84
22	404,846	9.7	442	1,181	581	87	81
77	511,379	11.5	438	1,163	574	86	81
1	346,881	8.5	432	1,159	574	86	79
70	501,282	12.4	387	1,031	515	77	71
111	722,469	15.3	375	1,012	538	79	70
57	411,659	11.1	353	936	462	69	65
9	298,479	9.7	326	871	428	64	60
73	369,776	11.8	317	841	415	62	58
116	333,660	10.6	314	832	406	61	58
86	265,748	9.9	290	775	381	57	53
15	238,292	9.5	260	695	342	51	48
71	267,620	11.0	252	667	325	49	46
749	201,229	8.1	251	672	333	50	46
47	222,845	9.7	244	650	320	48	45
31	351,822	13.1	242	647	328	49	45
32	462,063	15.1	240	647	344	51	45

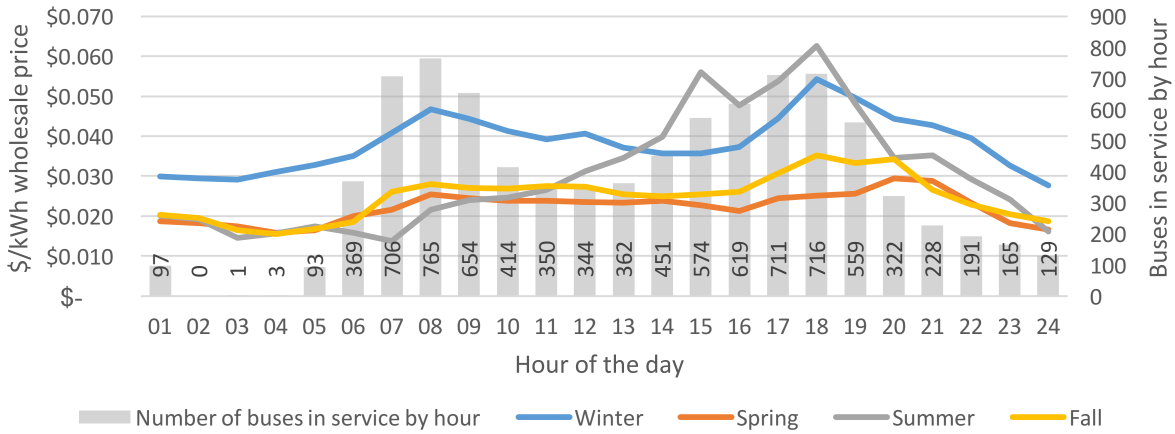
Figure 5-16 maps the top 50 MBTA routes by their estimated level of PM10 pollution operated under a diesel hybrid fleet, alongside estimated national percentiles of diesel PM exposure, and suggests the next sets of routes to be electrified ought to be those in thicker blue where existing air pollution exposure is high, such as routes that serve lower income areas like Chelsea, Roxbury, Dorchester, and Forest Hills. According to the total cost of ownership analysis in Chapter 3, prioritizing these types of higher mileage and slower speed routes will also accelerate the payback period for electric buses compared with fossil fuel buses.

Figure 5-16: Top 50 MBTA routes by estimated annual PM10 emissions with a diesel hybrid fleet and national percentile of diesel PM exposure in MBTA core towns (EPA EJ Screen)



From a cost effectiveness perspective, considering strategic electricity infrastructure buildout and charging will also be essential to minimize the costs of transitioning the MBTA fleet to electric buses. Having analyzed the Spring 2017 MBTA bus schedule, over half of the buses needed for peak service are pulled in by 8pm, and the peak number of vehicles are not needed again until 7am, suggesting a fairly long overnight charging window. With an estimated charging time of 3.5-5 hours for depot charge buses, the current schedule suggests it would be possible to stagger charging times overnight to some degree to minimize peak loads, and to avoid peak period high cost times to charge. Figure 5-17 overlays the MBTA bus schedule and wholesale electricity costs, and suggests that charging times for depot charge buses would be largely complementary with lower wholesale electricity costs throughout the year.

Figure 5-17: Number of buses in service by hour, MBTA 2017 weekday spring schedule and ISO New England 2016 average real time wholesale prices by hour and season



As the MBTA pursues investments in electric buses, the agency could take advantage of its position as a utility and wholesale electricity customer to access low cost electricity and leverage its robust electricity infrastructure to enable potential cost savings. To do so, the MBTA would need to further investigate the following strategies to minimize electricity costs and maximize potential savings:

1) The potential to leverage off-peak capacity from the SBPC network to charge electric buses and lessen costly demand charges.
2) The potential to stagger overnight charging by using charging management software, to understand whether such an approach could lessen demand charges without impacting operations.
3) The potential to maximize the amount of charging done during off-peak times, to understand to what extent current schedules can enable taking advantage of attractive off-peak rates.
4) The potential to avoid coincident demand charges, by managing the electric bus charging load during the system peaks, which tend to occur between 3 and 7pm.

SUMMARY

This analysis suggests the MBTA and MassDOT could meet most if not all of their MassDEP emissions reductions obligations from their fleet through investment in electric buses, even with moderate to substantial transit service expansions. Under expanded service scenarios, the MBTA bus fleet does begin to contribute substantial levels of criteria pollutant emissions relative to trucks in their core service area, suggesting that electric buses may be most relevant as an environmental strategy to address air pollution issues if the bus fleet is expanded. A preliminary cost analysis suggests that investing in electric buses would increase the MBTA's total costs only slightly, or may actually save money by doing so, depending on how the buses are deployed and charged, relative to continued investments in CNG and hybrid buses. Compared with diesel hybrids, battery electric buses are estimated to produce total cost of ownership savings, as price forecasts suggest the gap between diesel hybrid and electric bus costs will narrow in just a few years. A strategic approach for deployment within the MBTA's context should start with a large scale pilot on the MBTA's specialized services that necessitate zero emission vehicles, in order to rigorously assess performance, mitigate risks, and inform a next phase of larger scale deployments. Given the also high capital costs and more limited emissions reduction potential from diesel hybrid buses, pending a successful pilot, the MBTA should move towards a procurement approach of 100% electric buses for its planned procurements between 2020 and 2032, prioritizing deployment on high frequency, slow speed service in environmental justice communities that can maximize environmental, equity, and cost benefits.

6. Potential solutions to accelerate bus electrification

This chapter seeks to synthesize findings from the qualitative interviews and quantitative modeling to identify a range of strategies that could be adapted to different contexts to accelerate bus fleet electrification. First, this chapter outlines the different potential policies, programs, and strategies identified through interviews and background research, summarizes interviewee views about those approaches, and discusses the considerations for implementation. Next, these approaches are categorized and summarized, according to the factors identified in Chapter 4 that each helps address. Finally, a preliminary recommended set of policies, programs, and strategies is developed for each case study state.

6.1 Motivation strategies

The following strategies were identified based on stakeholder interviews and a literature review as helping to create the conditions for transit agencies to be motivated to pursue electric bus deployment.

6.1.1 Organizing and public engagement

Each case study state had examples of organizing and advocacy efforts to support electric bus deployment, with California having the most developed and broad-based coalitions. There, a local coalition in LA helped to garner support for the commitment to a 100% electric fleet by 2030, and has been working to ensure that such an investment can provide good, green jobs to those who need it most, while targeting early deployment in environmental justice communities. Statewide, environmental justice and traditional environmental groups have been working together to press for supportive policy changes for electric buses, such as more advantageous electricity rates and charging infrastructure incentives. Massachusetts advocates have also begun coalition organizing statewide, and in Kentucky, community organizing groups that have focused on air quality and environmental justice are working to support transit agencies in deploying electric buses.

Organizing efforts thus far have been important for creating motivation for more ambitious electric bus commitments, as well as garnering support for supportive policies. By collaborating with and inviting public participation and advocacy efforts, transit agencies and policymakers can seek out common policy goals that can further enable electric bus deployment, while helping to ensure that community priorities, particularly from marginalized communities, are considered in developing implementation plans and prioritizing routes for deployment. Advocates should consider supporting strategies that are simultaneously supportive of expanded transit service that also help accelerate electric bus deployment.

6.1.2 Goals and mandates

While mandates may speed deployment, agency representatives highlighted several key reasons why a strict zero emission procurement mandate could impact transit service, undermining another important carbon reduction strategy. While one agency interviewed felt that having a regulation in place, or a goal to strive for, would send a clear signal for agencies to electrify their fleets, agencies in California were nearly unanimous in opposing a regulation requiring certain levels of investment in zero emission buses, and were advocating instead for a more flexible regulation that would set emissions goals, but provide alternative options to reach them. Agencies seemed to feel proud that transit fleets had led clean technology deployment in heavy duty vehicles previously, but also found it unfair that they were usually the first vehicle class targeted with regulations simply because it's easier to do than regulate trucks:

> "Transit was the first fish in a barrel in terms of regulating tail pipe emissions at the state level. We're a good place to start because we have a lot of in-house expertise, engineering staff to deal with advanced technology. So they drafted the fleet rule for transit agencies. We were the first with DPFs, and the first to commercialize CNG in heavy duty applications."

> "Transit is the canary in the coalmine for anything because what they can force into transit they can use as leverage on trucking. Trucking is the holy grail. So by pushing us out of CNG and into zero emission, it opens the door to trucking. We're a captive audience, we're fixed route, we're not going anywhere, we're government funded. No excuse for not participating."

Agencies also felt that the earlier CARB rule on zero emission technologies had wasted time and money, forcing agencies into zero emission technologies that were unproven:

> That mandate cost a lot of wasted money, wasted resources spent going in directions that were not fruitful, wasted time in Sacramento dealing with this regulation that was unattainable instead of being here actually doing productive work, so that's my fear this go-around. If CARB drafts a regulation that is unattainable again, then we're going to spiral into that trap of wasted time and resources, when we should really be focused on how we electrify the fleets.

Ultimately the transit agencies interviewed hoped that CARB would put forward an alternative regulatory framework that would "focus on the result, not just mandate electric buses, but say what is our true goal? Our true goal is to reduce NOx, PM, greenhouse gases, and let us find the way forward", and that they would help financially support the transition given transits' role in helping to demonstrate the new technology for other sectors to adopt later: "Before we commercialized the DPF, the low NOx engines, CNG in heavy duty, so we're a very natural and capable target to commercialize electrification of heavy duty vehicles. With the caveat that someone is going to have to open their checkbook at some point."

In late 2017 CARB issued more details on its proposed regulation, which seems to acknowledge many of the transit agencies' concerns, citing a need to ensure technical feasibility, avoid negative impacts to transit service, provide continuing subsidies, and proposes to partner with transit agencies to make a zero emission bus fleet a reality (California Air Resources Board Innovative Clean Transit Working Group, 2017d). To do so, their proposal phases zero emission bus purchasing requirements in over time, incentivizes agencies to make purchases early, and enables flexibility by allowing joint compliance by agencies within a region. This proposal came after interviews done for this thesis, so agencies' perspectives on the proposal are unknown, though it appears the intention behind it and flexible approach may help address some of agencies' concerns.

CONSIDERATIONS FOR IMPLEMENTATION

Mandates have the benefit of creating a stable policy environment for manufacturers, which may also advantage other strategies like economic development, though agencies identified potential downsides to inflexible zero emission procurement mandates. Ultimately, given the climate benefits of increasing transit ridership and remaining uncertainty around larger scale electric bus deployments, setting a regulation that might impact service levels could be counterproductive. Instead, state agencies and other stakeholders should consider regulations that enable multiple options for compliance, and otherwise support widespread deployment by enacting policies that help overcome key barriers and incentivize voluntary commitments, supporting transit agencies to successfully demonstrate and commercialize heavy duty electric vehicle technology in order to spread deployment to other sectors like trucking.

6.1.3 Economic and workforce development

Stakeholders in California have helped create a potent example of how transportation electrification can support a just transition, by ensuring good paying, green jobs go to those most in need. A combination of incentives provided by state policymakers to manufacturers, a policy environment and advocacy efforts supportive of transportation electrification, and transit agency electrification commitments seems to have created confidence amongst manufacturers, and work by advocates has ensured that jobs created in the sector go to those who need them most. While it may not be possible to develop as large a cluster of companies as California, bus manufacturers have suggested they will consider opening factories elsewhere once there is a commitment to a certain purchase volume. By creating a complementary policy environment to support transportation electrification, policymakers may be able to advance other societal goals like good, green job creation, and further the commitment to electrification and climate goals.

In addition to manufacturing incentives, California advocates have worked to leverage job opportunities for disadvantaged communities by winning a community benefits agreement with manufacturer BYD, and previously by working with LA Metro to insert U.S. Employment Plan contracting language that helps ensure the creation of good-paying local jobs. Outside California, one Kentucky stakeholder mentioned that previous transitions to alternative fuel vehicles had spurred the creation of a workforce development program to train workers about alternative fuel vehicles through a technical automotive school, to ensure that students were prepared for jobs in any new vehicle technology.

CONSIDERATIONS FOR IMPLEMENTATION

While locating manufacturing centers may not be feasible everywhere, it may be worth other states reaching out to manufacturers to understand their likelihood to locate new factories. In addition, charging infrastructure installation and electric vehicle maintenance will be needed everywhere, so workforce training programs could focus on these skills. Focusing on equitable economic development outcomes can help garner a broader base of support for electrifying buses and other fleets.

6.2 Capital cost strategies

6.2.1 Grant and voucher programs

Nearly all interviewees stressed the importance of grant funds for being able to afford the electric buses in their fleets, and for some, for being able to afford any additional buses in the future. However, interviewees and publicly available data suggest that existing grant programs are already very oversubscribed, and sustaining or increasing grant funding levels can be politically challenging.

The following simplified analysis estimates the level of funding required to cover the incremental capital costs of electric bus deployment that could enable a transition to a 100% electric statewide fleet over the next 14 years. This analysis assumes an even procurement of 1/14 of each state's bus fleet each year between 2018 and 2031 with a discount rate of 3%, and assesses the incremental replacement cost for a battery electric bus compared with a diesel bus over time, taking into account projected purchase cost changes and charger purchase and installation costs. This analysis does not take into account differences in mid-life costs or the incremental cost of buses with larger battery packs, and assumes agencies will need to be able to afford the full incremental cost of a battery electric bus (i.e. that FTA formula funds will not increase to match the costs of an electric bus). This is not meant to be a precise analysis of the actual cost of converting a state's bus fleet to electric given the many variations across agencies, but is rather an indication of the level of a capital subsidy program required to afford the upfront costs for a complete turnover of the state fleet to electric, in comparison with existing grant funds. In addition to the total incremental cost required to transition to electric, the analysis also estimates the size of an HVIP-like program in each state that could provide sufficient vouchers each year, assuming a $95,000 voucher.

Figure 6-1: Estimated total incremental capital cost to convert state transit bus fleet to electric 2018-2031 (CARB, 2017)

State	Total bus fleet	Discounted total incremental cost (diesel baseline)	Discounted total incremental cost (CNG baseline)	Discounted total incremental cost (diesel hybrid baseline)	Discounted total cost for sufficient HVIP vouchers
CA	10,792	$2.7B	$2.3B	$879M	$852M
MA	1,620	$408M	$341M	$132M	$128M
KY	437	$110M	$92M	$36M	$34.5M
National	**70,000**	**$17.6B**	**$14.7B**	**$5.7B**	**$5.5B**

The analysis summarized in Figure 6-1 and Figure 6-2 suggests that the estimated grant funds to enable a complete transition of each state's bus fleet is greater than available programs in all cases, even relative to higher cost diesel hybrids. For example, in FY17-18 California has proposed that at least $35 million of the proposed $180 million for HVIP vouchers should be for zero emission buses, far short of being able to cover the incremental costs of electric bus investment for agencies statewide compared to any other bus technology. Nationally, the incremental cost dwarfs the available grant funds for electric buses.

Figure 6-2: Estimated annual incremental capital cost to convert state transit bus fleet to electric 2018-2031 (CARB, 2017)

State	Estimated buses replaced per year	Total annual incremental cost (diesel baseline)	Total annual incremental cost (CNG baseline)	Total annual incremental cost (diesel hybrid baseline)	Annual cost to provide sufficient HVIP vouchers	Size of existing state/local grant programs (annual)
CA	771	$230.6M	$192M	$72.6M	$73M	$22M (HVIP)
MA	116	$34.6M	$28.8M	$10.9M	$11M	$0
KY	31	$8.1M	$7.8M	$2.9M	$2.9M	$0
Nationa l	**5,000**	**$1.5B**	**$1.2B**	**$471M**	**$475M**	**$55M**

CONSIDERATIONS FOR IMPLEMENTATION

CMAQ, VW funds, and cap and trade funds may all be viable sources for extending a grant program to support electric bus deployment that don't compete or dilute other limited funds for bus replacement that might impact transit service. Besides California, other places have been able to implement clean truck and bus voucher programs, including Chicago and New York, which both used CMAQ funds to establish their programs ("Drive Clean Chicago," n.d., "NY Truck VIP - What is NYT-VIP?," n.d.). Massachusetts only provides grant funds for light duty public and private vehicles, though an initial analysis using the AFLEET model to estimate greenhouse gas reductions for passenger cars suggests that a $95,000 voucher like the HVIP program or make-ready incentive would be similarly cost effective as the MOR-EV incentive and much more cost effective than the EVIP incentive on a cost per ton CO_2 reduction basis based on the grid electricity emissions in Massachusetts. The analysis in Figure 6-3 divides the voucher amount by the estimated lifetime tons reduced compared with a conventional vehicle.

Figure 6-3: Estimated cost per ton of lifecycle CO_2 reductions for electric vehicle incentives

State	Implied cost per ton, HVIP voucher ($95,000)	Implied cost per ton, Make-ready incentive (~$55,000)	Implied cost per ton, light duty EV incentive programs
MA	$54	$31	$140 (EVIP - $7,500), $47 (MOR-EV - $2,500)
KY	$76	$44	(no state EV incentive)
CA	$55	$32	$48 (CVRP - $2,500)

Capital subsidies have been essential for driving deployments thus far, though current programs are largely oversubscribed. States are just getting prepared to develop plans for VW settlement funds, which could be leveraged in part to support an electric bus voucher, rebate, or other type of incentive program. Combined, CMAQ and VW funds (see Figure 6-4) might be able to cover a substantial portion of the estimated incremental costs to transition each state's bus fleets, though there are many competing interests besides electric buses for both CMAQ and VW funds that may make it difficult to establish and maintain funding programs at the levels needed to drive an accelerated transition to an electric bus fleet.

Figure 6-4: Available CMAQ and VW Settlement funds by state (Kentucky Transportation Cabinet, n.d.; "Massachusetts State Transportation Improvement Program, 2017-2021," 2017)

State	CMAQ (annual)	VW funds (total)
CA	$437M	$381M
MA	$46-78M	$75M
KY	$24.9M	$19M

6.2.2 Financing approaches

With limited funds for grant programs, some stakeholders have proposed financing strategies to enable transit agencies to afford the higher upfront cost of electric buses by leveraging anticipated operating savings. Multiple electric bus manufacturers have been offering leases, particularly battery leases which enable pricing for the vehicle at the same level as a diesel bus. Other proposed financing strategies have been directly translated from clean energy and energy efficiency financing approaches, such as tariffed on-bill financing and energy saving performance contracts (ESPC) models. This section considers different proposals for financing the incremental cost of electric buses, stakeholder views of these approaches, and potential implementation considerations. While grant programs have been essential for early pilots of electric buses, the substantial oversubscription of FTA's Low No program and California's HVIP program suggests that other approaches may be necessary to enable more widespread adoption. While experts in energy efficiency finance suggest finance alone is rarely sufficient to overcome barriers to enable investment in clean technologies, it can be a useful tool, particularly to address first cost barriers and enable further leverage of limited government funds.

CAPITAL, OPERATING, AND BATTERY LEASES

Leasing has been used widely in the residential solar market, including by well-known companies such as Solar City, and can be advantageous for consumers with debt limitations or otherwise looking for financing with simple terms. Up until recently, FTA rules were more onerous with respect to bus leasing, but the FAST Act changed the rules regarding capital leases to be less burdensome. Capital leases refer to arrangements in which the lessee intends to purchase the leased equipment, while an operating lease refers to the lessor retaining ownership of the equipment. In addition to eliminating a required cost effectiveness analysis before executing a lease, the FAST Act also specifically enabled a battery lease arrangement for electric buses, which helps shift the risk of the battery performance to the manufacturer and potentially enables a reduced capital cost. Amongst manufacturers, Proterra advertises on their website a capital lease, operating lease, battery lease, and short term bus rental for trials. The battery lease option they offer prices their bus at about the price of a diesel bus, and Proterra maintains ownership and responsibility for the battery (Proterra, n.d.). BYD and other manufacturers also offer leases.

While few agencies currently lease vehicles (just 7% of revenue vehicles acquired with federal funds), some are beginning to use capital, operating, or battery leases to afford more electric buses or reduce technology risk (Federal Transit Administration, 2016a). New York City Transit, for example, is using an operating lease in order to pilot electric buses in its fleet from two different manufacturers, as a way to avoid the risk of FTA requirements to keep buses for 12 years should the pilots not work out. Other smaller agencies such as LADOT, Park City and Sunline Transit are using capital or battery leases as a financing strategy to help afford the up-front capital costs of electric buses, or leverage grant funds to procure more buses than they would have been able to afford. JLL, a private bus operator in Chicago, has also initiated a battery lease for 10 buses (Proterra, 2016).

Amongst the agencies interviewed for this research, some say they would consider leasing primarily to shift the risk of battery performance to manufacturers, with one saying it would "be attractive to us on the battery and replacement cycle side of things. We have an interest in maintaining a set range of performance, and if it requires swapping batteries out every 3-5 years, there's some value in maintaining an even performance level." Other agencies interviewed weren't considering leasing, primarily due to being accustomed to outright ownership, as well as some agencies not being aware of FTA's change in rules. A few agencies said that the costs of capital for the leases available to them were less attractive than the other capital sources they had access to as a government agency. Another potential lease arrangement to consider might be what is known as a tax-exempt municipal lease purchase agreement, commonly used for school bus procurement, which enables lower interest rates due to agencies' tax exempt status.

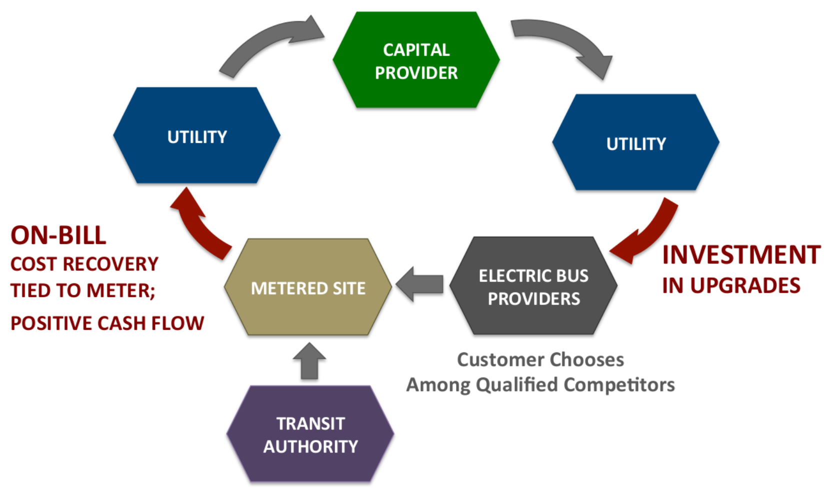
TARIFFED ON-BILL FINANCING

On-bill financing is one family of energy efficiency finance tools, in which "a financial product that is serviced by, or in partnership with, a utility company for energy efficiency improvements in a building, [is] repaid by the building owner on his or her monthly utility bill" (U.S. Department of Energy, 2015). The advantages of this approach include the ability to leverage a utility's unique relationship with energy customers to make it convenient to access funding and opt in, and the ability to attract capital which tends to view utility bill payment as secure. Programs are often structured so that consumers face no up-front cost, and pay for the upgrades through a charge on their utility bill less than their baseline bills; in other words, they pay for the upgrades out of a pre-determined portion of the savings. On-bill financing programs existed in 20 states as of 2011, and take the form of either loans or an incremental tariff on the utility bill. So far, on-bill financing programs have experienced very low rates of default (0-2%), have enabled consumers to achieve 15-30% utility bill savings, and have seen high utilization rates relative to other programs (Bell, Nadel, & Hayes, 2011). Researchers estimate that $1.83 billion in on-bill loans have been made since the late 1970s (Leventis et al., 2016).

In California, Greenlining Institute, in partnership with tariffed on-bill financing experts at Clean Energy Works and multiple environmental justice, traditional environmental groups, and ratepayer advocates including the Union of Concerned Scientists, TURN, Green for All, Sierra Club, and others submitted a proposal to use $4M of PG&E's open solicitation for priority review projects to implement a pilot tariffed on-bill financing program for transit buses (Greenlining Institute, 2017). This proposal garnered support from SJRTD in PG&E's service territory, with their letter of support stating that "grant funding is not a predictable long-term strategy for achieving our city's goals for clean air" (Greenlining Institute, 2017). The coalition members describe the proposed pilot as follows:

With Commission approval, PG&E can offer an opt-in tariff that would enable investment and cost recovery for the on-board battery and charging equipment included in electric buses procured by public transit agencies in its service territory. This would remove the upfront cost barrier that remains for transit agencies. To recover costs, PG&E would include on a transit agency's monthly bill a fixed charge capped at a level below the estimated savings relative to the cost of operating a traditional diesel bus.

Figure 6-5: Transaction path for a tariffed on-bill financing program for electric buses (Clean Energy Works)



In justifying this approach, Greenlining and partners highlighted both the translation of the success of this approach for clean energy investment, as well as the environmental justice rationale behind piloting such a method to accelerate deployment in disadvantaged communities:

> In the California Energy Commission's (CEC) work to implement the same law, it completed a landmark SB 350 Barriers Study, examining barriers to energy efficiency and renewable energy in low-income communities. Among its recommendations, the CEC recommended that the California Public Utilities Commission (CPUC) consider demonstration projects for tariffed on-bill programs that benefit low-income communities. Transit agencies across the state serve youth and elders, riders without documentation to obtain drivers licenses, low-income residents without access to private vehicles, and riders whose physical mobility is limited. If ratepayers will be asked to pay for the Priority Review Projects, these are among the first who should benefit…every year we wait, there is another round of transit buses that will be polluting the air of transit-dependent communities beyond 2030. We can't wait. We call on the CPUC to accept the CEC's recommendation through this SB 350 proceeding on electrification of the transportation sector, putting frontline communities in our cities literally at the front of the line for investment - starting with clean transit.

Greenlining and partners also highlighted that such a pilot could help inform a more widespread program that leveraged additional utility dollars, private sector dollars, or other government sources:

> Helping transit agencies procure more ZEVs faster is in the public interest, but there are real limits to an approach that depends on taxpayer or ratepayer subsidies. Therefore, this Priority Review Project will demonstrate the potential for a self-sustaining program for longer-range all- electric buses that are cost effective on a lifecycle cost basis. …If successful, the source of capital can shift from ratepayer funds to the utility's investment capital, a third party financial partner, or to competitive capital markets that typically yield low cost capital when utilities are the counterparty….Alternatively, the scale of this project can be

more than 10 times larger if the ratepayer funds are used instead to lower costs for private capital by establishing a reserve fund for charge-offs or by paying for a loan guarantee for the capital provider.

In interviews, transit agencies familiar with the approach were generally positive but somewhat cautious about the idea of tariffed on-bill financing. While they saw the value in being able to transition their fleets more rapidly, their caution stemmed from their uncertainty about whether cost savings would materialize, their lack of familiarity with financing, and potentially higher interest rates than they're accustomed to:

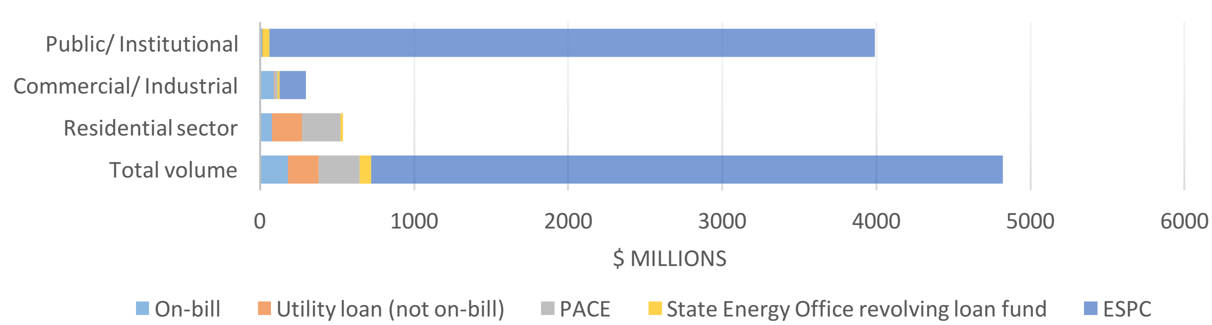
> "My concern is we've never financed buses in that way before, so there'd have to be a board level discussion. The other thing is, the interest rates would have to be favorable enough, while some of the rates we've discussed are 1-2 points higher than what we might be able to get from a commercial lending institution. So I'm interested theoretically, but I'm not going to pay 6% when we might be able to get a line of credit at a lower rate."

A pilot project such as the one proposed by Greenlining Institute and partners is a critical next step to test the applicability of this financing scheme for transit buses, and to help inform the design of a program that might be able to leverage more public, and possibly private, dollars. In doing so, the program should seek to address concerns expressed by transit agencies, including ensuring that interest rates are competitive, and that cost uncertainties are appropriately projected and managed to mitigate risks.

ENERGY SAVING PERFORMANCE CONTRACTS

An ESCO, or energy services company, provides start-to-finish services for an energy efficiency project, including conducting an energy audit, securing financing, installation, and monitoring performance. In what is known as an energy saving performance contract, or ESPC, "the ESCO guarantees or shares energy and/or dollar savings for the project and ESCO compensation is therefore linked in some fashion to the performance of the project" (Carvallo, Larsen, & Goldman, 2015). ESCOs have enabled public and commercial entities to finance equipment and facility upgrades and receive savings with no up-front investment, and often no public subsidy. Due to substantial transaction costs and tolerance for longer payback periods, ESCOs primarily target large public buildings, with roughly 84% of the estimated $5 billion annual U.S. ESCO market revenue coming from the 'MUSH' market, or municipal, universities, schools, and hospitals (Leventis et al., 2016). Researchers recently estimated that active ESCO projects saved 34 TWh in 2012 alone, or 2.5% of U.S. commercial electricity retail sales (Carvallo et al., 2015). A recent analysis of energy efficiency financing programs (Figure 6-6) found that the volume of ESPC financing dwarfs that of any other financing approach.

Figure 6-6: Energy efficiency finance volumes by program type and sector (Deason et al., 2016)



Some organizations have begun to propose adaptations of the ESPC concept to clean vehicle deployment for transit agencies and other public vehicle fleets, which may have some similarities to the 'MUSH' market where this strategy has been most successful. C2ES has issued a report about the potential for ESPC models to drive procurement of natural gas buses and other fleet vehicles, and VEIC (Vermont

Energy Investment Corporation) launched their T-ESCO initiative, which includes running a pilot with electric school buses in Massachusetts to establish baseline energy savings estimates (Morris, 2016; Nick Nigro, Dan Welch, 2015). There have been some initial attempts to finance alternatively fueled vehicles with an ESPC model. One of the largest ESCOs in the country, Johnson Controls, completed a project for a school district in Pennsylvania that involved upgrading the school's bus fleet to natural gas in conjunction with a building retrofit, and used guaranteed savings from the fleet transition to finance the project (Delaware Valley Regional Planning, 2016).

The state chapter in Kentucky of the Energy Services Coalition (Kentucky ESC), a network of groups supporting ESPC nationwide, had interesting insights about the potential application of ESPC to vehicles. Kentucky passed ESPC legislation in 1996 and has since become the state with the second highest per capita level of ESPC investment in the nation. As a result, the transit agency interviewees were all familiar with ESPC, and some had done projects on their facilities. One interviewee from Kentucky ESC said that public agencies tend to see a number of advantages to using ESPC, including being able to use a simpler procurement method, borrow money without impacting their debt capacity, overcome first cost hurdles, and see guaranteed savings on these projects with relatively little risk to their existing budgets:

> I look at performance contracting in Kentucky as a procurement tool. It's a way to purchase quality instead of the traditional low bid RFP response, so it's the better option to install quality and value engineered solutions. The savings are guaranteed, so that's essentially a revenue stream to service that debt.

Kentucky ESC also focused on the ability to roll several projects into one to make the financing work, which is how the school bus ESPC in Pennsylvania worked as well. While optimistic in some respects about the ability to apply such a model to vehicles, they were unsure whether ESCOs and financing entities would see vehicles differently than they see buildings, given that vehicles are a depreciating asset. Additionally, they were unsure as to whether the ESPC legislation as currently written would apply to transportation. Colorado appears to be the only state that has explicitly approved legislation to enable energy performance contracting in the transportation sector for government fleets (Colorado Revised Statutes 24-30-2001 through 24-30-2003 and 29-12.5-101 through 29-12.5-104). Finally, they stressed the importance of education in building a pipeline for ESPC, as agencies aren't always familiar with aspects of how the concept works, such as how an ESCO calculates the estimated savings and guarantee.

In Massachusetts, the CEIP program described in Chapter 4 functions similarly to an ESPC program, but with less onerous verification procedures, which can add cost and complexity to projects. While the savings aren't guaranteed, the agency that runs the program provides a free energy audit and uses a debt service coverage ratio to help guard against some of the uncertainty in achieving cost savings.

ESPC could be a useful approach to further operationalize through enabling legislation and working with ESCOs to identify business opportunities to assist transit fleets. Given the uncertainty for transit agencies investing in electric buses, a savings guarantee model could help eliminate some of the cost risk, and could likely be paired with agency building upgrades. Downsides of ESPCs can include higher costs of capital (to account for work an ESCO puts in and risk it takes on), and costs and challenges associated with measurement and verification of savings, so it may not be the right approach in all cases.

CONSIDERATIONS FOR IMPLEMENTATION

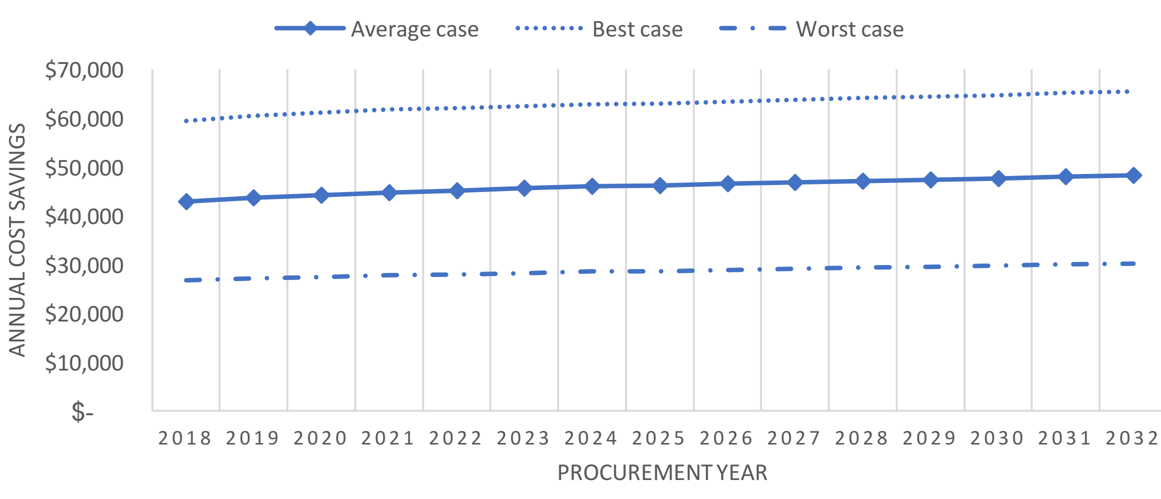
The total cost of ownership analyses in this thesis suggest that operating savings from depot charge electric buses relative to diesel buses in most utility service areas studied are sufficient, or will soon be sufficient, to afford the incremental capital investment of transitioning to an electric bus, within the lifetime of the vehicle. To attempt to understand the potential to finance the incremental cost of electric buses via one of the approaches described in this section, the total cost of ownership model described previously is adapted to the LG&E service area context to explore a prospective analysis of such a program for an area where agencies have interest in deploying more electric buses, but where the prospect of state or local grant funding to cover the incremental costs is limited. Given the significant challenge of savings estimate uncertainty in operationalizing financing approaches, this analysis attempts to quantify sources of uncertainty outside the agencies' control to identify the likely ranges of savings. Agencies interviewed expressed concern about financing approaches like tariffed on-bill financing that don't guarantee savings, because if anticipated operating savings didn't materialize, it might mean paying more in operating costs and competing with service needs:

> "What incentivizes agencies is to save on fuel costs, because that's money we can roll into more service on the street. If our savings are diminished because we're paying them off instead of putting them in our pocket for more service, it's less of an incentive than an agency just buying electric vehicles because they're committed to it."

Agencies also stressed the need for support in forecasting savings, with one saying, "I would like to take that model and say, here's what it's costing, here's what it costs for a new electric bus, and say, we can finance the difference. We just don't think that way, and it has to be a very well-structured argument with really good data behind it, or I won't get anywhere."

The analysis in Figure 6-7 explores sources of uncertainty for the Kentucky case, in particular maintenance savings and fossil fuel costs, under similar assumptions to the earlier total cost of ownership analyses in this thesis[2]. Under a worst case scenario, in which relative maintenance savings are less than expected (21% instead of 40%) and oil prices grow at a slower rate, annual cost savings per electric bus relative to diesel would be an estimated 38% lower than the average case. Under a best case scenario, in which maintenance costs were greater than expected (59% instead of 40%) and oil prices grow more rapidly, these agencies could expect to see about a 38% greater annual savings relative to diesel.

Figure 6-7: Range of annual cost savings per electric bus relative to a diesel bus for TARC/Lextran

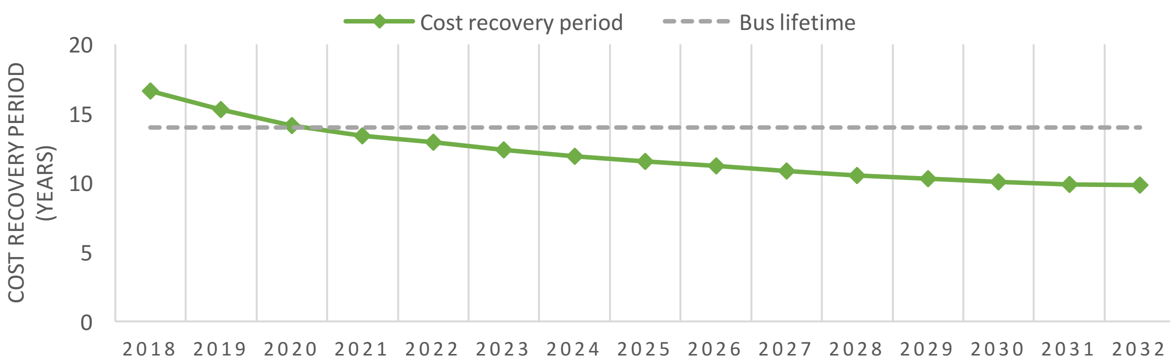


In tariffed on-bill financing programs, the estimated annual savings is used to set the tariffed charge to repay the upfront cost, but is lowered typically by 10-25% so that residents who retrofit their homes can

[2] The total cost of ownership analysis by different electricity tariffs in this section holds all of the same variables constant as in the base case analysis in Section 3.2.1, except for speed which is set at 12mph, closer to the average speeds of Lextran and TARC reported to NTD. The following charging assumptions are used to model electricity demand charge costs: percent of potential total draw connected (kw) during on peak (25%), mid-peak (50%), and off-peak (75%). The tariff for these agencies does not vary per kWh costs by time period. A 3% interest rate is used for the analysis, like the discount rate used in the sensitivity analyses.

achieve savings immediately on their energy bill. This "savings percentage" also works effectively like a debt service coverage ratio, helping to manage some of the uncertainty of the estimated savings. Even with a savings percentage as high as 35% to help manage the uncertainty of actual fuel and maintenance cost savings, TARC and Lextran could expect to recover the up-front costs of the bus within the 14-year life of a bus starting with procurements in 2020, and could be reasonably assured that they would see annual operating savings even in the "worst case scenario" described previously, as shown in Figure 6-8.

Figure 6-8: Estimated cost recovery period for electric bus tariffed on-bill financing LG&E service territory



This prospective analysis helps demonstrate the viability of financing approaches, and ways in which approaches can be tailored to project savings and help mitigate cost uncertainty for transit agencies. Given how limited public funds are for transit already at the federal, state, and local levels, financing the incremental cost of electric buses will likely be an essential strategy to enable accelerated adoption of electric buses, particularly in places like Kentucky where state and local policies and funds for emissions reducing investments are likely to be limited. However, not all agencies may be comfortable with financing, suggesting a need for multiple approaches and close partnership to develop suitable financing approaches. Each of the approaches highlighted have different pros and cons regarding cost, risk, and complexity as summarized in Figure 6-9, and ultimately, more research is needed to adapt these approaches and test them in the real world.

Figure 6-9: Pros and cons of different electric bus financing approaches

	Pros	Cons
Leasing	• Available now, no legislation needed • Shifts technology risk to manufacturer	• Leaves cost savings risk with agency • Tend to have higher interest rates
Tariffed on-bill financing	• Avoids traditional debt for agencies with debt limitations • Can be designed to enable (but not guarantee) immediate cost savings • Involving utility could have benefits for other fleets in service area, and re-use of second life batteries for storage	• Medium level of risk of actually achieving forecast cost savings (savings not guaranteed) • Program design, approval, and administration can take time, cost
ESPC	• Least risk of achieving cost savings through guarantee • "Turnkey solution" provides technical assistance through process	• Typically, higher transaction and interest rate costs • ESCOs typically only take on large contracts, may only be feasible for larger agencies

Policymakers can help to support financing approaches through a variety of strategies, including providing funding for cost modeling and evaluation to support these approaches, piloting one or more of these approaches using VW settlement or other funding sources, passing enabling legislation where necessary, interest rate buy downs and loan loss reserves to attract private capital, or being the direct lender by setting up a revolving loan fund or other public finance mechanism.

6.2.3 Transit bus make-ready rebates and other infrastructure incentives

A major barrier for nearly all transit agencies interviewed was the cost of installing charging infrastructure, as well as the uncertain costs for potentially needed transmission and distribution upgrades. Some utilities in California, and potentially Massachusetts, have begun proposing to help with make-ready infrastructure to cover the costs of infrastructure upgrades and installation costs up to the charger, as well as in some cases the cost of the charger itself.

Multiple agencies interviewed stressed how much it would help to have utilities cover the costs of installing chargers and upgrading distribution infrastructure. Those planning for larger scale deployments were particularly concerned, and uncertain, about the costs to upgrade electricity connections and install chargers at their depots. Agencies expressed that having help with this cost would help relieve some of the uncertainty associated with electric bus deployment, and members of the California Transit Association (CTA) weighed in in favor of utilities' SB 350 filings to provide make-ready infrastructure, stressing that transit agencies' need the utilities' help, saying in testimony "we are experts in owning and operating buses, we are not experts in utility infrastructure or high voltage power supplies", and that this kind of partnership "leaves us to do what we are best at doing providing safe reliable good transit service" (Rafeedie Khoury & Tozer, 2017). Additionally, CTA cited these investments as helping to deal with concerns agencies have about scaling the number of electric buses in their fleet and dealing with additional power needs.

Beyond the make-ready proposal, one agency expressed interest in essentially a public private partnership, much like some agencies currently do with companies who provide their CNG fueling infrastructure and fuel, to minimize the added complexity and cost of adding electric buses into their operations:

> I've been pushing to see if the utilities or some third party provider would run the charging stations and charge us just like we're doing for CNG. Maybe the utilities want to do that, or maybe a third party that's already providing CNG. Because it's distraction from our day to day operations, it's a challenge that if we can avoid it, there's value in us paying for it.

This would mean needing to go a step further than the make-ready incentives to get approval for utilities to actually own and operate the charging infrastructure itself, or contract the operation to private companies. While this could be difficult to achieve due to needing approval from a public utilities commission, the reduced complexity may be desirable for some agencies.

In California, both PG&E and SCE proposed to fund make-ready investments as part of their SB 350 filings, with SCE proposing $4M as part of a priority review project just for transit fleets, and $554M for a larger standard review project for other medium and heavy duty vehicles, which would be available to over 16 transit fleets in their service area. SCE also proposes providing a rebate to help cover the cost of the charger. PG&E has proposed to invest $210M in non-light duty make-ready projects as part its FleetReady standard review project, and estimates a cost of approximately $25,000 to $50,000 per heavy duty make-ready project, with additional incentives for investments in disadvantaged communities. In their filings, utilities highlighted the benefits of this approach, in contrast to them taking responsibility for the deployment and ownership of the chargers themselves, as preventing a risk of stranded assets by ensuring investments are made only where fleets take the initiative to pursue the program.

In Massachusetts, it has been unclear whether the National Grid and Eversource light duty make-ready proposals would apply to electric transit buses, though the proposals do stress a focus on deployment in environmental justice communities. Additionally, in response to advocacy organization the Conservation Law Foundation in the proceedings regarding the potential to use the program for electric bus charging infrastructure, the utility suggested they were open to that possibility:

> "While the Company did not propose addressing these site host types as part of the disadvantaged community portion of its Charging Program, the Company anticipated that they might be of interest to stakeholders and community members. Accordingly, the Company did indicate that it would consider recommendations from local groups closely affiliated with Environmental Justice communities for other qualifying site types in those communities. The Company will engage with MassDOT, local transit agencies, and other relevant organizations to evaluate recommendations for other qualifying charging site types, such as shared-ride services or transit buses." (National Grid, 2017)

CONSIDERATIONS FOR IMPLEMENTATION

Enabling utility investments in electric bus infrastructure is part of a wider active conversation taking place in public utility commissions around the country trying to determine the right level of engagement for utilities in deploying critical infrastructure to enable electric vehicle adoption. Thus far, it appears that key rationales for enabling these investments for transit buses include supporting the public interest by reducing criteria pollutants and greenhouse gases, targeting investments in disadvantaged communities, as well as potentially supporting utility business models by bringing additional customers and leveraging their expertise. Multiple stakeholders suggest make-ready investments strike a good balance between full utility ownership of charging infrastructure and no utility investment, ensuring that investments happen only where site hosts are committed, though other types of incentives and ownership models may also be beneficial. Gaining approval through a public utilities commission proceeding can take a substantial amount of time, but when approved has the potential to benefit multiple agencies at once.

6.3 Operating cost strategies

Some agencies interviewed, particularly in California where higher electricity prices and the comparison with CNG has meant increased operating costs for some, felt that the most important interventions would be helping to reduce operating costs: "The most important programs are the ones that deal with operating costs. Transit agencies have a number of sources to cover capital costs, to cover purchases. But they really don't have operating supports; that really comes down to local sources."

6.3.1 Vehicle charging management

To both minimize the capital costs of charging infrastructure, as well as ongoing electricity costs, transit agencies and other stakeholders discussed a variety of ways to manage bus charging, including strategic charging infrastructure planning, software integrations, and pairing energy storage and renewable energy with charging infrastructure. The following sections describe the status of implementation and agency perspectives on a few examples of bus charging management strategies.

STRATEGIC CHARGING INFRASTRUCTURE PLANNING

Some agencies discussed developing charging plans to minimize the costs of infrastructure buildout, highlighting the interplay between right-sizing infrastructure to save on capital costs, as well as electricity costs in the long run. For example, one agency received a very high quote from their utility for the power upgrades they would need if they transitioned their entire fleet and plugged in all buses at once. When they were told they'd need a costly new substation, they instead developed plans to cut their peak load to one third of what it would have been by using charging management software and staggering charging times, which allowed them to avoid that cost. Their primary advice to other agencies considering to go all-electric was to try and consider their ultimate buildout when investing in electricity upgrades, so as to avoid "digging twice". By planning strategically upfront, this agency was able to cut their capital costs, as well as develop a plan to minimize their electricity costs in the long run.

Agencies with heavy rail systems may also have an ability to strategically leverage their existing experience with electricity procurements and existing infrastructure to minimize costs. The MBTA for example could avoid some demand charges if they are able to connect some bus charging load to their traction power network particularly during off-peak times.

SOFTWARE

Multiple agencies discussed using or wanting to use software to manage their charging load, though some expressed concern that doing so wouldn't be viable given operational constraints. As one agency said, "Some say we can actively manage when to charge. No, sorry guys, we have a schedule, we're a public service." Others were already utilizing software to manage their electric load and were more optimistic about managing charging: "we have to charge buses in a way that meets our operational needs, that's non-negotiable. But within that, we can charge smartly to reduce the number of buses at any given time."

One of the challenges identified is that there isn't yet a software solution developed for this purpose, meaning agencies using this strategy thus far have had to develop custom integrations. Additionally, algorithms need to be developed that can strategically manage and prioritize operating constraints while minimizing electricity costs.

> "We need some kind of energy management system, but those kind of systems don't exist yet for this application. There are a lot of companies that make energy management systems, but they don't know transit. And then there are a lot of companies that make essentially operations dispatch software, and those don't know anything about electric buses. So a good solution would do both and that's what doesn't exist."

Transit agencies already rely on scheduling software to manage complex trip scheduling, vehicle scheduling, and operator scheduling, to which charging management could be an added module. In the future an off-the-shelf charging management that integrates with transit software will be essential.

ENERGY STORAGE AND RENEWABLES INTEGRATION

A few agencies interviewed were planning to integrate energy storage and/or renewable energy with their charging systems, though none had been implemented yet. Martha's Vineyard has plans to install energy storage and renewable energy to be able to avoid demand charges and save on electricity. Today, investments in these technologies are costly, though their costs continue to decline and some incentives are available. One agency hoped that in the future, they could re-use bus batteries for such a purpose. Some of the first batteries deployed in buses may soon be ready to be retired, and could serve as an important test case for this approach that could provide an important solution to manage electricity costs, as well as a means to delay battery recycling and reduce their environmental impact.

CONSIDERATIONS FOR IMPLEMENTATION

The benefit of some of these strategies is that agencies can largely pursue them independent of any needed policy changes. Agencies will need to determine the right strategies for their particular context, and there is likely a need for a technical assistance program to support agencies to learn from one another and be aware of the range of strategies available to them to manage their electricity costs, as well as to potentially support the development of software integrations that work for transit agencies.

6.3.2 Favorable electricity tariffs for electric buses

One of the main solutions recommended by agencies, particularly those in utility service territories with higher rates, was advocating for favorable electricity tariffs for transit buses through their utility and public utilities commission. Agencies and SB 350 testimony from multiple stakeholders stressed the public benefits of electrifying transit vehicles as a key reason to offer favorable tariffs, with one expressing "transit isn't a normal business, it's a public service, it's subsidized for a public good and needs to have a rate that's commensurate with that type of service." Agencies interviewed stressed the desire for their electricity costs to be reliable, which has been less likely when they are exposed to demand charges that can vary widely month to month if not managed well. By establishing rates that are tailored to electric buses' actual usage patterns and impacts on the grid, rather than the rates they are on that are designed for manufacturers or large commercial properties, regulators can help support deployment of electric buses, and prepare the way for school buses and other heavy duty vehicles that will also need favorable rates tailored to their usage patterns to aid deployment.

Thus far there are very limited examples of rate design for heavy duty electric vehicles due to their still limited numbers in operation. One of the first examples was in California, where Foothill Transit was able to win a temporary suspension of demand charges from its utility, Southern California Edison (SCE), for a period of three years for its on-route charge buses. Since then, SCE has approved new tariffs designed for commercial EV customers, which provided the most competitive electricity rates of the tariffs modeled in Chapter 5. While SCE is the only California utility thus far with a heavy duty electric vehicle tariff, PG&E is in the process of developing rates for transit buses and other heavy duty vehicles, and plans to introduce their rate proposals within 6-12 months of their SB 350 filing approval.

Through reviewing SB 350 testimony about new commercial EV rates from Southern California Edison (SCE), some of the primary issues to consider for electric bus rate design become apparent, which ultimately involve seeking a solution that can advance public benefits by supporting deployment of electric heavy duty vehicles, while also minimizing costs and maximizing potential benefits to other ratepayers and the grid as a whole. As one example, SCE's proposals for commercial electric vehicle rates thus far have primarily involved shifting demand charges to time-of-use per kWh charges, in such a way that can still recover all generation, transmission, and distribution costs. One agency was positive about this approach, expressing that it might not save them a lot of money, but that it would make their electricity costs more reliable:

> "The new approach is balancing the energy costs with the demand costs. So while at the end of the year, the total price won't be much different, it will make the price more reliable month to month. Because if you make a mistake one month and misuse it just one time in the month, you can have huge demand charges."

Analysis in Chapter 5 suggests that these rates would be much more favorable, at least for depot charge fleets, compared to SCE's original rates. To set their TOU EV-6 rate to recover all costs, SCE analyzed the following indicators for their transit bus customers relative to other customers in the same rate group (Southern California Edison, 2016):

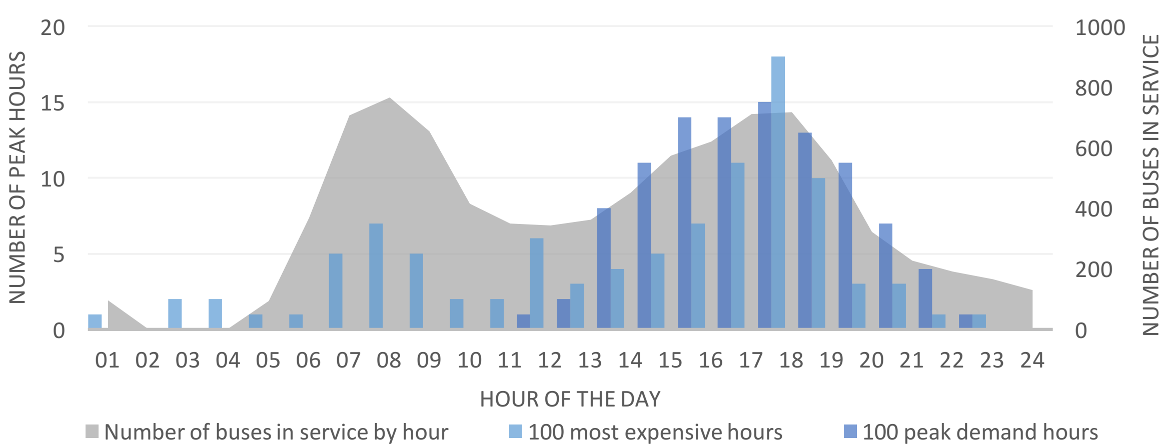
1) **Generation costs** were assessed based on the system's peak 100 hours;
2) **Transmission costs** were assessed based on the 12 monthly system coincident peaks, and;
3) **Distribution costs** were assessed based on the maximum non-coincident peak demand.

In looking at the peak 100 hours, SCE found that the peak hours had shifted as more renewables have come on-line, so they shifted the peak period to 2-8pm, a time when most transit buses are likely in service. In analyzing both the coincident and non-coincident peaks, SCE found that transit bus customers had a 67% and 28% lower peak respectively than the other customers in their rate group, leading them to lower the associated demand charges used to cover transmission and distribution costs. This analysis is useful to understand how transit bus charging costs have compared to other ratepayers on the same rate in one context, as well as how utilities analyze potential rate changes. This analysis was also for primarily on-route charge buses, suggesting that the coincident peaks for depot charge buses may be even less. Additionally, it highlights how agencies are typically put on tariffs not designed for their use, with other customers that likely have much higher load factors and coincident peak loads, such as manufacturing or large commercial buildings. The analysis also demonstrates the potential to seek out advantageous rates for transit given the potentially complementary charging schedules of depot charge buses that likely can largely avoid system peak hours.

While previous analysis demonstrated that the TOU EV-6 tariff performed best out of the electricity tariffs in the sample, testimony from rate design expert Melissa Whited testifying on behalf of NRDC in the SB 350 proceedings highlights additional important for even more advantageous for both transit agencies and the grid. For example, she suggests moving away from using the non-coincident peak to assess distribution costs; instead, she argues that using actual local circuit-level data that identified the top 50 circuit hours would be a better indication of actual distribution costs. In her testimony she stressed that otherwise there is "little incentive to reduce demand when it matters most", and suggests SCE "could implement local distribution circuit critical peak pricing for the top 50 circuit hours" (Baumhefner, Espino, Joseph, & Buckner, 2017).

Massachusetts is the only case study state with full retail choice, as California has a cap on the customers who can choose their energy supplier. MA transit agencies have the ability to negotiate rates with independent energy suppliers, and should be able to take advantage of low overnight wholesale energy prices when there is the least stress to the grid and when agencies will have the largest window for depot charging. Similar to Figure 5-17, Figure 6-10 shows the number of buses in service by hour for the MBTA compared with the 100 peak hours for the New England grid in 2016 by hours of the day, and again suggests that electric bus depot charging times will be largely complementary with the times of peak demand and cost on the grid. Such a service pattern is similar for many bus fleets, with higher frequency service during morning and evening peak times.

Figure 6-10: ISO NE 100 peak hours and MBTA buses in service by hour of the day



While Massachusetts agencies can choose their energy supplier, they still have to pay for delivery service from utilities, and many of the tariffs analyzed that would be applicable to depot charge electric buses did not have time-varying demand charges or energy charges that could send a better signal to transit agencies and other electric vehicle fleets for when to charge. A recent state report on the need for energy storage highlighted that the top 1% most expensive hours represent 8% of the state's electricity costs (Massachusetts Department of Energy Resources, 2016). Looking at the top 100 most expensive and highest demand hours for the New England grid in Figure 6-10, it appears that the peak hours tend to be between 2-8pm, when most transit buses are in service for evening peak service. This suggests that specialized time of use or critical peak pricing rates for depot charge buses could offer advantageous rates to transit agencies in exchange for avoiding the highest cost hours, with limited to no impact on transit agency operations. Unfortunately, neither of the current investor-owned utility proposals for EV deployment before the public utilities commission include rate designs for heavy duty electric vehicles.

In Kentucky, LG&E-KU is in the midst of a rate case, and transit agencies are intervening to pursue more favorable rates, particularly for their on-route buses which are currently exposed to high demand charges across multiple periods, and which they will have in operation for several more years (Hobin, 2017).

CONSIDERATIONS FOR IMPLEMENTATION

Due to the different electricity contexts in each state, each utility will require a slightly different solution, though similar principles likely apply. These include minimizing demand charges where possible, and establishing time varying demand charges and energy rates that can best reflect actual generation, transmission, and distribution costs incurred by transit bus charging. While system and local circuit peaks will vary, initial analysis suggests they are likely to coincide with when most depot charge buses will be in operation during evening peak hours. More analysis is needed, particularly to assess potentially large deployments of depot charge buses where the load factors will be substantially different than early on-route charge models, but there appears to be a strong potential to identify commercial EV rates that can be beneficial to transit agencies, the grid, and other ratepayers.

Pursuing favorable commercial EV rates will take time and effort to engage with public utilities commissions, though doing so can help overcome a major barrier for agencies that is currently highly variable across utility service areas. Additionally, if rates are designed correctly and reward transit agencies for charging during off-peak times, adding additional load to the grid during off-peak times can put downward pressure on rates for all ratepayers. Finally, establishing rates that work for heavy duty vehicles across utility service areas now, and principles to design them for different applications, can help pave the way to enabling deployment for electric school buses and trucks. Many transit agencies do not have time, expertise, or capacity to engage on their own with the public utilities commission for better electric rates, suggesting a need for the support of other stakeholders to implement this strategy. In California, the state has helped advance the conversation about rate design through the SB 350 proceedings, and advocates have played a key role in helping transit agencies engage to press for better rates. In Kentucky, a collaborative of energy experts, transit agencies, and environmental justice advocates are working together with their utility LG&E to pursue a better tariff. In Massachusetts, the state energy, environmental, and transportation agencies should collaborate with the Department of Public Utilities and the state's main utilities to initiate conversations about commercial electric vehicle tariffs that can support the deployment of electric buses, as well as future fleets of EVs.

6.3.3 Clean fuel standard or other pricing mechanisms

California's Low Carbon Fuel Standard (LCFS) creates a self-financing system in which fossil fuel distributors must buy credits each year from transit agencies, utilities, and other entities using alternative fuels for transportation. LCFS has been an important mechanism to provide a relatively predictable way to improve the business model for investing in electric buses through effectively changing the relative costs of fuel. Implementing a clean fuel standard elsewhere may be difficult, but other states could pursue other carbon pricing mechanisms that could help provide a stable source of revenue.

CARB estimates that the LCFS credits make battery electric buses cost competitive with diesel, diesel hybrid, and CNG technologies in most utility service areas in the state, similar to the findings of the analysis in Chapter 5 (California Air Resources Board Innovative Clean Transit Working Group, 2017a). LCFS has been critical for many of the agencies interviewed for deploying electric buses, with one suggesting they would receive more in credits than they'd pay in fuel this year. Still, there was confusion amongst some agencies interviewed about whether they were eligible to claim credits, suggesting there may be a need for more education to ensure transit agencies can take advantage of the credits. As of late December 2017, CARB was considering adjusting the LCFS regulation in such a way that would increase the value of LCFS credits by 20% for electric trucks and buses, further improving the business case for these vehicles (California Air Resources Board Innovative Clean Transit Working Group, 2017d).

CONSIDERATIONS FOR IMPLEMENTATION

While this policy has been very effective in California, the political feasibility for such an approach in the other case study states may be limited. In the Northeast, an earlier effort to establish a similar regional "clean fuels standard" stalled in 2012, due to what a Vermont energy official described as "fierce opposition from oil industry groups, and rising political conservatism in the region" (Gallucci, 2013). Reports described Koch Brothers and other industry-funded efforts that formed to block the legislation, and were simultaneously legally fighting its implementation in California, where the program was just beginning. While such a model is important in that it can build in operating cost support for transit agencies and other fleets investing in electric vehicles, its political feasibility may be limited. However, in the Northeast, there is a renewed discussion about a regional cap and invest effort to tackle transportation emissions from climate change that could potentially raise additional revenue to support electrification of buses and other vehicles (Georgetown Climate Center, 2017).

6.3.4 Maintenance contract or guarantee

Electric bus manufacturers claim substantial maintenance savings compared with conventional buses, and empirical studies are beginning to back up those claims, but agencies interviewed expressed uncertainty about actual maintenance savings. If manufacturers were willing to stand behind their claims, transit agencies may have more confidence in realizing lifecycle cost savings or entering into finance agreements. Additionally, turnkey maintenance contracts that guarantee savings could be provided for agencies that contract out maintenance, or as part of an energy savings performance contract (ESPC).

CONSIDERATIONS FOR IMPLEMENTATION

Through interviews and a literature review, it appears some electric bus manufacturers are offering extended warranties, in particular for batteries, and have often provided technicians on-site for the first years of deployments for free, though it isn't clear whether they are offering particular maintenance contracts or guaranteed savings. In many states, maintenance savings can be included in ESPCs, and are often a substantial amount of the savings in such an agreement (Birnbaum, 2017). There may be a need for technical assistance to track maintenance costs and accurately establish baselines, as some agencies interviewed said they did not have reliable maintenance cost data. Some form of maintenance contract, guarantee as part of an ESPC agreement, or warranty could likely be useful, and could be provided by manufacturers, an ESCO, or a private maintenance contractor. More research is needed to understand the viability of such an approach, which perhaps the FTA or APTA could undertake.

6.4 Technical/Information strategies

This category of solutions is in need of additional research, yet stakeholder interviews made clear that the added complexity of electric bus deployment, the importance of being able to learn and share best practices with peers, and the commonality of many barriers and solutions suggests a need for technical and program assistance at the federal, state, or regional council level.

6.4.1 Technical and program assistance

Through interviews, agencies expressed that they faced a variety of technical challenges, including infrastructure planning, electricity cost modeling, and incorporating electric bus charging into their existing operations. Nearly all agencies also described having connected with peer agencies who had deployed electric buses before them to learn. While no stakeholder mentioned this approach as a needed strategy, drawing from these learnings it seems that some form of technical and program assistance could provide a number of important services that could benefit multiple agencies, such as:

1) **Deployment planning:** A program could help agencies plan electric bus deployments, including infrastructure investment plans, operations and charging management plans, route prioritization, and identify grants, financing opportunities, and utility support. Alternatively, technical assistance grants could be provided to agencies to help them hire a consultant to do this planning.
2) **Advocacy for policies and programs:** Within a state or metropolitan region, centralized advocacy support for better electricity rates and infrastructure incentives at public utilities proceedings, and the development of other potential supportive programs like cooperative bulk purchasing could help advance electric bus deployment for multiple agencies at once.
3) **Performance and cost data tracking**: Some agencies interviewed didn't have systems in place to be able to track maintenance costs, fuel costs, or other performance measures, and also weren't able to then forecast potential savings for future procurements. Such a program might be able to help agencies set up and standardize such systems.
4) **Collect and share best practices:** With agencies already relying on peers for support in deploying electric buses, such a program could support early adopter agencies to document and share their best practices, lessons learned, as well as recommended contractors and equipment.
5) **Manage grant or financing program:** Such a program could also manage or support applications to a low cost financing program or voucher program, and help establish standards for cost savings forecasting and financing applications.

CONSIDERATIONS FOR IMPLEMENTATION

While no such program yet exists, these activities are happening in more informal ways, with non-profit organizations and agencies lobbying for beneficial policies at the state public utilities commissions, informal peer-to-peer learning, and reliance on consultants for technical assistance. One model to consider could be the Refuel Colorado program, which provides free energy coaches and consultants to fleets of all kinds throughout the state to help assess emissions savings, lifecycle cost savings, and pursue grant applications for cleaner vehicles. A technical support program could be established through local Clean Cities Coalitions, state energy or transportation agencies, or regional councils, and could also be expanded to focus on other fleets as technology matures, though more study is needed to identify the right institutional approach for each of the listed activities in particular contexts.

6.5 Summary and recommendations

A strategy to support widespread electric bus deployment should include multiple complementary solutions that can address the multiple barriers agencies face in transitioning their fleets, and that is well-adapted to each local context. This section concludes with a summary assessment of the top-mentioned policies and strategies for supporting electric bus deployment, as well as preliminary recommendations for each case study state. This analysis identified potential solutions to most factors identified through the qualitative interviews, though some of the minor factors were judged to be likely to resolve themselves, such as manufacturer scale limitations, while others such as noise were considered simply an important benefit to be aware of, and were not included. Figure 6-11 is meant to provide a generalized summary of the current best practices and proposals for policies and strategies to accelerate electric bus adoption.

The categorization of solutions to match the identified factors in Chapter 4 suggests a potential sequencing of strategies, with strategies that contribute to motivation to pursue electric bus deployment being foundational to generate demand. Next, agencies must believe they are capable of being able to deploy electric buses from an economic and technical perspective. By targeting strategies that can help improve the outlook of each of these factors, more agencies will likely see electric bus investment as increasingly feasible. Within each strategy category, strategies are ranked with *** (high priority), ** (medium priority), and * (low priority), based on a combination of potential impact and feasibility. Within motivation strategies, organizing and public engagement is ranked highest as a strategy to increase motivation, having had high levels of success thus far in California, and limited potential downsides compared with strategies such as strict zero emission bus purchasing mandates. Within capital costs, stakeholders should consider how to best use the opportunity provided by the VW settlement funds. Vouchers like the HVIP program already appear to be more cost effective on a cost per ton of CO_2 reduction basis than light duty incentives available in California and Massachusetts, but stakeholders should also consider developing low cost financing solutions that can further leverage these limited funds and provide a more durable, sustainable financing source for buses and other vehicle classes in the future. Infrastructure incentives would also be highly impactful and likely feasible, though dependent on potentially lengthy public utility commission proceedings. Within operating cost strategies, vehicle charging management is highly feasible and can have a large impact and so is prioritized highly, and favorable electricity rates, while somewhat more difficult to achieve, would have a major impact for multiple agencies at once.

Figure 6-11: Summary of potential policies, programs, and strategies to support battery electric bus deployment

	Recommended strategies	Priority	Example solutions	Environmental benefits	Equity benefits	Economic development benefits	Board or executive leadership	External political pressure	High first cost	Infrastructure cost	Capital subsidy availability	Tradeoffs w/ more service	Lifecycle cost	Electricity costs	Maintenance cost savings	Low fossil fuel costs	Diesel maintenance cost	Diseconomies of scale	Battery performance	Operational complexity	Fleet diversification	Learning from peers/experience	Data and analysis capacity	Uncertainty and risk
MOTIVATION	Organizing and public engagement	***	• Local campaigns for ZEB commitments • Advocacy for complementary policies • Prioritize EJ community engagement	X	X	X	X	X	X	X	X	X	X	X										
MOTIVATION	Goals and mandates	*	• Incentives for voluntary ZEB goals • Flexible mandates	X	X	X	X																	
MOTIVATION	Economic and workforce development	*	• U.S. Employment Plan • Community Benefits Agreements • Manufacturer Incentives • Workforce development programs		X	X	X	X							X					X	X			
CAPITAL COST	Capital subsidies	**	• Voucher or competitive grant program • Use of VW, CMAQ, or other funds						X	X	X	X	X											X
CAPITAL COST	Financing programs	***	• Tariffed on-bill financing • ESPC/ESCO financing • Operating, capital, and battery leases						X	X	X	X	X											X
CAPITAL COST	Infrastructure incentives	***	• Enable utilities to ratebase investments • Make-ready incentives • Charger and installation cost incentives						X	X	X	X	X					X			X			X
OPERATING COST	Vehicle charging management	***	• Strategic charging infrastructure planning • Software • Energy storage • Public private partnership						X	X		X	X	X		X		X	X	X				X
OPERATING COST	Commercial EV rates	***	• TOU rates based on bus service profile • Spread demand charges to energy charges									X	X	X		X								X
OPERATING COST	Clean fuels standard or other pricing mechanism	**	• LCFS-like program • Carbon pricing w/ revenues used as credits									X	X	X		X								X
OPERATING COST	Maintenance contract/ guarantee	**	• Manufacturer maintenance guarantee • Maintenance contract									X	X		X		X			X	X		X	X
TECHNICAL / INFORMATION	Technical and program assistance	***	• Deployment planning/technical assistance • Advocacy for policies and programs • Performance and cost data tracking • Collect and share best practices • Manage grant or financing programs	X	X	X					X	X	X	X	X		X	X	X	X	X	X	X	X
			Factor category	MOTIVATION					CAPITAL COST			CAPITAL/ OPERATING		OPERATING COST				TECHNICAL/ INFORMATION						

Transit agencies can take on some of the solutions in Figure 6-11 on their own, such as pursuing maintenance contracts or vehicle charging management strategies, but most will require collaboration with other stakeholders, which should consider taking on the following roles:

- **State, regional, and city environmental, energy, and transportation officials:** Government officials looking to support accelerated deployment for climate or air quality reasons have a key role to play in helping to develop city, regional, or statewide policies and programs that can benefit multiple transit agencies at once, such as supporting efforts at public utilities commissions to enact favorable electricity rates and enable utilities to incentivize charging infrastructure, developing implementation and funding plans for voucher or low cost financing programs, and implementing technical assistance programs.
- **Advocates:** Advocates have a critical role to play in developing a strong equity and sustainability rationale and motivation for electric buses, and ensuring that investments advance environmental and economic justice community priorities. While advocating for mandates alone may have an appeal, supporting voluntary goals at the agency level and advocating for supportive policies may be a more effective strategy. Given the new state of technology and risk of negative impacts to transit budgets and service levels, advocates should consider focusing primarily on state or utility-level supportive policies like low cost financing programs, charging infrastructure incentives, and better electricity rates that can change the context to be more favorable for electric bus deployment. That way, advocates can help accelerate deployment of transit buses, but also put in place strategies that will likely be useful to accelerate adoption of other heavy duty vehicles like school buses and trucks as they become commercially available.
- **Utilities:** Utilities have much to gain in proactively planning for electric bus deployment in their service territory, in order to gain new sales, as well as to pave the way for other electric vehicle classes in the future. As utilities across the country begin to plan for electric vehicles, they should plan not just for light duty vehicles, but also heavy duty vehicles, to ensure that their rate structures and incentives can send the right signals about when and where to add load to the grid in a way that can minimize costs for all ratepayers, and generates new business for them.

While outside California it may be unlikely to implement all of the solutions recommended here, by targeting some of the interventions in each category, advocates, policymakers and transit agencies can work together to make electric bus deployment more feasible in a variety of contexts. The following sections provide a preliminary adaptation of the identified strategies to each case study context.

6.5.1 Recommendations for California

California provides an important example of the implementation of a set of complementary policies that have helped increase the political will to electrify bus fleets, reduce first costs, reduce electricity costs, all while driving economic development and green job creation. California should prioritize the following to continue leading the nation in supporting a sustainable transition to electric bus fleets:

- **Motivation strategies:** California has robust environmental justice and traditional environmental advocate coalitions that have been increasing political will for bus electrification, as well as delving into the details to support new rate structures, financing programs, and agreements to ensure economic development from electric buses is equitable. As CARB decides whether to mandate electric bus purchases, advocates and regulators should carefully consider the potential downsides to a regulation that appears to have disparate impacts for transit agencies around the state, and could negatively impact strapped transit agency budgets, and ultimately transit service. Instead, CARB and advocates should consider how to develop a flexible mandate that provides multiple pathways for compliance, while continuing the robust supportive policies that are helping agencies transition to electric. Electric buses provide an important test case for other heavy duty electric fleets, so CARB and advocates should ensure these transitions are successful, and conduct research to inform strategies and regulations for other vehicle classes.

- **Capital cost strategies:** With the HVIP program oversubscribed, CARB and other stakeholders should pilot multiple low cost financing programs that can further leverage public subsidies and avoid limiting deployment based on the number of available vouchers. The tariffed on-bill financing proposal from Greenlining Institute and the Union of Concerned Scientists before the Public Utilities Commission provides a key opportunity to pilot such a strategy in the PG&E service area, and then consider spreading the program to other utilities. Ensuring approval of the make-ready proposals in the SB 350 proceedings is also essential to drive down capital costs.
- **Operating cost strategies:** Regulators should ensure that favorable rates for transit buses are available in all utility service areas throughout the state, that are time-varying and minimize demand charges, much like the rates proposed and implemented thus far for commercial electric vehicles by SCE. Additionally, regulators should ensure that agencies are aware of their ability to leverage LCFS credits to further improve the cost effectiveness of electric buses.
- **Technical strategies:** Multiple stakeholders in California could be well suited to providing a technical assistance program, including CARB, the air quality districts, the California Energy Commission, or third parties like CALSTART who manages the HVIP program. Such a program could help develop and implement low cost financing programs, support agencies to plan for charging infrastructure development and charging management, and more.

6.5.2 Recommendations for Massachusetts

While Massachusetts has similar carbon reduction targets, electric vehicle deployment targets, and politics as California, thus far they have pursued far fewer supportive policies to advance electric bus deployment. This suggests they should learn from California, in particular focusing on the current opportunity to ensure that the utility proposals before the public utilities commission can be leveraged to support charging infrastructure deployment, as well as the opportunity provided by VW settlement funds. In addition to the deployment strategies described for the MBTA, Massachusetts should consider the following approaches:

- **Motivation strategies:** Massachusetts has growing advocacy coalitions pressing for electric bus commitments throughout the state, and MassDEP has regulated the emissions of the state's largest transit fleet, though has not mandated a technology path to achieve those goals. Advocates and regulators should take care to not damage efforts to increase transit service and non-auto modeshare with inflexible mandates on transit fleets, and should instead focus on supportive strategies that can level the playing field statewide, accelerate adoption, ease the transition for other heavy duty fleets, and ensure deployment advances equity priorities.
- **Capital cost strategies:** With the influx of VW funds, Massachusetts should pilot a low cost financing program, leveraging its success with energy efficiency financing programs. The CEIP program that leverages operating savings to pay for state agency building upgrades could be an ideal mechanism to pilot extending to electric transit buses. Over the long run, Massachusetts could make additional funds available for such a program, like they do with their successful no interest energy efficiency HEAT loans funded through an increment on utility bills, or through the potential regional transportation cap-and-invest program. There is also a case to be made for making direct subsidies available at the level available for private vehicles, given that transit bus vouchers at the HVIP level of $95,000 per bus are estimated to be more cost effective per ton of CO_2 reduced than the light duty Massachusetts EVIP vouchers currently offered, and could be enacted through House Bill 3742 that proposes a grant program for electric buses.

- **Operating cost strategies:** Stakeholders should also pursue more favorable electricity tariffs, which can help support the state's goals to reduce electricity costs by adopting rates that send the right signals to fleet operators. State officials should do what they can to level the playing field statewide, and ensure that transit agencies and fleets everywhere have a similarly favorable environment to deploy electric vehicles.
- **Technical strategies:** In Massachusetts, the state transportation agency supports both the MBTA in transportation planning and the regional transit authorities, making it a prime candidate for a technical assistance program for electric buses. This program should support a large pilot at the MBTA that can test performance under cold weather and heavy load operating conditions, and ready the state's fleets for widespread adoption pending the success of that pilot. Additionally, such a program should pursue the opportunities to access make-ready infrastructure incentives through the state's investor owned utilities. Such a program could also help run or facilitate a low cost financing program, including standardizing ways to track and forecast costs and savings.

6.5.3 Recommendations for Kentucky

In Kentucky, and other more conservative states like it, some policies may be less feasible, though organizing efforts, financing programs, and efforts to ensure transit buses are included in public utility commission proceedings likely are more feasible. Particularly if a utility is already going through a rate case, as is the case for TARC and Lextran, it may be more possible to intervene to pursue a more favorable tariff.

- **Motivation strategies:** The emergence of advocacy by KFTC and other allies for electric buses will be critical in helping to secure supportive policies to enable deployment, and support agencies to have the political will to pursue voluntary emissions reductions goals in a more conservative environment where mandates are unlikely. Additionally, focusing on the economic development and job creation potential may be another important angle to pursue.
- **Capital cost strategies:** The VW settlement funds, as well as potentially CMAQ funds, provide a critical opportunity to develop a sustainable, low cost financing program that can further leverage these limited public funds, and build on the state's success in energy efficiency financing. The tariffed on-bill financing program being pursued by stakeholders in the LG&E-KU service areas provides a key opportunity to test and further develop such an approach. Additionally, public agencies' familiarity with ESPC in Kentucky suggests this could be another important approach to pilot that could pair fleet upgrades with building efficiency investments. Stakeholders should also pursue make-ready incentives through the utilities and public service commission to improve electric bus cost effectiveness.
- **Operating cost strategies**: While an LCFS-like program is unlikely to be feasible in Kentucky, advocating for more advantageous rate structures that can lower the operating costs of electric buses likely is feasible, and transit agencies are working with LG&E-KU to adopt such a rate. Stakeholders should look to the cases in California for rate design principles that can benefit electric buses, as well as all ratepayers.
- **Technical strategies**: In Kentucky, the Clean Cities Coalition which has supported multiple fleets in writing grants and other technical assistance activities, could be well suited to implement a technical assistance program for transit buses and other fleets.

7. Conclusion

7.1 Summary of findings

Through a quantitative and qualitative investigation of the barriers and drivers affecting transit agency decision-making, this research sought to better understand the key factors that help or hinder the likelihood of transit agencies to pursue electric bus deployment across three case study contexts: California, Massachusetts, and Kentucky. Quantitative and qualitative analysis across each case study context produced the following key findings summarized in the sections that follow.

EMISSIONS ANALYSIS

Through lifetime well-to-wheels greenhouse gas and criteria pollutant emissions analysis, battery electric buses were found to have a substantial advantage over other bus technologies across nearly all pollutants in each case study context, though buses deployed in Kentucky are projected to have higher electricity greenhouse gas emissions than in Massachusetts or California, and are expected to have higher emissions for some criteria pollutants than conventional buses due to a heavier reliance on coal-fired electricity. Overall, externality cost analysis indicates substantially lower health and natural environment damages from battery electric buses in all case study contexts. Additionally, due to an increasingly cleaner electricity grid, electric buses are expected to have increasingly lower emissions over time.

TOTAL COST OF OWNERSHIP ANALYSIS

A total cost of ownership analysis produced the following findings about the **factors impacting electric bus cost effectiveness that are applicable across all of the case study contexts**:

1) **Most sensitive factors:** Through a sensitivity analysis, total cost of ownership savings from a battery electric bus in comparison with a diesel bus in 2020 is estimated to be most sensitive to the annual miles a bus is driven, followed by fossil fuel price scenario, the average speed of the bus, the maintenance savings of an electric bus compared with a diesel bus, the per kWh electricity rate, the degree of charging management, and finally the demand charge rate.
2) **Agencies can strategically optimize some key factors:** Agencies may be able to actively increase their total cost of ownership savings by prioritizing deployment on slow speed and high mileage routes, and managing their charging to save on electricity costs.
3) **Other key factors are outside agencies' control**: Other key factors such as future fuel prices, actual maintenance savings, and available electricity tariffs may be less under their control. However, by switching to electric, agencies can shield themselves from oil price uncertainty and volatility, as seen by a much narrower range of forecast fuel costs for electricity than for diesel.
4) **Cost effectiveness is estimated to improve over time**: Ongoing decreases in battery cost and increasing economies of scale suggest battery electric buses could become cost effective relative to other bus technologies even more quickly than modeled, with one agency already receiving pricing for a bus below $700,000, similar to a CNG bus, in 2017.

In addition, the total cost of ownership analysis across the three case studies and individual fleets suggests the following specific **contextual factors** also impact the cost effectiveness of electric buses:

1) **Baseline bus:** This analysis finds that the baseline for cost comparison matters, and estimates that all agencies studied would save money by deploying electric buses compared with diesel hybrid buses starting in 2018, nearly all would save money compared with diesel buses, and far fewer would save compared with CNG buses.

2) **Utility service area:** This analysis highlights the impact of the high variability of available electricity tariffs on realizing total cost of ownership savings, with a specialized commercial EV tariff piloted by Southern California Edison providing the greatest savings of the tariffs analyzed.
3) **Policy context:** Programs like California's LCFS, HVIP vouchers, and proposed make-ready incentives help reduce cost uncertainty and improve the business case for agencies to invest in electric buses, which are not yet available in the other case study states.

In the MBTA context, the total cost of ownership and emissions analysis produced the following findings and recommended approach for deployment:

1) **Meeting emissions reductions goals:** The MBTA and MassDOT could meet most if not all of their MassDEP greenhouse gas emissions reduction requirements through investment in electric buses, even with moderate to substantial transit service expansions. Under expanded service scenarios, the MBTA bus fleet does begin to contribute substantial levels of criteria pollutant emissions relative to trucks in their core service area, suggesting that electric buses may be most relevant environmentally for addressing air pollution that has a more local impact than greenhouse gases if the bus fleet is expanded.
2) **Electric buses could save money relative to current MBTA bus technologies:** A preliminary cost analysis using moderate to conservative assumptions suggests that investing in electric buses might increase the MBTA's total costs relative to continued investments in CNG and hybrids slightly, or may actually save money by doing so, depending on how the buses are deployed and charged, and that electric buses would save money relative to investments in diesel hybrids alone.
3) **A strategic approach for deployment**: Pending a successful larger scale pilot in Silver Line or Harvard tunnel services that provides empirical data in the MBTA operating context, the MBTA should move towards procurements of 100% electric buses for its planned procurements between 2020 and 2032, prioritizing deployment on high frequency, slow speed service in environmental justice communities that can maximize environmental, equity, and cost benefits.

INTERVIEW ANALYSIS

Qualitative analysis of interviews and publicly available documents across the three case studies found many similar key factors in common across agencies that affect decision making about electric buses:

1) **Nearly universal factors:** Barriers that were nearly universally expressed include upfront cost, the lack of available capital subsidies, and infrastructure cost and complexity. Some major factors were nearly universal, but listed by some as drivers and by others as barriers, such as external political pressure, electricity costs, and overall lifecycle costs, with a divergence between agencies based on their utility tariffs and a variety of other cost and contextual factors.
2) **Common drivers:** Common motivating factors cited by agencies included environmental benefits, board or internal leadership, and maintenance cost savings, while fewer agencies cited equity benefits, economic development, and economic justice benefits.
3) **Minor factors:** A number of other factors expressed were more minor, though nevertheless important for increasing the likelihood and ability for agencies to transition their fleets, including low fossil fuel costs, the rising cost of diesel maintenance, battery performance limitations, added operational complexity, data availability and analysis capacity, and uncertainty and risk.

An analysis of actual current procurement intentions with respect to battery electric buses revealed how these different factors combine in complex ways in different organizations:

1) **Policy and political context matters:** A wide variability of stated intentions to deploy more electric buses across the case study states suggests that policy context and political pressure are key factors driving deployment decisions, with multiple fleets in California where policy supports are numerous and political pressure is strong committing to wholly electrify their fleets. While some California agency representatives were concerned that even with supporting policies electric buses could increase costs, they also expressed confidence that the supportive policy and political environment would enable their transition. Outside California, where much fewer supportive policies currently exist, just one fleet was planning additional procurements.

2) **Economic factors matter:** In both Massachusetts and Kentucky where transit agencies were more cash strapped and had fewer policy supports available than in California, cost considerations and budget competition with other institutional priorities like providing more service appeared to be the primary reasons behind agencies' intentions not to procure electric buses, combined with concerns of uncertainty and technology risk.

IDENTIFIED STRATEGIES

Finally, findings from the quantitative and qualitative portions of this research were synthesized to propose strategies and recommendations for each case study context. Different potential strategies were identified, categorized, and mapped to factors driving deployment, including the following top policies in each category:

1) **Supporting motivation to deploy electric buses:** Organizing has been a critical strategy to increase motivation, having had high levels of success in California, and limited potential downsides compared with strict zero emission bus purchasing mandates, though flexible mandates and voluntary agency goals may be important strategies for supporting accelerated deployment.
2) **Improving the capability of agencies to invest through lowering capital costs:** Stakeholders should leverage the opportunity of the VW settlement funds to either provide vouchers for the incremental vehicle cost, or better, create a more sustainable low cost financing program that can further leverage these limited funds, and provide a blueprint to finance other heavy duty electric vehicles as they become commercially viable. Additionally, infrastructure incentives from utilities is a highly impactful and likely feasible strategy that should be pursued.
3) **Improving capability through lowering operating costs:** Vehicle charging management is highly feasible and can have a large impact and so should be prioritized, and favorable electricity rates, while somewhat more difficult to achieve, would have a major impact for multiple agencies at once, and eventually for other heavy duty vehicle fleets.
4) **Supporting implementation with technical and information strategies**: Added operational complexity suggests a need for technical and program assistance that could be provided by a number of different stakeholders to assist in deployment planning, accessing grants or financing, sharing best practices, collecting and analyzing performance data, and advocating for supportive policies.

The experience of California, as well as clean energy adoption, suggests a need for multiple complementary policies that can work to support agencies through each phase of deployment, and ensure deployment prioritizes equity and environmental benefits. California has been an early leader in demonstrating how complementary policies across these categories can work together to support deployment, while Massachusetts, despite having similarly ambitious climate policies on paper, lacks many of the same supportive policies. Kentucky being a more conservative and less urban state has far less supportive policies than either state, though recommendations are identified that could be feasible in their context, which is likely similar to many parts of the country where transit agencies operate.

7.2 Future research

This research only addressed the key factors driving deployment decisions amongst early adopter agencies, suggesting that future research could seek to understand the perspectives of early and late majority transit agencies to be able to better tailor policies and strategies to them. Additionally, in order to enable confidence in forecasted total cost of ownership savings, as well as potential financing programs, an additional line of future inquiry could investigate ways to better quantify the uncertainty of key parameters and develop a standard approach to forecasting, measuring, and verifying fuel and cost savings, particularly as more performance data becomes available. The work on mapping solutions to barriers and drivers is also somewhat limited, particularly for some strategy areas, suggesting that future research could go further in developing these strategies, perhaps in partnership with transit agencies and communities, and evaluating their effectiveness.

Beyond buses, future research could apply a similar mixed methods methodology to identify barriers, drivers, and potential solutions to enable widespread electrification of other fleets. Additionally, stories from transit agencies about how the technologies they first piloted were then deployed in trucking were interesting, but not explored deeply. It would be interesting to further investigate how this technology transfer has occurred in the past between vehicle classes, as well as how to support it in the future.

7.3 Discussion

"Every year we wait, there is another round of transit buses that will be polluting the air of transit-dependent communities" (Greenlining Institute, 2017)

Meeting ambitious midcentury climate change goals and air quality goals requires urgent action; with vehicles likely to be replaced just 2-3 times between now and 2050, it's essential to drive adoption early to avoid technological lock-in and ensure midcentury climate goals are attainable. Research about clean energy deployment and the very small market share of electric buses thus far suggests that accelerated, widespread deployment is unlikely to happen on its own, but is possible with a concerted effort to assess barriers and develop complementary strategies to overcome them that meet the four criteria of successful sustainability policy: efficiency, effectiveness, equity, and political acceptability.

Today's successes in clean energy deployment follow years of action-oriented research, policy implementation, and organizing. To achieve that level of success in accelerating transportation electrification will likely require similar levels of focus and effort. This research has attempted to provide an example of action-oriented research that seeks to identify key barriers, drivers, and potential sustainable transition pathways to accelerate electrification for a particular type of vehicle fleet across a range of contexts. Starting with transit buses has previously been an important step on the road to technology transition for other heavy duty vehicle fleets, and insights from this research can hopefully help inform efforts to drive widespread adoption of other heavy duty vehicle classes that have greater emissions and public health impacts, such as school buses, urban delivery trucks, and refuse trucks.

While there is growing evidence that improvements in battery technology make it likely that conversion to battery electric buses can be both financially viable and environmentally superior to fossil fuel-based bus technologies, public transportation agencies need to be careful in embracing new technology, as they have been exposed to risks in the past by attempting to play a role as leaders for the heavy duty sector without the complementary supportive actions necessary to make the new technologies fiscally achievable and environmentally sustainable. Given the importance of bus service to communities across the country and its importance as a climate strategy to reduce auto reliance, care must be taken to accelerate electric bus deployment in a way that is simultaneously supportive of transit service and expansion goals.

Pending larger electric bus pilot projects at larger transit agencies such as the MBTA in Boston, the CTA in Chicago, and LA Metro where empirical data can be collected and can help hone the modelling assumptions made here as well as to help answer many questions regarding real or perceived barriers, multiple complementary solutions should be developed and tailored to accelerate electric bus deployment in each context. Some of the most important interventions identified include pursuing favorable electricity tariffs and electric charging infrastructure incentives through public utilities commissions, and overcoming the limitations of unstable and oversubscribed capital subsidy programs to develop more sustainable, low cost financing approaches similar to those utilized in the clean energy sector that can pledge anticipated operating savings to afford incremental upfront costs, potentially by leveraging the opportunity of the Volkswagen settlement funds.

With most public funds for transportation electrification thus far going to higher income drivers, investing in electric buses and other heavy duty fleets in a way that prioritizes deployment in environmental justice communities and creates good, green jobs for marginalized communities offers an important opportunity to demonstrate a just transition to an electrified transportation system. Electric buses have the potential to create a win-win-win-win solution if deployed strategically, with transit agencies saving money they can put toward additional service, utilities being able to better leverage their grid assets, cities and states making progress towards climate and air pollution goals, and transit dependent communities reducing the impacts of air pollution in their communities.

Appendix – Background interviews

Thank you to representatives of the following organizations who shared their time and insights in background interviews conducted to inform this research.

Acadia Center (MA)
Build Your Dreams (BYD) (National)
CALSTART (CA)
Clean Energy Works (National)
Greenlining Institute (CA)
Department of Transportation, Boston Public Schools (MA)
Jefferson County Public Schools (KY)
Jobs to Move America (CA)
Kentuckians for the Commonwealth (KY)
Kentucky Clean Fuels Coalition (KY)
Kentucky Energy Services Coalition (KY)
LG&E/Kentucky Utilities (KY)
Los Angeles Department of Water and Power (CA)
Louisville Air Pollution Control District (KY)
Louisville Fleet & Facilities (KY)
Louisville Partnership for a Green City (KY)
Massachusetts Chapter of the Sierra Club (MA)
Massachusetts Clean Cities Coalition (MA)
Massachusetts Department of Energy Resources (MA)
Massachusetts Department of Environmental Protection (MA)
Massachusetts Department of Transportation (MA)
Massachusetts Public Interest Research Group (MA)
National Grid (MA)
Northeast States for Coordinated Air Use Management (NESCAUM) (MA)
Pacific Gas and Electric Company (PG&E) (CA)
Proterra (National)
Southern California Edison (CA)
Sustain Louisville (KY)
Torrance United School District (CA)
Union of Concerned Scientists (CA)
Vermont Energy Investment Corporation (National)

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