Title
Exploring the Costs of Electrification for California's Transit Agencies

Journal
ITS Reports, 2017(03)

Authors
Ambrose, Hanjiro
Pappas, Nicholas
Kendall, Alissa, PhD

Publication Date
2017-10-01

DOI
10.7922/G2PZ570Z

UNIVERSITY OF CALIFORNIA

Exploring the Costs of Electrification for California's Transit Agencies

A Research Report from the University of California Institute of Transportation Studies

Hanjiro Ambrose, Institute of Transportation Studies, UC Davis

Nicholas Pappas, Institute of Transportation Studies, UC Davis

Alissa Kendall, Institute of Transportation Studies, UC Davis

October 2017

PROJECT ID: 2017-03 | DOI:10.7922/G2PZ570Z

ITS UCDAVIS INSTITUTE OF TRANSPORTATION STUDIES

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UC-ITS-RR-2017-03		

4. Title and Subtitle	5. Report Date
Exploring the costs of electrification for California's Transit Agencies	October 2017
	6. Performing Organization Code Enter any/all unique numbers assigned to the performing organization, if applicable.
7. Author(s) Hanjiro Ambrose, https://orcid.org/0000-0002-6502-5191 Nicholas Pappas Alissa Kendall, Ph.D. https://orcid.org/0000-0003-1964-9080	**8. Performing Organization Report No.** 2017-03
9. Performing Organization Name and Address Institute of Transportation Studies University of California, Davis 1605 Tilla Street Davis, CA 95616	**10. Work Unit No.**
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address University of California Institute of Transportation Studies	**13. Type of Report and Period Covered** Final report (September 2016 – October 2017)
	14. Sponsoring Agency Code

15. Supplementary Notes
N/A

16. Abstract
The California Air Resources Board is considering regulatory changes to require an increasing share of public transit buses to produce zero-emissions by 2040. This report attempts to identify and assess critical drivers of electric bus adoption costs, characterize uncertainty in forecasting agency transition costs, and provide an approach to support agencies' assessment of strategic investments in new vehicle technologies. While current purchase costs for electric buses are 40% higher compared to conventional diesel or clean-natural gas buses, by 2030, electric buses are likely to become the most cost-effective option. Taking total cost of ownership into consideration, replacing a bus fleet by 2030 with a 100% electric fleet is estimated to decrease overall costs by $0.1 to $3.6B compared to replacing the current fleet. Results are likely to vary depending on agency size as small and rural agencies have orders of magnitude smaller fleets than the largest agencies and the estimates take into account current subsides for purchases electric buses. The report concludes that total costs of ownership for electric buses are likely to be lower than current fleets and that agencies need better tools to be able to evaluate integrated technology and systems planning, particularly as it relates to transit bus electrification.

17. Key Words	18. Distribution Statement
Public transit, transit operating agencies, electric buses	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	65	Refers to the price of the report. Leave blank unless applicable.

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ABOUT THE UC ITS

The University of California Institute of Transportation Studies (ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

ACKNOWLEDGMENTS

This study was made possible through funding received by the University of California Institute of Transportation Studies from the State of California's Public Transportation Account. The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project. The authors would also like to thank the following people and organizations for providing critical review, data, and other material support to this project: Steve Miller, Golden Gate Transit; Michael Pimentel, California Transit Association; Len Engel, Antelope Valley Transit; Bill Sprawl, San Diego Metropolitan Transit System; Kwesi Annan and Steve Shupack, Los Angeles Metropolitan Transit Authority; Zach Khan and Andy Swanton, BYD; and Cal Silcox, PG&E.

DISCLAIMER

Exploring the Costs of Electrification for California's Transit Agencies

UNIVERSITY OF CALIFORNIA INSTITUTE OF TRANSPORTATION STUDIES

October 2017

Hanjiro Ambrose, Institute of Transportation Studies, University of California Davis

Nicholas Pappas, Institute of Transportation Studies, University of California Davis

Alissa Kendall, Department of Civil Environmental Engineering, University of California Davis

[page intentionally left blank]

TABLE OF CONTENTS

EXECUTIVE SUMMARY 4
Introduction 8
Objective of this Study 10
Factors Affecting the Costs of Ownership for Transit Buses 13
Purchase Costs 13
Fuel Costs 16
Repair and Maintenance Costs 20
Depot and Infrastructure Costs 24
Vehicle Life 27
Technology Performance 28
Vehicle Fuel Efficiency 31
Annual Mileage 33
Externalities and Damages 34
Summary of Cost Drivers 36
Limitations of the Unit Cost Approach 37
Results 38
System-wide Replacement Costs 43
Drivers of Variance in Current Vehicle Costs 45
Discussion 47
Battery Replacement 49
Uncertainty in State-Wide Adoption Costs 50
Emissions Benefits 51
Appendix 1: In-Depth Discussion of Methods 53
References Cited 59

List of Figures

Figure 1 California Transit Fleets and Service Areas....9

Figure 2 Bus Purchase Cost Assumptions....15

Figure 3 Bus Purchase Subsidy Assumption....16

Figure 4 Average per-mile fuel costs for transit buses....17

Figure 5 California and U.S. Retail Diesel Prices (DGE = Diesel Gallon Equivalent)....18

Figure 6 Fuel Cost Assumptions (DGE=Diesel Gallon Equivalents)....19

Figure 7 LCFS Credit Value for E-buses....20

Figure 8 Financial Service and Maintenance Statistics for the 20 Largest Agencies by Bus Fleet 21

Figure 9 Distribution of Expenses per Mile and Failure Type per Mile in 2014 NTD....22

Figure 10 Maintenance Costs per Mile....23

Figure 11 Midlife Overhaul Cost Assumptions....24

Figure 12 Depot Capital Amortization....26

Figure 13 Age Distribution for Active Transit Buses in 2014....28

Figure 14 Electric Bus Replacement Rate Assumption for Large Agencies....30

Figure 15 Replacement Rates by Agency and Period....31

Figure 16 Vehicle Fuel Example....32

Figure 17 Average Fuel Economy by Agency, Fuel, and Length....33

Figure 18 Annual Mileage Distribution of Active Buses....34

Figure 19 Annual Revenue and Non-Revenue Mileage Assumptions....34

Figure 20 Lifetime Costs of Ownership per Bus....40

Figure 21 Lifetime Costs of Ownership per Mile....42

Figure 22 Per Mile Costs by Agency and Length....42

Figure 23 Statewide Bus Transition Costs....44

Figure 25 Screening Analysis of Lifetime Costs of Transit Buses by 2030....45

Figure 27 Screening Analysis of Statewide Fleet Replacement with 100% Electric Buses....46

Figure 28 Change in Annual Expenditures for Large Agency with 100% Electric by 2040....51

List of Tables

Table 1 Average Bus Prices for 2010 to 2015 Model Year Vehicles Reported to APTA................14

Table 2 Average Active Buses per Depot for California Agencies 27

Table 3 Total Costs by Fuel-pathway and Length (Current Prices, No Incentives).......................38

Table 4 Total Costs by Fuel-pathway and Length by 2030 (No Incentives).................................39

Table 5 Per Mile Costs by Pathway and Length (Current Prices, No Incentives)..........................40

Table 6 Per Mile Costs by Period and Length by 2030 (No Incentives).......................................41

Table 6 Summary of Average TCO by Pathway and Period...43

Table 7 Total System Replacement Costs (Billion USD$)...44

Table 8 Per Mile Emissions Comparison for E-buses and CNG (grams)) 52

EXECUTIVE SUMMARY

The California Air Resources Board (CARB) is considering regulatory changes that would require an increasing share of transit buses to be zero-emissions by 2040 to mitigate transit's contribution to local air pollution and greenhouse gas (GHG) emissions. Battery electric buses (E-bus) are expected to be the primary technology adopted to achieve this policy goal. While a transition to E-buses may support emissions reductions targets and provide other benefits for urban areas, a transition to electricity from conventional liquid and natural gas fuel buses could also create new costs and uncertainties for transit agencies. Resource-constrained transit agencies must consider tradeoffs between service coverage, frequency, and operating expenses against investments in new technologies. This research explores how bus electrification will impact these costs by assessing the total cost of ownership (TCO) using a probabilistic approach.

The goal of this report is to identify and assess the key drivers of electric bus adoption costs, characterize uncertainty in forecasting agency transition costs, and provide an approach to support agencies' assessment of strategic investments in new vehicle technologies. This report specifically considers two replacement periods, the current and next replacement for each agency, across several combinations of bus size and powertrain. The report also considers how agency size, operations, and route structure might affect agency adoption costs. An estimate for how state-wide replacement costs might change between now and 2030 is also provided.

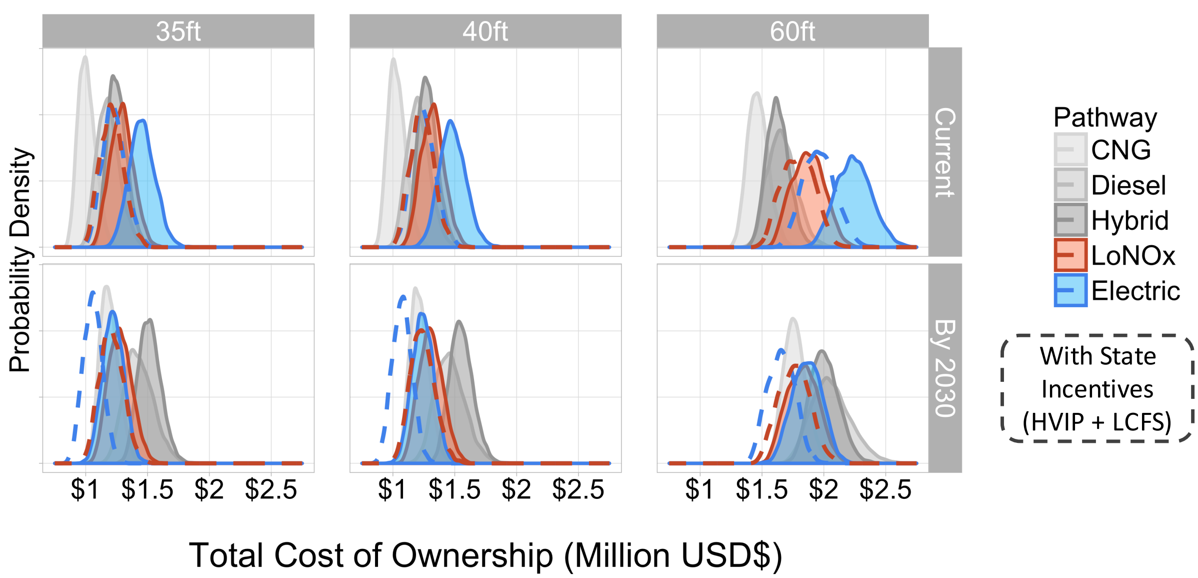
Methods: Transit agencies with active bus fleets were identified through reporting to the National Transit Database. Operations data, including routes, service schedules, financial performance, fleet size, and fleet composition, were collected for each agency from a variety of sources. Unstructured interviews were also conducted with a handful of transit agencies, manufacturers, and electric utilities. Pricing and vehicle performance information were gathered from agency interviews, published literature, government reporting, and manufacturer information. The costs of five vehicle fuel and powertrain combinations (pathways) were modelled across individual agency operations; these included diesel, diesel-hybrid, compressed natural gas (CNG), CNG Low-NO_X ($LoNO_X$), and electric. The lifetime cost is estimated as a function of vehicle purchase price, scheduled and unscheduled maintenance, midlife repower or refurbishment, fuel, powertrain efficiency, duty cycle, upgrades to depot and maintenance infrastructure, infrastructure and equipment maintenance, vehicle lifetime, and policy incentives. All costs are reduced to their net present value assuming a discount rate of 5%.

Results and Discussion: Currently, purchase costs for electric buses are 40% higher compared to conventional diesel or CNG buses. These costs are expected to fall by up to 25% in the coming decade, even while vehicle range increases by 50% or more due to improvements in battery systems. Over the vehicle lifetime, current market electric buses have approximately 11% higher costs than diesel, and 21% higher compared to CNG. The costs of necessary vehicle infrastructure, including charging systems and upgrades to depot facilities, are also considerable. Price trends for lithium-ion batteries are expected to drive long-term changes to purchase and mid-life overhaul costs. While E-bus costs are expected to fall over the coming decade, costs of all the other bus pathways are expected to increase due to increasingly stringent emissions standards and increasing fuel prices.

Figure E1 shows the results of the analysis for the current and next replacement period for the considered pathways across bus sizes. Adoption of E-buses increases TCO compared to the lowest cost conventional option (CNG) in the current replacement period. By 2030, E-buses are likely to become the most cost effective option for many transit agencies in California due to the convergence of three factors:

- Changing costs for conventional alternatives (i.e. CNG and diesel)
- Policy subsidies for E-bus purchase and operation.
- Improving technical performance and range for E-buses

Figure E1. Total Cost of Bus Ownership for California Transit

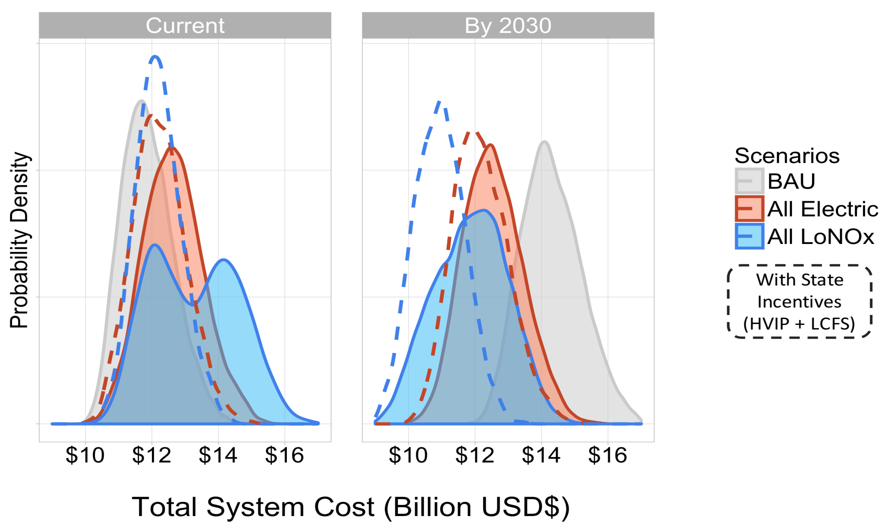


The results presented in Figure E1 summarize the expected TCO for all California transit agencies probabilistically, which may obscure some of the insights relevant to particular transit agencies.

Heterogeneity in agency, size, route structure, etc. lead to different costs of adoption. E-bus cost estimates are very sensitive to assumptions about electricity prices, maintenance costs, purchase costs, and fuel efficiency. In addition, small and rural agencies have orders of magnitude smaller fleets than the largest agencies, operate fewer high density routes (e.g. a higher percentage of low stop density/high speed routes), and have smaller reserve fleets compared to urban agencies. These differences result in adoption costs that are 7% higher on average for small agencies, and up to 75% higher for small rural agencies (compared to the largest urban fleets). Small, rural agencies operate ~ 5% of active buses, but represents more than 30% of transit agencies in the state.

In addition to assessing the TCO of transit bus options from a transit perspective, this study also considered the costs of system-wide adoption of different pathway scenarios today and in 2030 (Figure E2). Scenarios include business-as-usual (BAU), $LoNO_X$, E-buses, and mixed compliance, where agencies' current CNG fleets adopt Low-NO_X upgrades while diesel fleets adopt electric. The mean lifetime cost for replacing and operating the current fleet is $11.87 billion dollars. The lifetime cost of replacing the current fleet with 100% electric buses with current prices increases net costs for agencies by $2.5 and $4 billion dollars. Agencies are also eligible for an additional $1 to $3.7 billion dollars in subsides from the California's Hybrid Vehicle Incentive Program (HVIP) and Low Carbon Fuel Standard (LCFS). When these incentives are included, the cost of electrifying the entire fleet in the current period is not statistically different from business as usual costs.

Figure E2. System-wide replacement costs for Bus Replacement Scenarios



By 2030, replacing the fleet with 100% electric is estimated to decrease total costs by $0.1 to $3.6 billion dollars, not including the potential of an additional $1.6 billion in HVIP and LCFS subsidies for agencies. By 2030, both the cost difference between conventional vehicles and E-buses, as well as the value of purchase subsidies offered to E-buses, are expected to decline. A key takeaway is the importance of subsidies for E-buses. At $0.12/kWh, the upper end of expected LCFS subsidy for transit agencies, the change in fuel cost would represent more than 10% of the lifetime cost of the bus.

Conclusions: A transition to electric buses increases annual expenditures as new investments in infrastructure are made. Over time, electric buses are expected to deliver lower operating costs and lower lifetime costs compared to conventional powertrains. The time required for agencies to realize savings from electrification is dependent on technology performance and policy support. The overall investment required to realize lower operating costs is driven by capital costs; namely the extent to which existing infrastructure will need to be upgraded. The heterogeneity in costs and benefits suggested across agencies and routes is an important concern for the scope of prospective policy. In general, agencies likely need better tools to analyze integrated technology and system planning, particularly as it relates to transit bus electrification.

Introduction

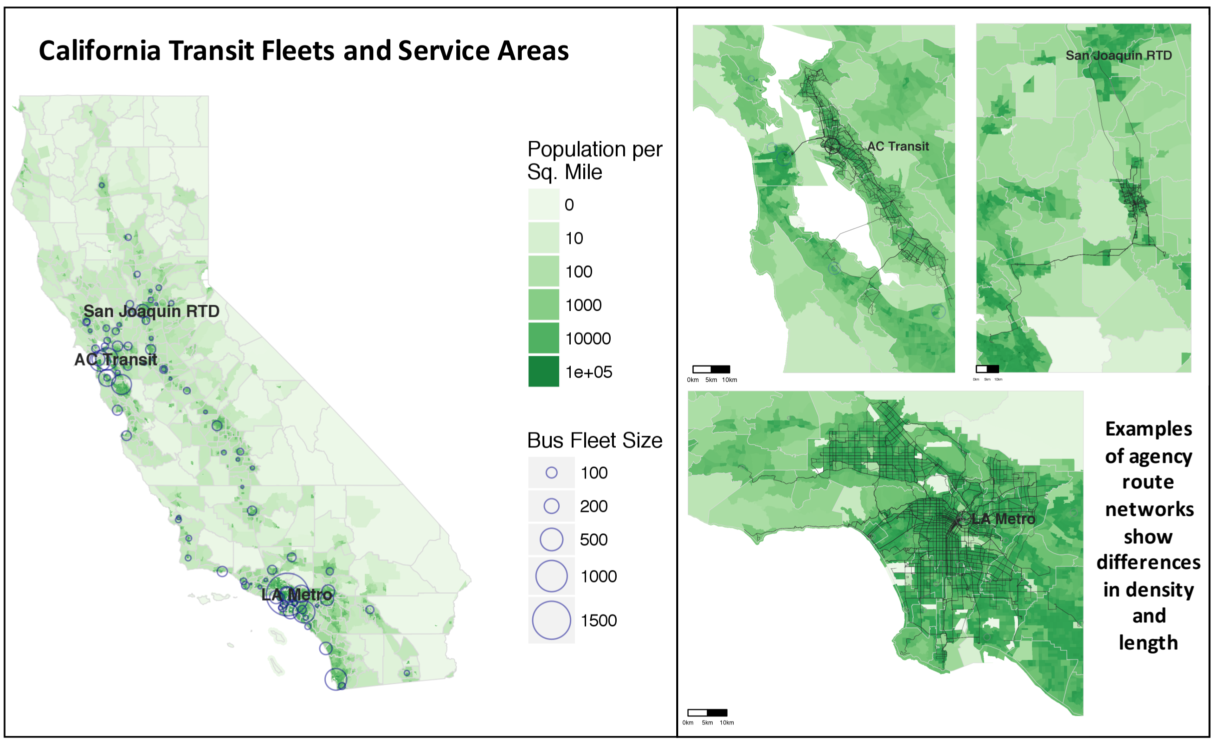
The California Air Resources Board (CARB) is considering regulatory changes that would require an increasing share of transit buses to be zero-emissions by 2040 to mitigate transit's contribution to local air pollution and greenhouse gas (GHG) emissions. Transit operators serve multiple goals, including providing low-cost mobility to underserved populations and reducing pollution in urban communities. The proposed regulation will lead transit operators to purchase an increasing number of battery electric and fuel cell buses, which qualify as zero-emission buses (ZEBs). Battery electric buses (E-buses) are expected to be the primary zero-emission technology that will be adopted in the coming decades due to the high capital costs and limited availability of fuel cell buses. While a transition to ZEBs is aligned with the state's larger emissions reductions targets and has other benefits for urban areas, a transition to electricity from conventional liquid and natural gas fuel buses could create new costs and uncertainties for transit agencies. Resource-constrained transit agencies must consider tradeoffs between service coverage, frequency, and operating expenses against investments in new technologies; this research explores how electrification will impact these costs.

ZEBs combined with renewable transportation fuel pathways are likely critical to meeting demand for mobility in a low carbon future. The last fifteen years has witnessed a dramatic decline in the costs of vehicle hybridization, biofuels, renewable electricity generation, and vehicle light-weighting with advanced materials, which are enabling technologies for all zero-emission vehicles (ZEVs), and key to increasing the efficiency of vehicles while shifting them away from direct fossil energy combustion. Rapidly improving economics of battery storage, in particular, enable new ZEV applications, such as transit buses (Nykvist & Nilsson, 2015). Today, there are a growing number of commercial offerings of ZEBs for transit agencies to consider, as well as demonstration data to draw upon (Center, 2014, 2015a, 2015b; Cooney, Hawkins, & Marriott, 2013; Eudy, Prohaska, Kelly, & Post, 2016).

Transit agencies considering fleet technology upgrades need to consider the costs of vehicle ownership and operation when weighing vehicle purchase decisions. ZEB vehicle and fuel technology adoption offer new trade-offs between purchase and operation costs, uncertain vehicle and component system lifetimes, and the potential to consider environmental performance improvements. The lifetime cost of electric buses include not only the purchase cost of the vehicles, but also of charging equipment, maintenance costs, the cost of energy, and potential battery replacement costs (Ellram & Siferd, 1998). Lifetime cost of ownership models are often used to compare vehicle purchase options or fleet operations scenarios, and take into account both the fixed costs of vehicle acquisition and operation (Jørgensen, Pedersen, & Solvoll, 1995). Total cost, life cycle cost, product life cycle cost, and total cost of ownership are all related concepts that consider purchases in the context of longer term decision making (Ferrin & Plank, 2002).

Previous studies have found that the total cost for a transit bus over its lifetime is determined mostly by purchase price and fuel costs, when labor is excluded (Ahluwalia, Wang, & Kumar, 2012; Lajunen, 2014; Lowell, Seamonds, Park, & Turner, 2015). This has also been true for ZEBs, although limited purchase price data or demonstration costs have often been available for study (Bubna, Brunner, Gangloff, Advani, & Prasad, 2010; Karlaftis & McCarthy, 2002). Battery replacement costs for E-buses, and fuel cell stack replacements, have also been raised as potentially significant cost drivers. E-bus charging equipment and other infrastructure upgrades can also have a significant impact on overall vehicle cost (Ambrose & Jaller, 2016). Another potential confounding factor for estimating the costs of ZEBs for agencies is the presence of other enabling technologies that can affect operating performance. For example, on-route charging infrastructure for E-buses could both increase the costs of a system upgrade, but also allow for greater utilization and storage system size reductions (Cooney et al., 2013; Jang, Ko, & Jeong, 2012; Shirazi, Carr, & Knapp, 2015).

Figure 1 California Transit Fleets and Service Areas



(AC Transit = Alameda County Transit, LA Metro = Los Angeles County Metropolitan Transportation Authority)

Transit agencies in California operate a wide range of fleets in a diversity of service areas and route systems, all of which will impact the costs of agency or route electrification. There are over 150 transit bus agencies in California operating more than 9000 buses that collectively travel 316 million vehicle miles annually. The 20 largest agencies by vehicles in service represent over 75% of all transit buses in California, and 85% of all passenger miles reported to the Federal Transit Administration (FTA). Los Angeles County Metro (LACMTA) operates nearly one quarter of all transit buses in the state, about four times that of the second largest fleet.

Among and within these transit agencies, route distance and frequency are highly variable (Figure 1). Route distance and frequency affect the substitutability of E-buses for diesel and natural gas buses. Approximately 40% of the 6500 buses operated by the 20 largest agencies drive less than 150 miles per day and could be substituted for an E-bus given today's technology.

The State of California provides approximately a quarter of the capital and operating funds for transit agencies, with a slightly higher percentage for large agencies than small agencies by fleet size. Additional subsidies designed to accelerate the market for electric vehicles and to increase the use of alternative fuels in fleets are currently available to transit agencies adopting E-buses. These subsidies significantly affect the economics of adoption and should be considered alongside other costs of adoption. One issue raised around the discussion of the Advanced Clean Transit (ACT) regulation has been the future value of these subsidies. Transit agencies, who must make long term commitments to capital and operating expenditures on constrained funding cycles, are reticent to commit to relying on these subsidy programs, which they view as uncertain.

Objective of this Study

The objective of this study is to compare the TOC of adopting E-buses to the TOC of conventional transit buses under uncertain future cost and technology parameters. The study considers five possible vehicle and fuel technology combinations (referred to as pathways): diesel, diesel hybrid (hereafter called hybrid), compressed natural gas (CNG), CNG with a Low-NO_X engine[1] ($LoNO_X$) technology. The analysis includes adoption costs for transit agencies, considering expected changes in vehicle and fuel costs over subsequent purchase decisions. This report specifically considers:

- Purchase Costs
- Scheduled and Unscheduled Maintenance
- Midlife Repower/Refurbishment
- Fuel Costs
- Powertrain Efficiency
- Vehicle Duty Cycle
- Infrastructure Upgrades
- Existing Agency Infrastructure
- Vehicle Replacement Ratios and Schedules
- Vehicle Life
- Policy Subsidies

This study provides a rank ordering of how these factors contribute to uncertainty in predicting agency costs for adopting electric buses. The study also provides an estimate for how state-

[1] CNG and LoNOx CNG engines include buses using Renewable Natural Gas (RNG). Further discussion of RNG costs and incentives can be found in the section on fuel costs.

wide replacement costs might change between now and 2030, and discusses the role of policy incentives. The study does not directly consider some operational labor costs, such as bus drivers and dispatch staff. Aggregated per-mile costs, which include labor, are used for all repair and maintenance costs.

The study considers two purchase periods; each period represents intervals over which agencies will commit to bus replacement purchase decisions, and the likely costs agencies will experience over those replacements. The first period compares prices for conventional alternatives to electric buses for 2016-2018 new vehicle deliveries. The second period represents costs agencies might experience over the subsequent replacement decision, or 2028-2032 new vehicle deliveries, incorporating forecasted vehicle and energy costs across technologies. As agencies replace approximately 7%-8% of their bus fleet each year[2], CA transit agencies are likely to replace approximately one quarter of the active transit bus fleet during the first purchase period. The second five-year period represents the range of time when these same buses are likely to be replaced again.

Purchases are simulated for different agency profiles identified by agency size, route structure, historical financial performance, and existing infrastructure. Three agency clusters (large, small, and rural transit agencies) were identified based on fleet size, operations data, route network, and service schedule:

Scenarios for Agency Type:

- **Rural** – less than 20 vehicles, limited depot infrastructure, NTD partial or rural reporter,
- **Small –** less than 300 vehicles, mid-sized depots, split of dense and rural routes (<2 stops per-mile)
- **Large** – 300 – 1500 vehicles, over 100 vehicles per depot, high number of dense routes (>5 stops per-mile)

Extrapolating from the current population of buses and major agency characteristics, we then estimate system-wide replacement costs under three scenarios for each time period.

Scenarios for System Cost Estimates:

- **BAU** – Full replacement of existing fleet with same vehicle and fuel pathway
- **All Electric –** 100% replacement of existing fleet with electric buses
- **All LoNO$_X$ CNG** - 100% replacement of existing fleet with LoNO$_X$ CNG buses

These scenarios are used to simulate statewide transition costs over the same time intervals based on the current population of transit agencies and fleet composition. All results are presented in net present value, discounted to the year of purchase, assuming a 5% discount rate for base model runs. Further discussion of methodological choices are addressed in the

[2] This is consistent with a 12 to 14 year service life for transit buses.

Appendix. The next section discusses the key parameters affecting adoption costs, how these parameters were incorporated into this study, and the specific assumptions adopted.

Factors Affecting the Costs of Ownership for Transit Buses

The lifetime cost of ownership for a vehicle is an important indicator for transit agency operators considering new bus technologies and fuels. The lifetime cost of ownership generally includes changes in capital expenses (vehicle purchase, infrastructure, and facility upgrades) as well as operational expenses (fuel, repairs, and maintenance). Additional considerations that could impact the costs of adopting electric transit buses include the effects of route structure, planning for infrastructure investment, and decisions about technical configurations (i.e. on-route vs. optimized depot charging vs. convenience charging only).

This section of the report discusses each of these issues in more detail. Each subsection begins with background on the available data related to a set of key cost considerations, and closes with the specific assumptions adopted by the study. In each case, a probability distribution for parameter assumptions is estimated for each purchase period. Infrastructure investments, including storage depots, maintenance bays, and refueling facilities, are amortized through the use of a capital recovery factor and normalized by service life or mileage. In the sections on purchase prices and fuel prices respectively, we discuss state policies which incentivize the use of E-buses and significantly affect the cost structure of E-bus operations. Finally, we discuss some of methodological issues in estimating lifetime cost of ownership, and how certain methodological choices might lead to different conclusions.

A key focus of this study is characterizing how changes to key parameter assumptions contribute to uncertainty in estimating the lifetime costs of transit bus ownership. Including uncertainty is crucial to making robust cost comparisons. Uncertainty in lifetime costs stems from stochastic and cyclical variability in key costs, as well as uncertainty that arises from a lack of knowledge about likely parameter values. The latter is especially important when considering future costs, as costs for emerging technologies are not well established and are subject to considerable future change. It is also difficult to disaggregate variability from measurement errors and conflicts in the historical data for existing powertrains and fuels. To assess the effects of these variations on total cost, probabilistic parameter assumptions are combined through economic discounting and correlated random sampling to estimate the net present value of lifetime vehicle costs.

Purchase Costs

The American Public Transportation Association (APTA) Public Transportation Vehicle Database offers a micro-level view on transit bus fleet composition with information including purchase price, vehicle age, and powertrain type. The APTA database includes purchase prices for 1,000 price points of 40’ diesel, CNG, diesel hybrid, battery, and hydrogen bus purchases made by reporting transit agencies, and was used to assess the distribution of bus purchase prices by powertrain type for this study.

The average costs California agencies paid for buses over the most recent replacement decisions is shown in Table 1. Over the last ten vehicle model years (2005 to 2015), diesel bus prices have increased by 13-15%, while CNG bus prices have increased by almost 20% in California. For comparison, CARB's Transit Agency Workgroup reported from stakeholders that new 2016 diesel and CNG bus costs were approximately $480,000 and $520,000 respectively. This also aligns with trends in the APTA data for California; conventional bus prices are forecast to continue to increase by more than 2.3% per year between now and 2030 (CARB, 2015). Agencies we spoke with during this study also cited increasing costs for conventional buses.

Table 1 Average Bus Prices for 2010 to 2015 Model Year Vehicles Reported to APTA

Bus Length	CNG	Diesel	Hybrid	Std. Error
35 ft	$475,000	$441,639	$606,620	$14,308
40 ft	$485,038	$446,651	$619,439	$2,125
45 ft	$550,307	$541,112	$702,794	$2,109
60 ft	$802,000	$724,442	$850,000	$6,433

The use of diesel and gas engines with improved combustion and emissions control is part of the CARB mobile sources strategy to achieve ozone attainment in the South Coast Air Quality Management District. Engines meeting the 2023 NOx emissions standard of 0.02 gNOx/bhp are common referred to as Low-NOx ($LoNO_X$) LoNOx engines that are compatible with renewable natural gas (RNG) have also been proposed as a low-carbon heavy-duty fuel pathway. As an example, CNG transit buses are available with a Cummins Westport ISL G-Near Zero (NZ) engine, which achieves 2023 NOx standards. An ISL G-NZ upgrade is estimated to cost from $8,000-$25,000 more than the traditional ISL G engine, and currently there is no diesel engine on the market that meets the same emissions standard (Kassel & Leonard, 2016). In contrast, E-bus and hydrogen fuel cell bus purchase costs are expected to continue to decline with advances in battery technology (Eudy et al., 2016) and fuel cell systems. The CARB Transit Agency Workgroup expects that a 300 kWh battery bus will decline from roughly $850,000 in 2015 to $730,000 in 2030, assuming that the battery is the sole source of cost reduction (CARB, 2015). While the cost reductions for E-buses could be moderate to negligible, low cost reductions will likely coincide with considerable performance improvements, which could enable further system resizing and impact the costs of adoption.

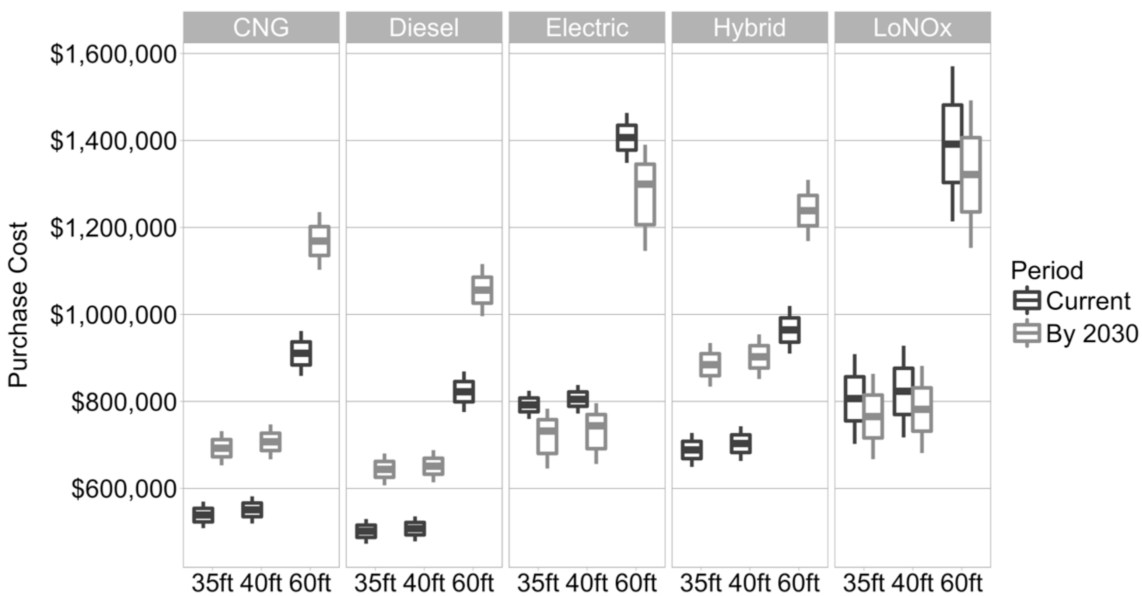
Many E-buses are eligible for special incentive programs which can decrease purchase costs. The Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) is a program implemented by CARB that provides purchase subsidies for vehicle purchases, including E-bus transit buses. Several E-buses were eligible for the HVIP under the most recent funding period, with subsidies ranging from $80,000 to $101,000 per vehicle[3]. HVIP funding is allocated by the

[3] A complete list of HVIP approved vehicles is released by the ARB each year: https://www.californiahvip.org/docs/HVIP_EligibleVehicles.pdf

state each year through the budget process. The principal sources of funds, the Low Carbon Transportation and Air Quality Improvements Program (AQIP), is also experiencing high competition, and ARB maintains a tracker on its website to display how quickly and when HVIP funds are exhausted. In general, the HVIP program is not expected to serve as a reliable, long-term funding source for transit agencies; but, it is likely the state will continue to provide some form of subsidies for fleet electrification, perhaps in a reduced form.

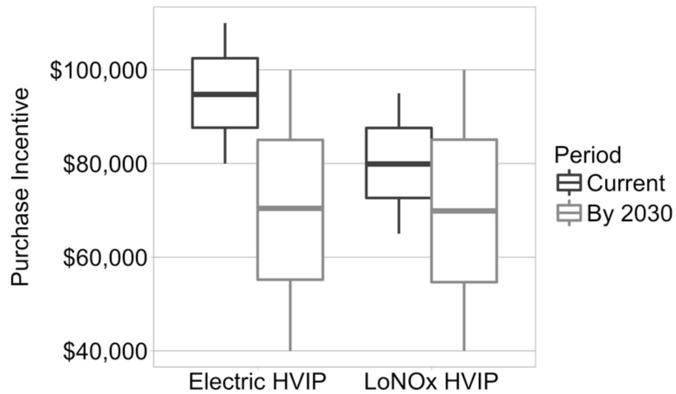
This study assumes the purchase prices for buses shown in Figure 2.The price distribution in the current period is derived from the APTA purchase data. For the future purchase period, conventional vehicles' purchase price are assumed to increase 3% per year, while the average costs of E-buses decreases by ~1% (Figure 2). This assumes that E-bus battery costs reductions and increasing production scale will be equal to or greater than price inflation for conventional buses between the two periods.

Figure 2 Bus Purchase Cost Assumptions



This study also assumes continued subsidization by the state of both E-bus fuel and vehicle purchases. For comparison, purchase subsidies are also included for the $LoNO_X$ pathway. Subsidies are assumed to decrease by ~50% between the current and future purchase period, from just under $95,000 on average, to $50,000 (Figure 3).

Figure 3 Bus Purchase Subsidy Assumption



Fuel Costs

The Low Carbon Fuel Standard (LCFS) provides a per unit of fuel subsidy for the use of low carbon fuels, such as the electricity consumed by E-buses or hydrogen consumed by fuel cell vehicles. The LCFS credit for E-buses replacing conventional transit buses is $0.10-$0.14 per kWh of charging energy (the credit value fluctuates with the LCFS market). The LCFS credit can represent 100% or more of the electricity rate proposed by some utilities for over-night, managed charging. The LCFS credit value potentially reduces the fuel costs of E-buses to a few cents per-mile (Figure 4). The range for diesel cost in Figure 4 reflects vehicle fuel economy for both conventional and hybrid powertrains. Boxes show 25th and 75th percentile of per-mile costs with medians indicated on the centerline, while the whiskers represent maximum and minimum costs. "Electricity with LCFS Credit" represents the expected per-mile fuel costs with credit revenue. [4]

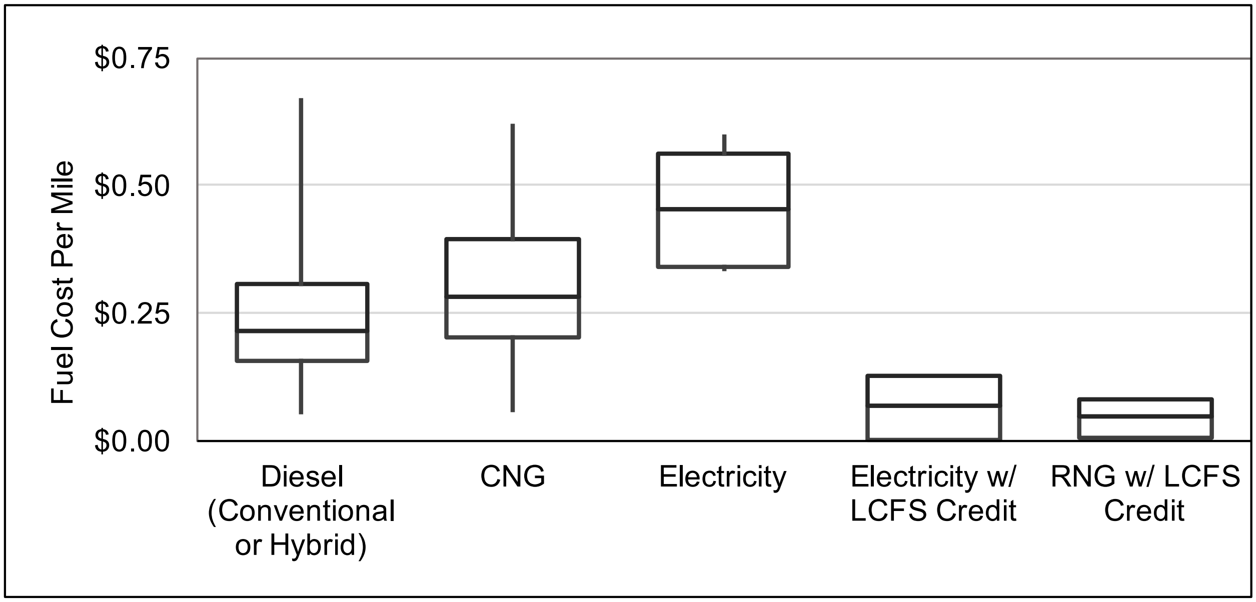
LCFS is one of several state climate programs intended to improve the value proposition of low-carbon alternatives, including Cap and Trade, which generates considerable funding for low-carbon projects. Cap and Trade funds have become a robust source of funding for many of the state's GHG-related initiatives, with $2.2 billion in Cap and Trade funds budgeted for the 2017-2018 fiscal year alone.[5] While the LCFS is authorized until 2030 under SB32 (signed in 2016), the recently passed extension to Cap and Trade also gives the ARB authority to apply additional market-based declining annual emissions limits to 2020 (AB398 Sec. 5. 38562.(a)). For these reasons, E-bus fuel subsidies are likely a secure source of funding for the expected life of

[4] This analysis assumes diesel or diesel-hybrid fuel economy of 2.5-6.5 MPDGE, a CNG fuel economy of 2-5 MPDGE, and electric bus energy requirements of 2-3 kWh/mile. These ranges are drawn both from the NTD 2014 data, and the range of E-bus fuel economies from Eudy et al. (2014) and data from Antelope Valley Transit. The LCFS prices assume an LCFS credit price of $100 with energy efficiency ratio for diesel displacement. The net LCFS credit was calculated to be $0.11 to $0.13 per kWh using the CARB LCFS credit calculator or $0.10 to $0.29 per MPDGE for RNG (https://www.arb.ca.gov/fuels/lcfs/dashboard/creditpricecalculator.xlsx).

[5] For a longer discussion of issues to be considered in the long-term viability of Cap and Trade Funds and LCFS linkage see http://www.lao.ca.gov/Publications/Report/3553

vehicles. Thus the net fuel costs for agencies using electricity will depend on both the utility rate structure and policy incentives.

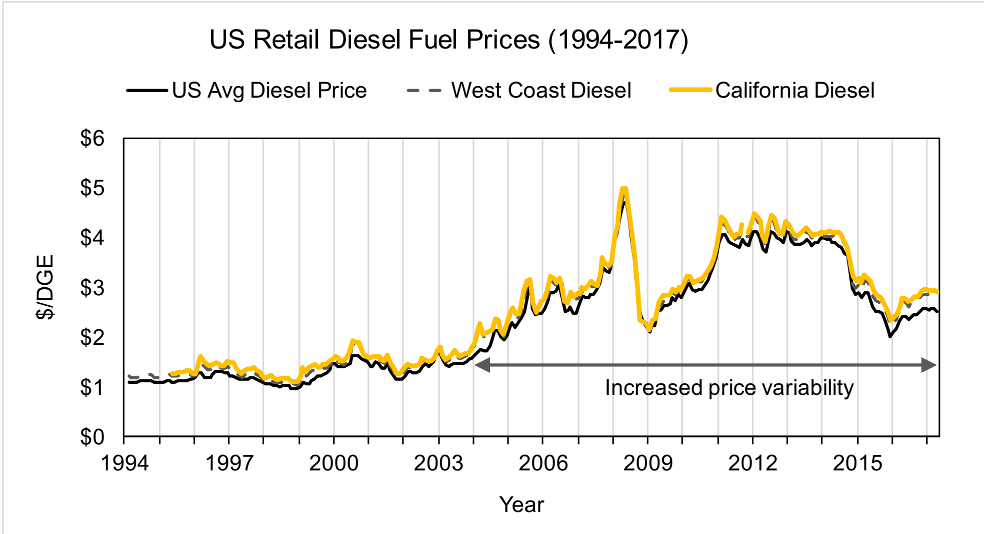
Figure 4 Average per-mile fuel costs for transit buses



Predicting and accounting for electricity costs is fundamental to understanding the overall costs of transit electrification. However, accurate prediction of electricity costs is complicated by complex and changing utility pricing structures. Utility services are generally billed with multiple components, including a commodity component (in kilowatt-hours), a capacity component (in kilowatts) billed at the customer's peak monthly or annual capacity, and customer charges billed per meter regardless of usage. These can be highly variable depending on the time of year, time of day, location of charging, and other factors, and pricing structures will depend on the size of the fleet being charged. Further, utility pricing is not fixed for the life of the fleet. Unlike most procurement, utility contracts are generally not developed bilaterally between the customer and the utility, but instead developed by the utility and approved by a regulator or local governing board. As a result, agencies are not able to secure fixed price contracts over the life of a bus or of charging infrastructure.

Diesel has historically been the dominant fuel for transit buses, and continues to be at the national level. In California, about 37% of active buses in the state rely on diesel fuel. Diesel prices have shown considerable volatility over the last 15 years, ranging from $1.12 to $4.97 (Figure 5). Adjusting for seasonality, the average expected price currently is $2.21 per gallon, with 90% prediction interval of $1.86 to $3.82 per gallon. The price of diesel is expected to increase by 2030 in part due to climate and renewable fuel policies like LCFS. If LCFS credit prices increase, the costs of offsets for diesel refiners will also increase, which in turn is likely to be passed through to consumers.

Figure 5 California and U.S. Retail Diesel Prices (DGE = Diesel Gallon Equivalent) [6]



CNG buses deliver very competitive per-mile fuel costs due to the low market price of natural gas. Average CNG transit bus fuel economy is actually equivalent to or lower than conventional diesel buses for most routes (Clark, 2009; Lajunen & Lipman, 2016). As recently as 2015, agencies reported paying less than $0.50 per diesel gallon equivalent for CNG. Prices of CNG have increased moderately in the last two years, and are expected to continue to do so. In 2016, the average prices of CNG were $0.60 to $0.84 per DGE for commercial and residential deliveries respectively ($8.4 - $12 per thousand cubic feet)[7]. The EIA Annual Energy Outlook forecasts that commercial CNG prices will increase almost 40% by 2030, which is slightly more than the forecast increases in diesel fuel prices over the same period (33%). Individual agencies are likely to enter into fuel price contracts, which could offer more competitive rates than average retail prices.

RNG is an alternative fuel option for CNG fleets. RNG can be produced from biomass or animal wastes and can generate revenue through LCFS credit sales. Recent reports and response to solicitations offered to transit agencies suggest that RNG would be available at the market rate for CNG.[8] In this case, the natural gas provider would collect any revenue from LCFS and reflect those offsets in the market price offered. LCFS credit generation varies depending on the fuel production pathway (geography and feedstock); as there is little information on where RNG would be sourced, the impact of LCFS revenue on market pricing for RNG is difficult to estimate. RNG is also an approved pathway under the Federal Renewable Fuel Standard (RFS), and credits earned under the RFS (Category D3) represent a significant potential source of revenue for RNG producers. Considering average prices for D3 RINs, the overall impact of RFS credits on RNG

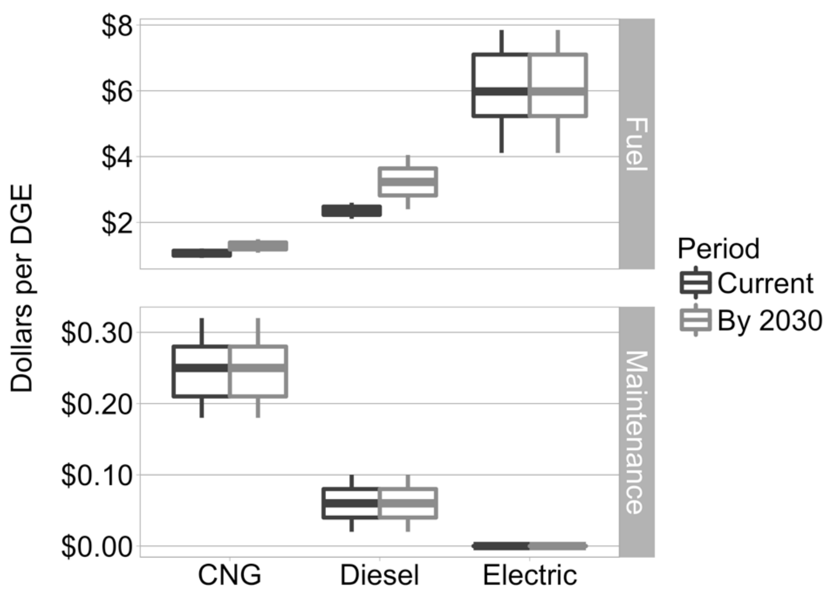
[6] U.S. Energy Information Administration, Gas and Diesel Fuel Updates https://www.eia.gov/petroleum/gasdiesel/
[7] California Natural Gas Prices, https://www.eia.gov/dnav/ng/hist/n3010ca3m.htm
[8] Ramboll Environ and MJ Bradley & Associates, 2016, "Zero Emissions Bus Options: Analysis of 2015-2055 Fleet Costs and Emissions."

prices is likely much greater than the LCFS ($3000 per MMBTU in RFS revenue vs. <$100 per MMBTU for LCFS). This further complicates predicting the price of RNG.

At current electricity prices, agencies can only anticipate significant reductions in fuel operating costs from electrification with credit incentives through the LCFS. These credits may change over time. A $100 dollar LCFS credit price, with the conversion ratio for displacing fossil fuels in buses, would amount to a credit of $0.11-$0.12 per kWh consumed for E-bus charging. The price of electricity and the per-mile E-bus efficiency likely need to be below $0.10/kWh and 2 kWh/mile respectively for per-mile E-bus fuel costs to fall below $0.20/mile (the low end of conventional per-mile fuel costs). With the LCFS credit, electric buses could deliver a fivefold reduction in per-mile fuel costs; without the LCFS credit, there could be no significant differences in per-mile prices *when compared against current prices for CNG*.

This study assumes the relative fuel costs depicted in Figure 7; prices are shown for both the current and future purchase period. In the future purchase period, the range of electricity prices are assumed to be effectively constant. Diesel and CNG costs are assumed to increase in the future purchase period by approximately 3.5% per year, in line with forecasts from the U.S. Energy Information Administration and CARB.[9] Fuel system maintenance includes costs for maintaining compressors and tanks (in the case of a CNG system), as well as chargers (in the case of Electric).

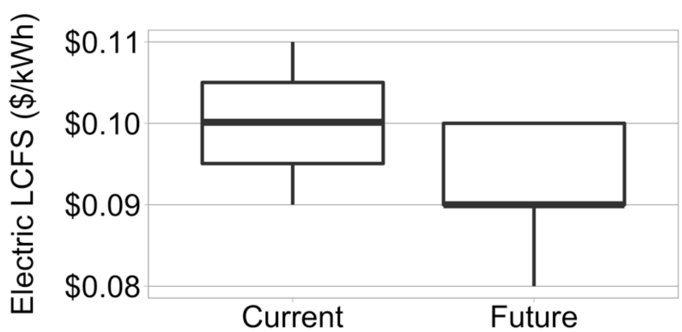
Figure 6 Fuel Cost Assumptions (DGE=Diesel Gallon Equivalents)



[9] The Annual Energy Outlook and complete pricing forecasts are available at the EIA website https://www.eia.gov/outlooks/aeo/data/browser/

For electricity, an LCFS credit price of $100 is assumed for both periods. In the future period, the energy equivalent ratio (EER) used to calculate the displacement credit value is decreased from 4.2 to 2.7, making the incentive equivalent to that received for heavy truck electrification and other heavy duty fuel displacements. Simultaneously, the carbon intensity of grid electricity decreases due to the State's Renewable Portfolio Standard and increasing penetration of lower-carbon electricity generators. The net effect is a decrease in the future per kWh LCFS subsidy of 12.5% (Figure 8). Overall, the net cost of electricity for E-buses will be highly sensitive to changes in the EER.

Figure 7. LCFS Credit Value for E-buses



Repair and Maintenance Costs

Operations and maintenance costs at some agencies represent over 75% of annual expenditures. With the exception of labor,[10] maintenance and fuel are the most significant contributors to per-mile operations and maintenance costs. A long-range study of early model Proterra E-buses at Foothill Transit reported 10% lower per-mile maintenance costs and 50% lower overall maintenance costs compared to CNG buses. This was owing to the simpler propulsion systems of electric buses and fewer replaceable/serviceable power or drivetrain components.[11] The Foothill Study has been very influential in setting initial cost expectations; however, forecasting remain uncertain due to a lack of other data to corroborate the results of this early work.

In addition to the lower maintenance and repair costs, the study also showed that the E-buses had higher rates of unscheduled maintenance issues or repairs that required the bus to be taken out of service. Unscheduled maintenance events decreased the overall utilization of the E-buses (as measured by days of available service), which can increase overall operating costs.

[10] One potential source of uncertainty for this assumption is the time duration of bus assignments. Where CNG buses are replaced with multiple electric buses due to range restrictions, changing out buses may require additional return trips to a depot facility or require additional labor hours. In general, buses are in service longer than a single driver's shift and are already organized around changing drivers during shifts, but labor costs could be significant.

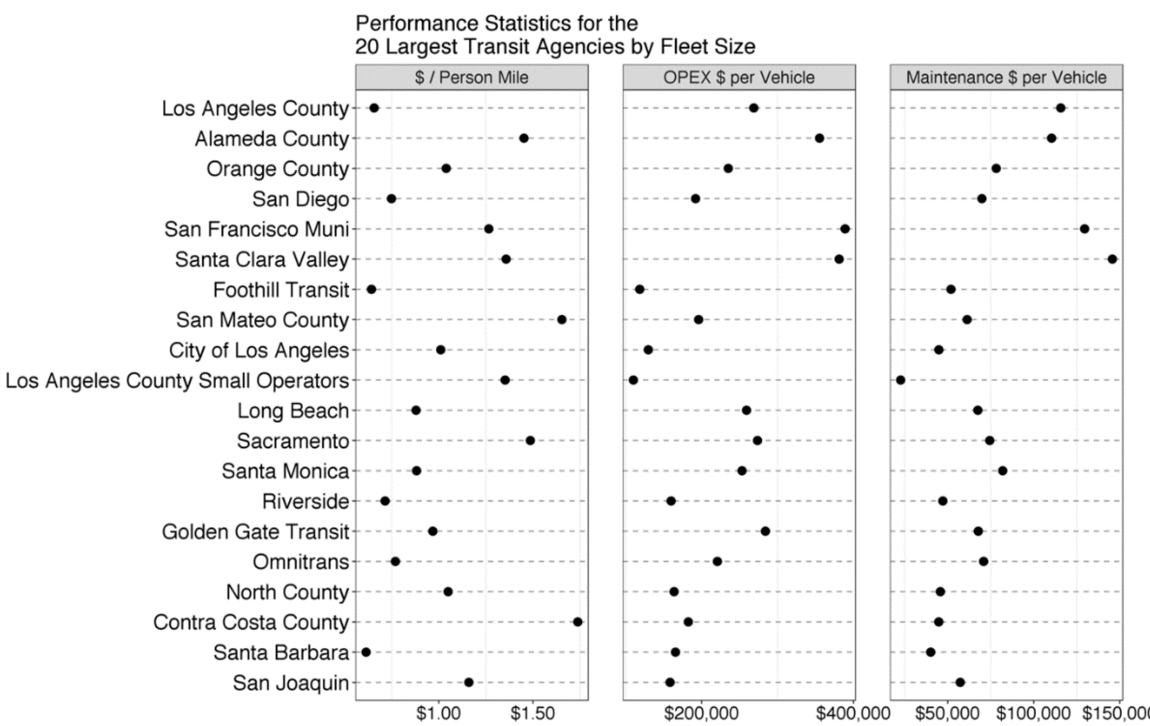
[11] Proterra Model BE-35, See L. Eudy, R. Prohaska, K. Kelly, M. Post, "Foothill Transit Battery Electric Bus Demonstration Results," National Renewable Energy Laboratory (NREL), Golden, CO, 2016.

The study found that decreases to scheduled maintenance repair and maintenance costs offset the increases in unscheduled maintenance issues and additional labor hours. But the net 10% per-mile cost reduction does not include potentially significant cost considerations resulting from these reliability issues. These could range from providing roadside assistance or compensating passengers due to drained batteries, to the need to purchase additional reserve buses to compensate for limited bus range. These issues were not addressed by the study.

The Federal Transit Administration (FTA) National Transit Database (NTD) contains extensive data on a wide array of operational attributes of transit agencies.

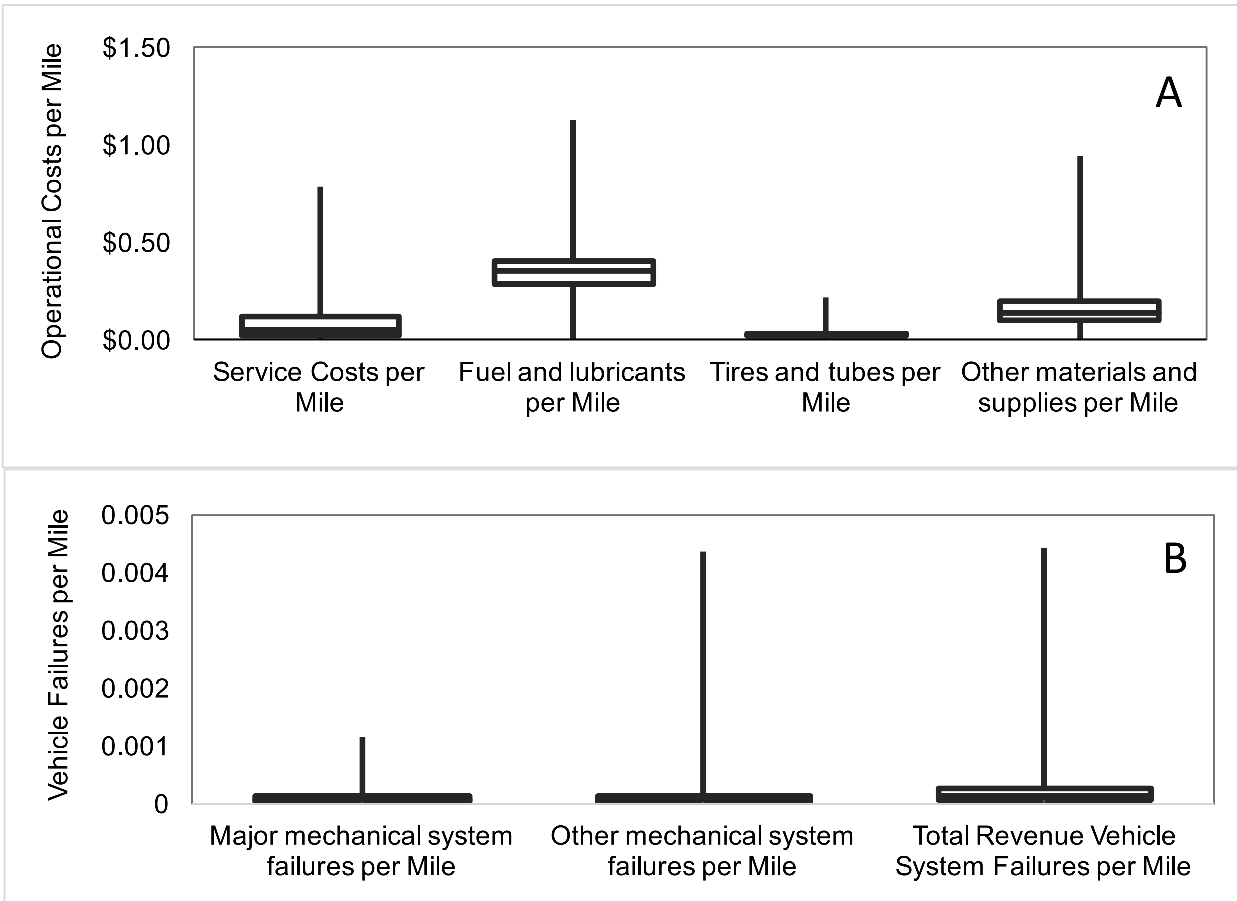
Figure 8 Illustrates the heterogeneity among the 20 largest transit agencies in California in terms of vehicle operating expenses, maintenance costs, and per passenger costs. The variability in costs reflects the diversity of operating structures, conditions, and systems experienced by agencies.

Figure 8 Financial Service and Maintenance Statistics for the 20 Largest Agencies by Bus Fleet



NTD 2014 database tables were used to inform maintenance cost analysis, collision probabilities, and the distribution of bus age by powertrain type. 2014 NTD maintenance data for per-mile maintenance cost, including mechanical failures, was cross-referenced with estimates from other sources. Because many transit fleets have heterogeneous fleets in terms of powertrain type and bus size, weighting is required to estimate operating costs and service mileage by fuel type from the NTD. For any given fleet, if more than 80% of agency fuel costs came from a single fuel type (on an energy equivalent basis), maintenance cost observations for that fleet were assigned to that fuel type. Figure 10a shows the aggregate distribution of per-mile expenses for diesel, diesel-hybrid, and CNG active transit buses in California. Historically, per-mile maintenance costs often exceed fuel costs for conventional diesel buses. Figure 10b shows that per-mile maintenance related vehicle failures have very low occurrence for transit buses on average, which suggests that a small portion of the fleet is likely to experience a majority of issues. The highly-skewed distribution of per-mile maintenance costs also suggests that average maintenance costs may be inflated by a small number of vehicles with significantly higher-than-average occurrence of high cost maintenance events.

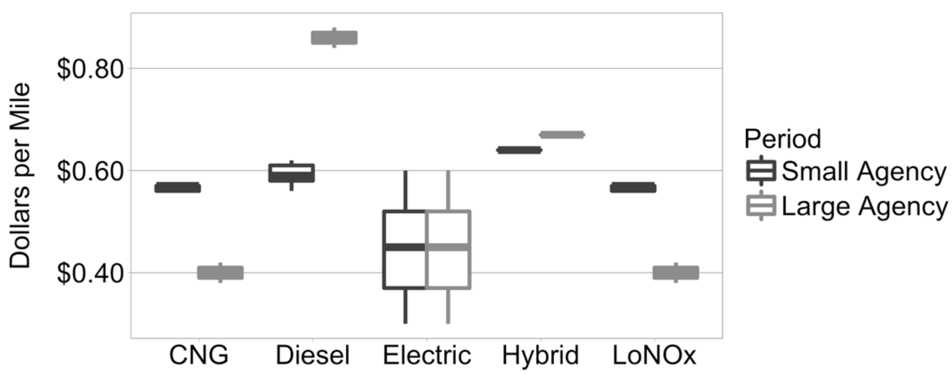
Figure 9 Distribution of Expenses per Mile and Failure Type per Mile in 2014 NTD



A: service costs per-mile for all vehicle types in the NTD, and B: occurrences of mechanical failure during service.

This study assumes maintenance costs to be constant for each powertrain type. Table 2 shows the assumed range of per-mile maintenance costs by fuel type estimated from the NTD. E-bus maintenance costs are estimated based on reporting to the ARB, the study by Eudy et al. (2014), and data provided by LACMTA. Per mile maintenance costs for the LoNOx scenario assumes the same per-mile maintenance costs of CNG. Future maintenance costs of E-buses are highly uncertain; past transitions and pilot studies suggest that initial deployment may involve increased maintenance costs and unscheduled vehicle outages. Over the long run, E-buses are expected to deliver lower per-mile maintenance costs compared to conventional vehicles because of simplified powertrains and service schedules. However, decreasing maintenance costs may be attributable to improved operational systems and best practices, knowledge that may be slow to spread between firms. System improvements may also be predicated on significant capital investments or be restricted by existing agreements (i.e. new maintenance facilities or union contracts). As there is little data to reliably estimate the potential decrease in maintenance costs for E-buses, the study adopts the conservative assumption that there are no improvements to maintenance costs between the study periods.

Figure 10 Maintenance Costs per Mile



Midlife Overhauls

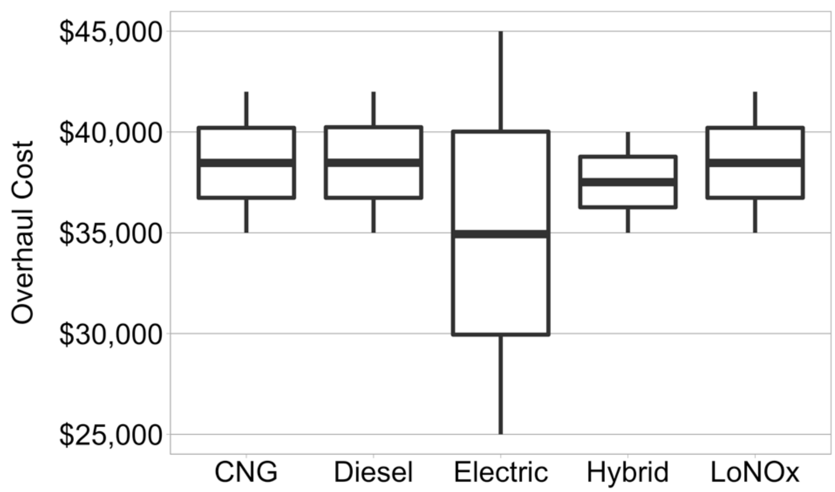
Midlife overhaul is a special kind of maintenance operation that has a high fixed cost and occurs at a dependable interval for many buses. It is also a key potential cost difference for electric buses, as the midlife may be a point for replacement of the traction batteries depending on current performance. Mid-life bus overhauls can cost between $35,000 and $65,000 dollars depending on the vehicle design, powertrain, and fuel system according to data reported to APTA. Battery replacement for a ~250 kWh battery is expected to be $50,000 to $75,000 based on target price of $200-$300 per kWh, making battery systems a significant portion of E-bus purchase costs and the largest cost of a mid-life overhaul if they require replacement.

One E-bus manufacturer, BYD, offers a 12 year warranty to 80% of the original capacity on their battery, suggesting that there would be no additional liability for battery replacement at midlife. For other E-buses, the used batteries could be sold for second-life applications, leading to a resale value and mitigating some of the replacement cost. Alternatively, used batteries could be used in stationary applications for strategic timing of electricity storage and charging and by the transit agency itself.

Many agencies do not conduct midlife overhauls for the entire fleet, instead focusing on only required maintenance schedules and other proactive activities including sample tear downs and inspections. While midlife overhauls are assumed to occur in this study, this reflects the conservative outlook of agencies that must prepare for a worst-case scenario of fleetwide midlife rebuilds.

This study assumes midlife overhauls occur for 95% of vehicles by the 7th year of service, with a small probability that some vehicles retire at 12 years of service with no overhaul; Figure 11 shows the assumed costs for each of the pathways. While this likely represents a much higher probability of midlife overhauls than agencies could require, it also represents a risk averse view of potential funding for midlife overhaul costs. Midlife overhaul costs are assumed to be 5% higher for $LoNO_X$ compared to conventional CNG engines, with a correlated 30% increase in the standard deviation of expected prices. E-bus midlife overhaul costs are expected to decrease significantly due to both declining battery prices and improvements to battery cycle life (i.e. fewer mid-life battery replacements).

Figure 11 Midlife Overhaul Cost Assumptions



Depot and Infrastructure Costs

Infrastructure costs can be a significant driver of the overall costs of bus fleet operations over the long term. Infrastructure costs include construction of depots, maintenance, and refueling systems, as well as operations and maintenance of those assets. There are some examples of recent construction projects to draw on. The Los Angeles Metropolitan Transportation Authority, the largest agency in the state, opened its newest depot in 2014; a garage depot with maintenance, cleaning, and refueling infrastructure capacity for 200 buses. The construction cost was reported to be $95 million dollars which is equivalent to about $85,000 per bus in parking and storage costs per year[12].

[12] When the costs are amortized over the average number of buses that might occupy each unit of capacity over the life of the depot.

A smaller operator, Antelope Valley Transit, is in the process of converting their fleet with 85 all-electric BYD buses and a depot upgrade. Costs for construction and upgrades to onsite electrical infrastructure were almost $6 million dollars, which included the construction of an onsite 1.5 MW diesel generator. The agency has plans to purchase renewable diesel to maintain the 77,000 gallon backup tank. While operations and maintenance costs for E-bus chargers might be very low, back-up electricity systems could pose extra costs.

The costs of additional electric charging infrastructure are likely to vary by depot due to a number of factors, including existing utility connections, facility age, and location. Recent filings at the California Public Utility Commission, including proposed rate cases for southern California utilities, suggest that interconnection costs may by significantly lower than these projections. In addition, BYD, one of the largest E-bus suppliers, provides depot chargers at no cost with purchased buses. Conversely, the selective use of on-route charging could significantly increase capital costs for agencies, as on-route charging systems currently cost as much as 10 times comparable depot systems. The study assumes all buses rely on depot charging in both purchase periods.

Yet another complicating factor for agency investments is the timing of previous capital investments in fuel infrastructure and vehicles. Several transit agencies in the South Coast Air Basin began transitioning to CNG fleets in response to the 2000 CARB Fleet Rule for Public Transit Agencies, which required that agencies either purchase advanced technology vehicles or switch to an alternative fuel in order to meet a 2007 engine model year standard for transit fleet emissions. The alternative fuel path required agencies to have 85% of bus purchases be diesel alternatives by 2009 or meet the 0.1 g/bhp-hr NO_X standard, essentially requiring extensive investment in CNG infrastructure. Some agencies are concerned that investments in fuel infrastructure, including CNG stations and storage, could become stranded before their scheduled depreciation. While diesel agencies tend to manage their own fuel systems, CNG fleets have options for third party CNG fueling station contracts. LA Metro, among others, has adopted this approach; in these cases, there is minimal ownership of CNG refueling systems and therefore no sunk-cost infrastructure investments.

Depot expansion costs are difficult to predict precisely, and do not necessarily scale with small changes in bus capacity. For instance, agency bus fleets can vary by 15% or more over five year periods without change to depot infrastructure. Attributing specific depot expansion to E-bus purchases is also highly uncertain. As agencies increase the share of their fleet running on electricity, it may become possible to explore additional economies of scale, including reducing the number of additional charger purchases per bus acquired. Further assessment is necessary to evaluate the costs of depot improvements or expansions for different agencies. This would include an evaluation of parking/service capacity, egress and right of ways, building electrical systems, and level of utility interconnection. This ranking process would also inform route prioritization and long-term planning.

In this study, infrastructure costs are amortized over their capacity and service life through the use of a capital recovery factor. Figure 12 shows the amortization of depot retrofits based on the agency type. Capital recovery factors for electric and conventional depot infrastructure are based on a 40 year and 50 year life respectively, with fixed costs identified based on reported depot capacity and operating structure in NTD. Depot upgrade costs are assumed to range from $2 to $7 million dollars. Average depot capacity and occupancy was used to identify likely quadrants for depot costs (only a portion of the table is shown for larger agencies).

Figure 12 Depot Capital Amortization

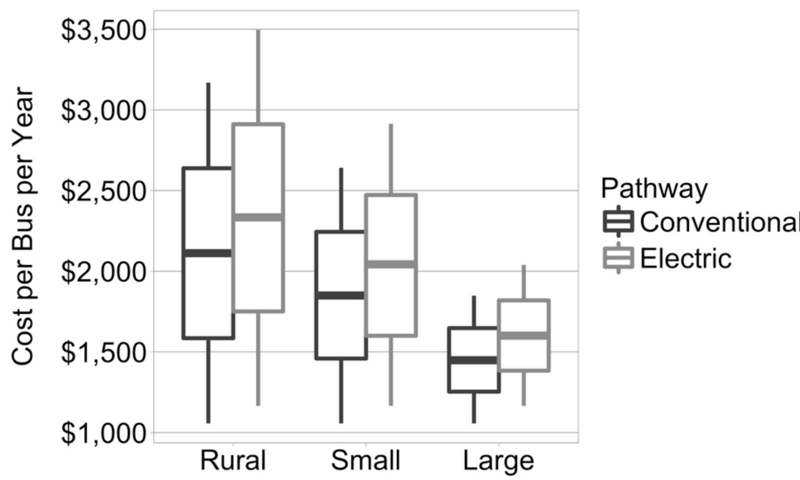


Table 4 shows the average buses per depot for California transit agencies, which were used to estimate depot upgrade costs for agencies. Despite the presence of a number of depots reported with 200 and 300 bus capacity by some mid-sized agencies, the average number of active buses per depot facility is usually low. Comparing with Table 2, we see the large differences between the expected per bus costs of depot retrofits, which are not expected to scale linearly with depot capacity. For this reason, we assume a conservative minimum cost of $2 million dollars per depot.

Table 2 Average Active Buses per Depot for California Agencies

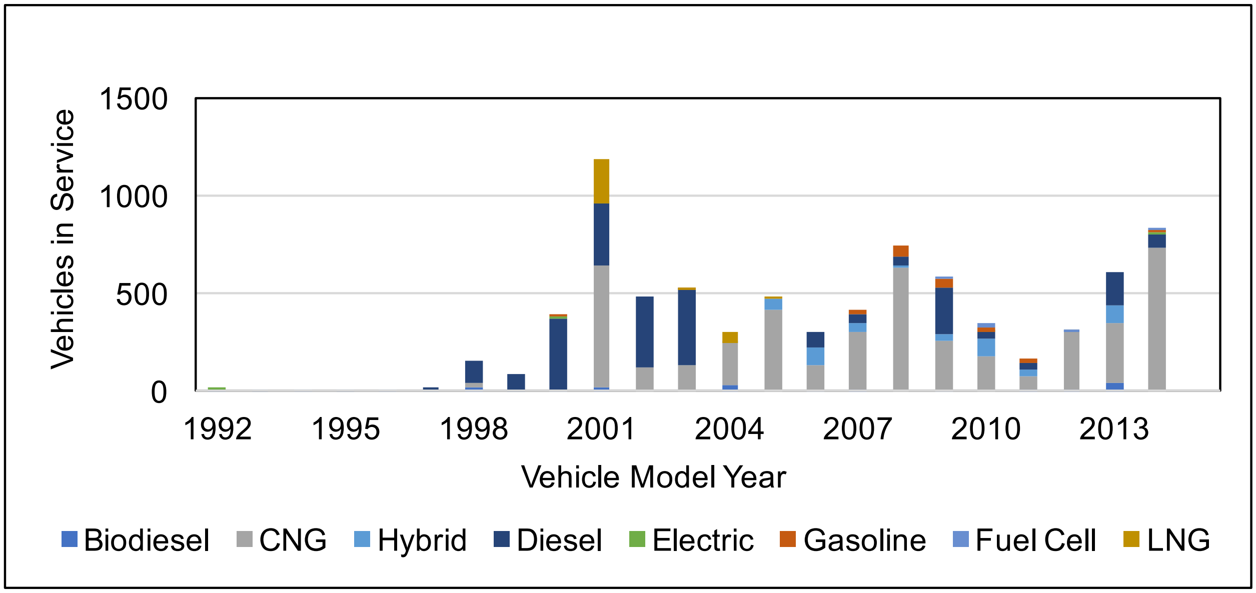
	Excluding Rural	With Rural Agencies	> 75 Buses/Depot Average	< 25 Buses/Depot Average
Mean	**38**	**28**	**112**	***8***
Median	25	14		
Max	175	175		
Min	2	1		
St Dev	37.8	34.8		
Total Buses	**8016**	**8285**	**5087**	**928**
Agency Count	**89**	**128**	**13**	**80**

Vehicle Life

While the service life of some buses exceeds or falls short of the average expected lifetime, the majority of transit buses in the state are replaced based on a set schedule dictated by funding. The largest of these programs for California agencies are the FTA Urbanized Area Formula Program (5307) and Bus Facilities (5339), as well as FTA Capital Program (5309) and State of Good Repair (5337), which have requirements for the minimum service life of capital assets. Buses are generally required to meet a minimum service life of 12 years, but many agencies keep their vehicles for 14 years to minimize their lifetime costs of ownership on a per-mile basis. A countervailing factor is that agencies are motivated to take advantage of replacement funds when they become available. Because of these constraints, we do not assess potential differences in vehicle life across powertrain technologies as it is assumed all vehicles are designed to meet these requirements.

Figure 13 shows the age distribution for active transit buses in the state from the 2015 reporting to APTA, which shows a sharp decline in active buses after 14 years of service in 2001.

Figure 13 Age Distribution for Active Transit Buses in 2014



In this study, the distribution of average vehicle lifetimes is assumed to be governed by two key factors: one, each agency's decisions on how long to keep buses after they are eligible for replacement; and two, the random chance that buses fail due to accident or mechanical issue prior to their expected retirement. The probability of serious mechanical failure is simulated based on early retirement and accident data from NTD. The resulting distribution of vehicle lifetimes is assumed to be constant in both purchase periods for all powertrains. $LoNO_X$ CNG engines are assumed to have the same probability of failure and vehicle lifetime as conventional CNG buses, as the service lifetime is driven primarily by funding requirements.

Technology Performance

Technology performance, in particular range and downtime, may affect the number of vehicles required by an agency. Because E-buses have shorter ranges and longer fueling times than CNG, diesel and hybrid buses, E-bus adoption may require a larger fleet.

Range

Agencies may require additional buses if the effective range a bus can travel per charge is insufficient to meet the distance required by the duty cycle. The number of additional buses that must be purchased depends on the route structure, the vehicle range per charge, and the charging system. Examining routes for the 20 largest agencies, we conclude that roughly 9% more bus purchases may be required if the fleet is fully electrified by 2030; that number drops to 8% or 4% if the target year is 2034 or 2040, respectively.

However, this estimate assumes no alternatives to depot charging. Depending on the route structure, on-route charging can decrease the number of additional buses needed by facilitating a longer daily service range. However, on-route charging systems can currently cost more than three times as much as depot charging systems.

On-route charging systems come in multiple varieties. Fast-charging systems can cost as much as $500,000 for a 500 kW system, while smaller 60 to 80 kW systems have been installed at much lower costs. Depot systems are typically $20,000 to $60,000 per charger for 20 to 80 kW.[13] The costs of additional buses and charging systems and the route-specific logistics of charging would need to be evaluated in more detail to determine whether on-route or depot charging is more cost-effective for specific agencies.

The real-world deployments of E-buses in California can provide some insights on the technology performance factors that affect fleet size requirements. Antelope Valley Transit, which recently transitioned their entire fleet to electric, has been experiencing high variance in effective range across drivers (from 120 miles to 220 miles for the same vehicle). But, this also indicates that current market E-bus technology is capable of delivering nearly 220 miles of effective service in some cases on ~300kWh batteries. Proterra is currently marketing a new E2 series with a proposed capacity up to 660kWh. While no E2 buses are currently in service, expected improvements to battery capacity and performance suggest that longer range E-buses will be available in the near term.

Replacement Rate

Replacement rate is a difficult performance metric to generalize across agencies because of the diversity of design solutions agencies might adopt. In addition, replacement rate is also a function of both effective range and bus daily travel distance, both of which are correlated with the route structure. In most cases, transit agencies do not assign specific buses to specific routes, and in some, rotate buses between domicile depots for maintenance purposes. This makes it increasingly difficult to estimate the number of buses that will be required for agencies to replace their existing active and spare flees.

[13] For further discussion of charging system costs, see the ACT working group discussion documents or data assumptions at https://www.arb.ca.gov/msprog/bus/actmeetings.htm.

Figure 14 Electric Bus Replacement Rate Assumption for Large Agencies

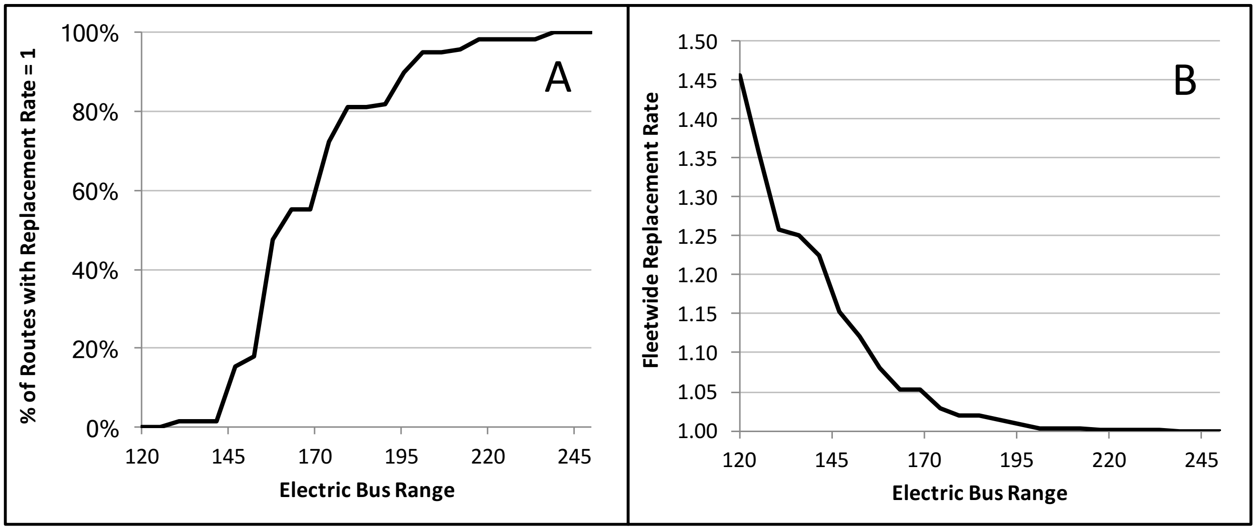
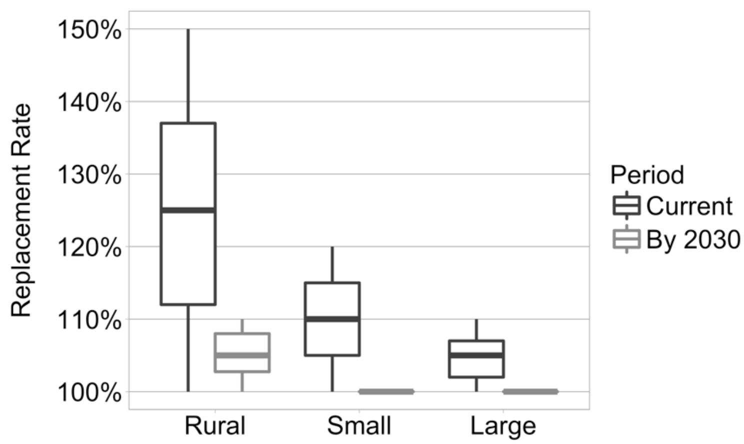


Figure 13a illustrates the relationship between E-bus range and the percent of routes that can be replaced with E-buses on a 1:1 basis. Figure 13b illustrates how that relationship translates into fleet-wide replacement rates. Once E-buses reach a range of 245 miles, replacement rates settle at one. In the most conservative case, every bus in the fleet must be available to meet any random series of assignments at an agency. A series of assignments represents some number of trips (>1), for all or a portion of a given route, over a given service day. Based on these assignments, we can quantify the distribution of daily effective range required by buses at agencies. Electric buses, particularly in the near term, cannot always meet daily range requirements. Over the course of a year, these mismatches result in electric buses realizing fewer miles, which in turn increases per-mile costs over the lifetime of the vehicle.

In this study, replacement rate is estimated for each class of agency based on their current service patterns. The E-bus effective range constraint in the current replacement period is assumed to be 120 miles per charge. This represents a conservative view on the reliable range delivered by buses currently in operation or being delivered. For the second replacement period, effective range is assumed to improve to 220 miles. This translates to a ~73% reduction in average daily mileage mismatch, but varies between agencies. Figure 14 shows the shows the replacement ratios assumed for each agency type by period.

Figure 15 Replacement Rates by Agency and Period



Vehicle Fuel Efficiency

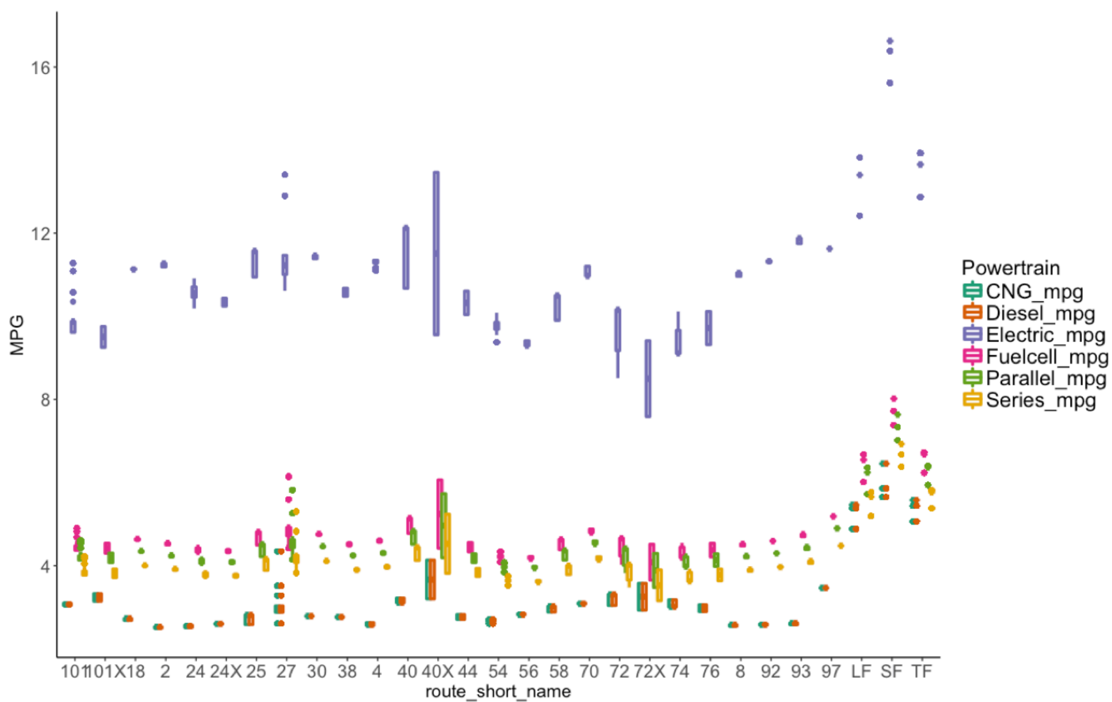
Variability in fuel efficiency is an important consideration when comparing transit buses, as the variability across powertrains can directly translate to fuel savings. Fuel economy can also be variable across agency routes and schedules. The duty cycle variability represents the combined and interacting effects of powertrain, route, traffic conditions, operator, and other environmental factors. Numerous studies have pointed to the strong correlation between operating conditions and average efficiency of transit buses. Because transit bus efficiency is so low, small improvements in fuel economy can translate to substantial savings. A five percent fuel economy improvement can produce savings of $25,000 to $50,000 dollars over the life of a bus (approximately 500,000 miles). Transit bus fuel economy can vary by as much as 2-3 times across combinations of duty cycles.

Vehicle fuel consumption is often modelled as a function of the forces acting on the vehicle, otherwise known as road load. Excepting for auxiliary energy demands, the energy required to power a vehicle can be attributed to the need to overcome primary physical forces including inertia, aerodynamic resistance, friction at the wheels, and internal friction (e.g. transmission). Aerodynamic resistance is a significant driver of fuel consumption at higher speeds. Acceleration forces, which urban transit buses experience more often, have high power demands and translate to energy fuel consumption differences depending on powertrain. Both speed and acceleration are important for estimating fuel consumption for a given duty cycle.

The specific fuel consumption (SFC) represents the average vehicle energy demands per unit mass and distance travelled. SFC is a function of aerodynamic resistance, rolling resistance, average speed, acceleration, powertrain efficiency, auxiliary loads, and vehicle mass. Aerodynamic resistance is a function of air density, the frontal area of the vehicle, the mass of the vehicle, and the square of the velocity. Rolling resistance is a function of the vehicle mass and the tires; different tires and tire configurations produce a range of coefficients of rolling resistance. Inertial forces relate to the energy required to accelerate and decelerate the vehicle mass. SFC can be estimated from the road load equations, which are described in more detail in Appendix 1.

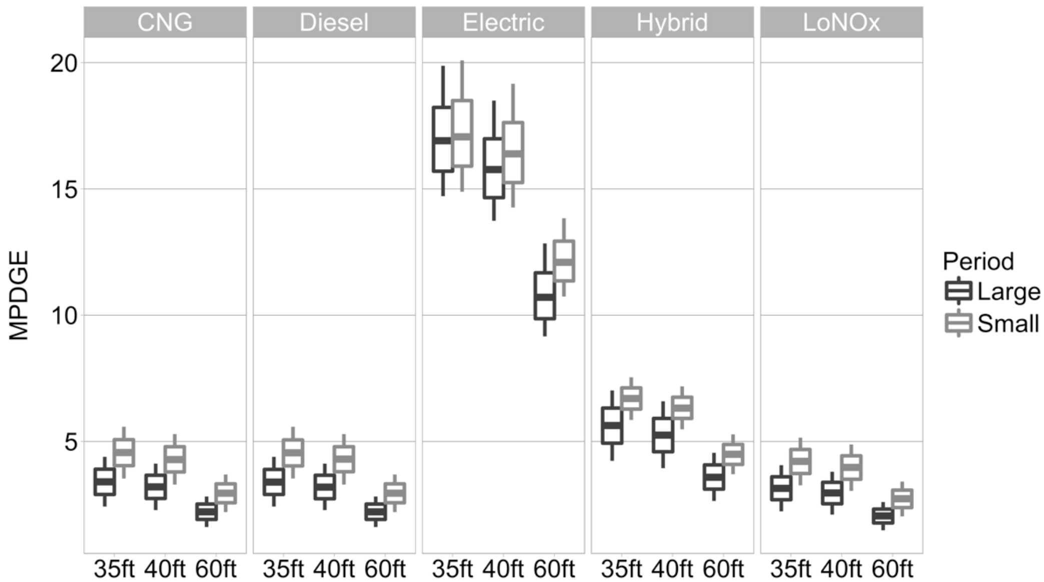
In this study, we estimate vehicle fuel economy across a series of powertrains using route schedule information and data from Google Maps. Sixty-seven agencies were considered and route fuel economy projected based on average speed, stop density, and trip length. The average distribution of fuel economies was used, with subsets estimated for smaller and larger agencies by bus fleet size. Figure 16 is an example of the fuel economy modelling for routes operated by Golden Gate Transit. Further discussion of the route fuel economy modelling is included in the appendix.

Figure 16 Vehicle Fuel Economy Example



The average fuel economy by bus length and agency type is depicted in Figure 17. Due to a lack of grade data which significantly affects the fuel requirements on many rural routes, no reliable estimates were available for fuel economy for rural agencies.

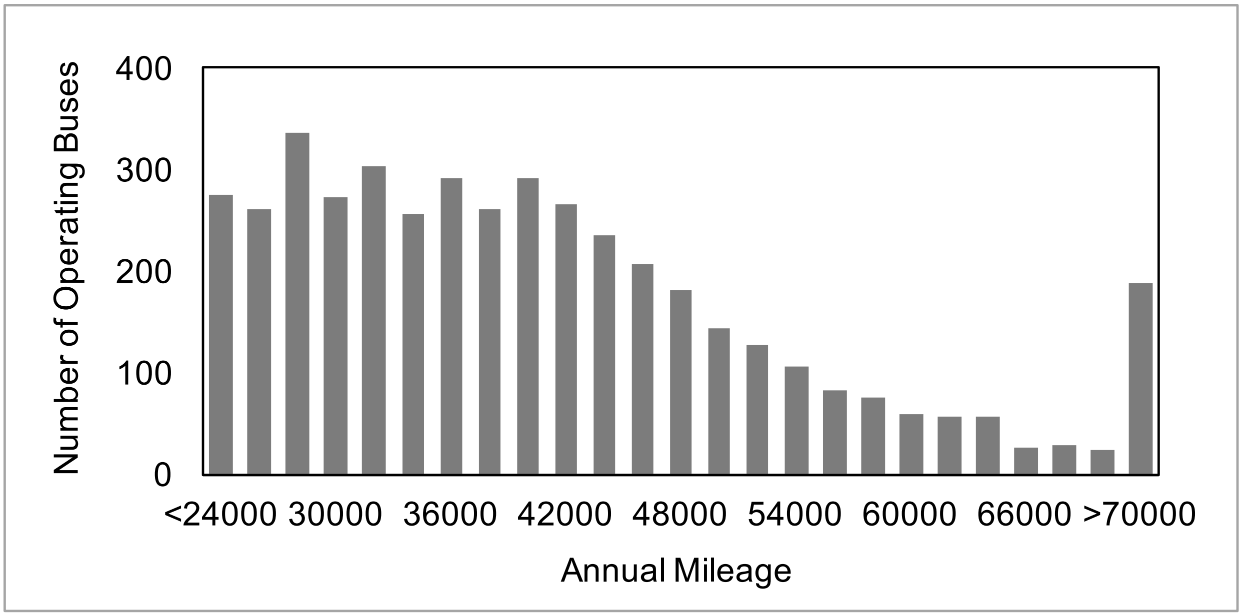
Figure 17 Average Fuel Economy by Agency, Fuel, and Length



Annual Mileage

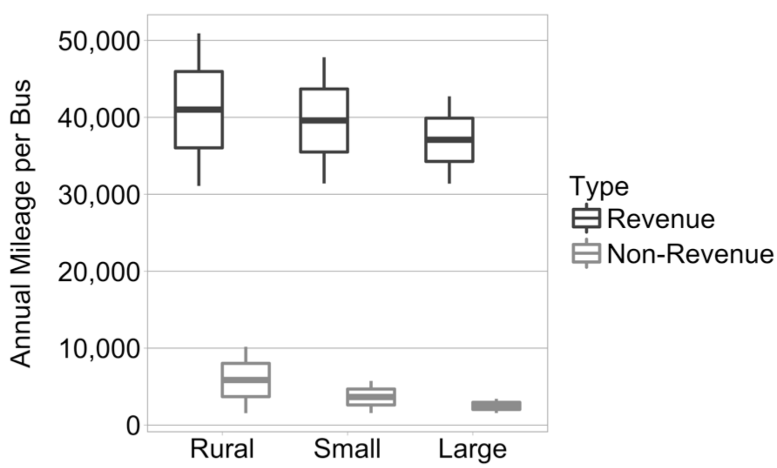
While transit buses on average experience approximately 40,000 miles per year, the actual annual mileage can vary strongly by agency. In general, agencies do not assign buses to specific routes or even tours; but agencies do have buses that generally operate on a set of routes or domicile in certain depots. Low average speed routes generate fewer miles travelled for the equivalent service hours. While there is little resolution at the top and bottom end of annual mileage (Figure 18**Error! Reference source not found.**), we can observe a longer tail in the buses experiencing higher-than-average mileage. While average mileage variation is very high, variation in lifetime mileage is expected to be far lower for each agency. Over the course of the bus lifetime, transit agencies are also incentivized to even out the mileage of buses to ensure maximum utilization of the asset.

Figure 18 Annual Mileage Distribution of Active 40ft Buses



In this study, buses are assumed to average between 440,000 to 590,000 revenue service miles over their life, which translates to 36,000 and 42,000 miles per year. To estimate the range mismatch of electric buses (e.g. replacement rate), daily estimated travel mileage was used. Daily travel mileage has much higher variance than annual travel mileage; to improve estimates, both revenue and non-revenue annual miles are estimated for each agency class (Figure 19). Annual mileage is assumed to be constant across the two periods.

Figure 19 Annual Revenue and Non-Revenue Mileage Assumptions



Externalities and Damages

Air quality effects and changes in service quality are also important outcomes for the communities served by transit agencies in the State; these effects might be considered alongside financial considerations or they may be integrated into an economic assessment by estimating their value. Environmental damages may have significant economic value, but are difficult to assess and there is still high methodological uncertainty. But there are many types of externalities of electrification that may prove beneficial, but difficult to quantify in this attributional cost assessment.

Many studies have pointed to the potentially significant health costs of emissions from large buses in urban areas. Tong et al. (2017) found that climate and are pollution damages for transit buses could range from $60,000 to $120,000 over the service lifetime (Tong, Hendrickson, Biehler, Jaramillo, & Seki, 2017). While health costs are not considered directly in this study, decreased or eliminated mobile source emissions from bus electrification are likely to offer additional benefits for transit agencies and urban centers. This is especially true in California, which has a high share of renewable generation in the electricity grid.

In addition to emissions, e-buses likely have other difficult to price benefits. Based on Altoona testing, electric buses are quieter for passengers, operators, and pedestrians, which reduces noise pollution.[14] Electric buses can be 6-9 decibels quieter than average CNG buses, and 12-17 dBA quieter than diesel. In addition, electric powertrains do not require a clutch or other transmission which can reduce driver fatigue. Decreased vehicle noise also creates a better environment for passengers and operators.

For the purpose of this study, the direct and indirect costs of environmental damages and social impacts are not considered. In the discussion section, we allude to some of the research needed to better internalize societal costs into purchase decisions and pricing.

[14] See Pennsylvania Transportation Institute and Bus Testing and Research Center. (2015). New Flyer, Model XE40, University Park: Pennsylvania State University. **LTI-BT-R1405**. And, Pennsylvania Transportation Institute and Bus Testing and Research Center. (2015). Proterra, Inc. Model BE-40, University Park: Pennsylvania State University. **LTI-BT-R1406**.

Summary of Cost Drivers

- The purchase price of an E-bus is 40%-60% *higher* than a conventional bus, and some agencies must acquire more depot or maintenance yard capacity for bus electrification. This significantly increases capital costs, necessitating a shift in the quantity and source of income for agencies.
- Currently, federal sources provide a majority of capital funding for bus projects; however, the formula for calculating the capital cost subsidy is not cost reflective, and federal funding may not match increasing investment.
- Operating costs currently comprise 75% of annual expenditures, and fuel costs are a key contributor. Electricity costs can be highly variable over time and space, and a utility's contractual terms may change during the life of the bus. Given current prices, only with credit incentives through the Low Carbon Fuel Standard (LCFS) can an agency anticipate significant reductions in fuel operating costs.
- Variable maintenance costs for electric buses can be 50% *lower* per-mile thanks to simplified propulsion system, but maintenance costs at transit agencies show strong heterogeneity; not all agencies will experience the same magnitude in maintenance costs reductions from electrification
- Depot expansion costs are a significant investment for agencies but vary strongly by depot characteristics; amortized over the life of the vehicle, can represent $15,000-$40,000 in real additional costs.
- Vehicle fuel efficiency varies across agencies operating areas and route characteristics, but system planning on vehicle purchase are currently separate decision-making operations
- The costs of purchase and operation for conventional transit bus pathways, including Diesel and CNG, are expected to increase significantly over the next decade.
- E-bus effective range is increasingly rapidly, but technology performance mismatch when replacing conventional vehicles remains an issue

Limitations of the Unit Cost Approach

Uncertainty in comparing alternatives stems from multiple sources, including the parameter uncertainty and variability discussed in the previous section. An additional confounding factor for policy analysis could be described as decision uncertainty. There are two model frameworks traditionally adopted for comparing purchase alternatives in the context of fleet replacement. The first, a unit replacement model, is often used to compare the total cost of ownership across several purchase alternatives. The unit replacement model focuses on costs related to the acquisition, maintenance, and operation of an asset over its useful life. For example: does alternative A cost more than alternative B? The second, a systems operations model, looks at the total costs of a handful of state decisions over the course of some defined decision space. And an equivalent question, what is the cost of operating a given system over some time x given alternative A vs. alternative B. Analysis of unit or system costs can provide contrasting conclusions and support different decision making outcomes.

A potential key difference between unit and systems cost approaches is the endogeneity of labor costs. An agency system cost model could include an explicit ledger of positions and salaries for operations and overhead management. Due to the heterogeneity of agency operating structures, areas, and service requirements, a generalized agency system cost function is difficult to estimate. Even estimating individual agency operational labor costs requires assumptions about the route network and schedule, which could ignore the opportunity for optimization of system planning and technology deployment.

While it is possible to incorporate additional labor costs into unit cost comparisons, scaling of unit costs up to the system level is likely to provide only a coarse estimate of actual system costs. This can easily be illustrated by the fact that mean vehicle costs often do a poor job of representing the real costs experienced by each agency. Whether looking at system *or* unit costs, decision making is improved by an understanding of how a lack of knowledge about the future and variability in assumptions contribute to uncertainty when comparing technology alternatives.

This study focuses on uncertainty in comparing unit costs for agencies. Some agency system costs are considered by way of infrastructure investment and route structures, but the study does not directly consider labor costs for operations, including drivers, which can be a key component of per-mile system cost.

Results

Based on the range of prices transit agencies have been experiencing, current replacements of CNG, Diesel, or Hybrid transit bus cost between $1,009,283 and $1,663,309 on average to own and operate over the lifetime of the vehicle (Table 3). The cost of an electric bus ranges from $1,457,594 for a 35 ft bus, to $2,243,745 for a 60 ft bus. While costs for electric buses are higher on average in the current replacement period compared to $LoNO_X$ and conventional options, they are also eligible for increased incentives which could mitigate the cost differential. In the current period, purchase and fuel incentives decrease Electric TCO by $224,00 to $284,000, compared to $80,000 on average for purchase incentives on $LoNO_X$ options.

Table 3 Total Costs by Fuel-pathway and Length (Current Prices, No Incentives)

	length	***mean***	*sd*	*min*	*max*
CNG	*35ft*	**$1,009,283**	$68,705	$830,996	$1,306,957
	40ft	**$1,031,649**	$70,115	$844,422	$1,272,759
	60ft	**$1,467,920**	$82,703	$1,255,888	$1,796,200
Diesel	*35ft*	**$1,184,842**	$88,692	$948,543	$1,548,364
	40ft	**$1,207,792**	$90,434	$968,066	$1,563,480
	60ft	**$1,663,309**	$112,114	$1,349,373	$2,133,882
Electric	*35ft*	**$1,457,594**	$103,484	$1,124,418	$1,926,870
	40ft	**$1,482,993**	$105,591	$1,172,864	$1,955,112
	60ft	**$2,243,745**	$142,617	$1,837,121	$2,859,840
Hybrid	*35ft*	**$1,255,245**	$75,394	$1,049,107	$1,544,680
	40ft	**$1,281,118**	$76,627	$1,078,655	$1,579,615
	60ft	**$1,629,124**	$89,927	$1,397,001	$1,993,127
LoNOx	*35ft*	**$1,291,721**	$92,078	$1,056,398	$1,602,729
	40ft	**$1,320,942**	$91,622	$1,076,154	$1,635,541
	60ft	**$1,874,295**	$127,055	$1,547,259	$2,291,260

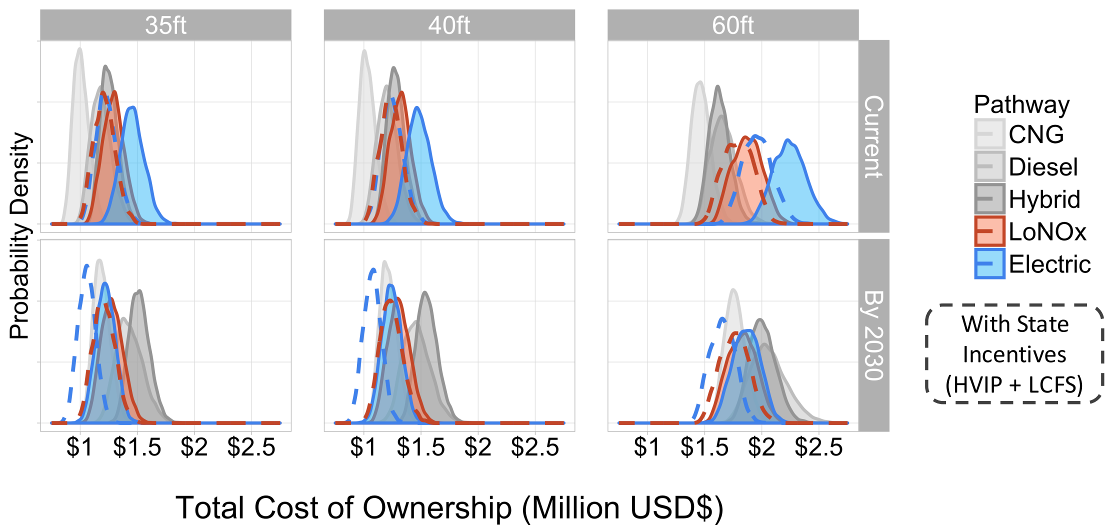
By 2030, the costs of replacing the conventional transit bus fleet is expected to increase; 2030 TCOs for conventional options ranged from $1,190,00 to $2,060,000. The average TCO of an electric bus decreased by 16% on average by 2030, in-line with CNG and $LoNO_X$ options. While the average costs of buses all increase, electric buses are expected to have the lowest lifetime vehicle cost by after 2030. As reported in Table 4, by 2030, purchase and fuel incentives were on average 12% of the electric bus TCO.

Table 4 Total Costs by Fuel-pathway and Length by 2030 (No Incentives)

	length	mean	sd	min	max
CNG	*35ft*	**$1,190,605**	$73,872	$982,589	$1,517,056
	40ft	**$1,216,324**	$74,706	$1,012,306	$1,533,674
	60ft	**$1,767,293**	$91,485	$1,510,232	$2,157,085
Diesel	*35ft*	**$1,433,000**	$116,296	$1,110,427	$1,975,647
	40ft	**$1,463,584**	$120,193	$1,113,982	$2,050,889
	60ft	**$2,060,027**	$159,178	$1,575,978	$2,753,648
Electric	*35ft*	**$1,222,590**	$84,708	$935,251	$1,548,293
	40ft	**$1,243,567**	$85,936	$945,470	$1,596,988
	60ft	**$1,864,846**	$119,013	$1,495,618	$2,319,163
Hybrid	*35ft*	**$1,518,651**	$90,247	$1,262,949	$1,918,517
	40ft	**$1,553,500**	$92,826	$1,266,178	$1,948,299
	60ft	**$2,007,075**	$115,926	$1,653,252	$2,530,584
LoNOx	*35ft*	**$1,279,258**	$94,312	$984,840	$1,616,734
	40ft	**$1,308,181**	$95,588	$1,045,794	$1,670,869
	60ft	**$1,829,271**	$125,366	$1,494,942	$2,275,287

Looking at the distribution of likely cost outcomes in Figure 20, we observe the difficulty of reliably distinguishing the difference between powertrain or pathway costs. In both purchase periods, the differences between average costs may not fully characterize the experience of any agency, as evidenced by the large overlapping probability densities. We can also observe the strong delta caused by policy subsidies; in the current replacement period, HVIP and LCFS rebates over the vehicle life are worth ~$250,000 dollars, with a slight majority coming from fuel subsidies. By 2030, purchase subsidies are expected to decrease but fuel subsidies increase as electric buses realize more annual miles due to improving range.

Figure 20 Lifetime Costs of Ownership per Bus



The current average per-mile cost of conventional transit bus operations is $1.82 to $3.01 per-mile (Table 5). Electric transit buses in the current replacement period had an average per-mile cost of $2.62 - $4.04, 18-20% higher than the comparable CNG bus. In the second replacement period (Table 6), the per-mile cost differential between CNG and Electric has decreased to less than 3%.

Table 5 Per Mile Costs by Pathway and Length (Current Prices, No Incentives)

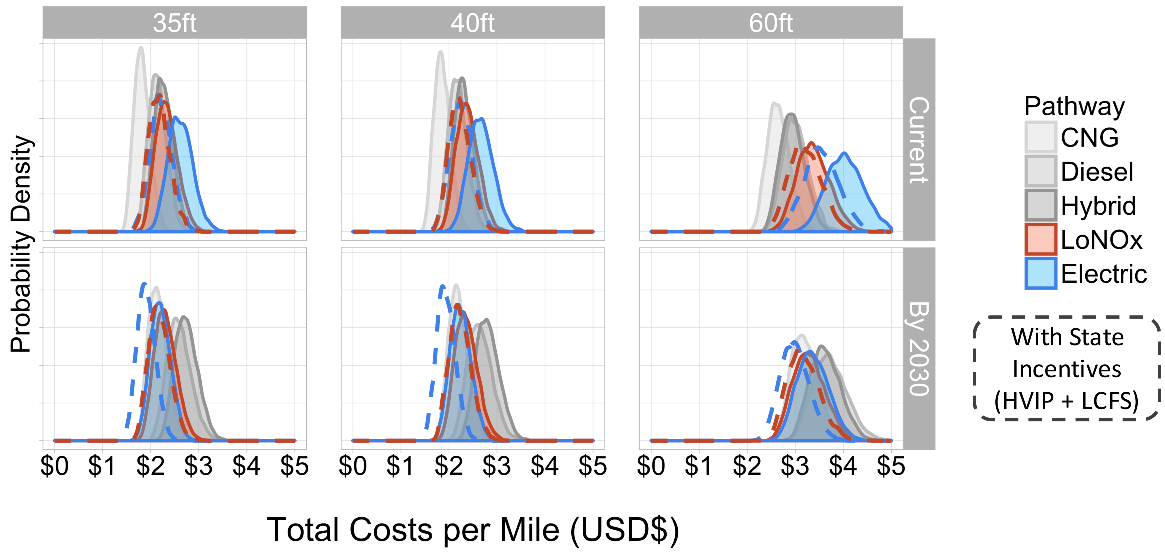
	length	***mean***	*sd*	*min*	*max*
CNG	*35ft*	**$1.82**	$0.16	$1.38	$2.50
	40ft	**$1.86**	$0.17	$1.42	$2.54
	60ft	**$2.65**	$0.23	$2.05	$3.63
Diesel	*35ft*	**$2.14**	$0.19	$1.68	$2.87
	40ft	**$2.19**	$0.19	$1.69	$2.91
	60ft	**$3.01**	$0.26	$2.33	$3.90
Electric	*35ft*	**$2.62**	$0.25	$1.91	$3.71
	40ft	**$2.67**	$0.26	$1.92	$3.71
	60ft	**$4.04**	$0.39	$2.91	$5.52
Hybrid	*35ft*	**$2.27**	$0.19	$1.78	$2.99
	40ft	**$2.31**	$0.19	$1.79	$3.04
	60ft	**$2.95**	$0.24	$2.28	$3.88
LoNOx	*35ft*	**$2.33**	$0.23	$1.75	$3.40
	40ft	**$2.39**	$0.23	$1.75	$3.44
	60ft	**$3.38**	$0.34	$2.49	$4.53

Table 6 Per Mile Costs by Period and Bus Length by 2030 (No Incentives)

	length	mean	sd	min	max
CNG	*35ft*	**$2.15**	$0.19	$1.65	$2.83
	40ft	**$2.19**	$0.19	$1.67	$2.91
	60ft	**$3.19**	$0.27	$2.46	$4.27
Diesel	*35ft*	**$2.59**	$0.24	$1.86	$3.54
	40ft	**$2.65**	$0.25	$1.92	$3.67
	60ft	**$3.73**	$0.35	$2.72	$5.07
Electric	*35ft*	**$2.21**	$0.21	$1.57	$3.01
	40ft	**$2.24**	$0.21	$1.55	$3.05
	60ft	**$3.37**	$0.33	$2.42	$4.67
Hybrid	*35ft*	**$2.74**	$0.23	$2.10	$3.65
	40ft	**$2.81**	$0.24	$2.09	$3.65
	60ft	**$3.63**	$0.31	$2.67	$4.78
LoNOx	*35ft*	**$2.31**	$0.23	$1.71	$3.24
	40ft	**$2.36**	$0.23	$1.71	$3.24
	60ft	**$3.29**	$0.33	$2.43	$4.57

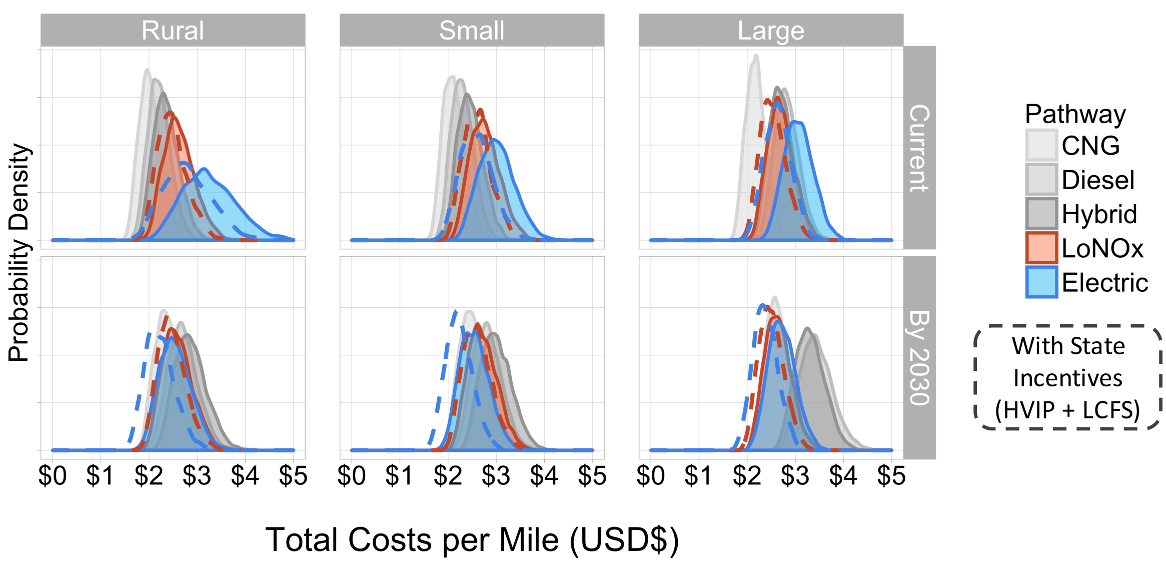
Turning back to the graphical representation, Figure 21 shows the high probability of equivalent per-mile costs from conventional and $LoNO_X$ buses for near-term replacement period. For the second replacement period, costs for replacing any bus with an electric or CNG could have similar per-mile costs over the vehicle lifetime. With state incentives, the costs of E-buses in the next replacement period are lower than CNG or $LoNO_x$ options.

Figure 21 Lifetime Costs of Ownership per Mile



The effects of electric buses range restrictions are more apparent in the near term when looking at lifetime costs of ownership normalized on a per-mile basis by agency. In the left panel of Figure 22, we can observe the wide range of potential costs for electric buses in rural applications, with ~50% higher cost uncertainty compared to large agencies.

Figure 22 Per Mile Costs by Agency and Length



Finally, averaging across bus lengths and agency types, Table shows the average TCO in both the current and 2030 period, as well as the value of incentives. The magnitude and direction of change in E-bus costs relative to conventional options between the first and second purchase period are indicative of both the change in average costs for conventional alternatives and the change in E-bus prices. In the second replacement period, the lifetime costs of E-buses are 16% lower on average. Incentives in the 2030 period are likely to lower the costs of electric buses by an additional 12%. When incentives are included, the $LoNO_X$ pathway is not significantly different than the average price of CNG buses by 2030. In both periods, incentives decrease TCO for $LoNO_X$ by 5% on average.

Table 7 Summary of Average TCO by Pathway and Period

	Current Average TCO	Average TCO 2030
CNG	$1,169,617	$1,391,407
Diesel	$1,351,981	$1,652,203
Hybrid	$1,388,495	$1,693,075
LoNOx	$1,495,652	$1,472,237
Electric	$1,728,110	$1,443,667
LoNOx Incentives	-$80,658	-$68,598
Electric Incentives	-$249,389	-$180,008

System-wide Replacement Costs

If a regulation is adopted that shifts the entire fleet to E-buses over a normal replacement cycle (i.e. no accelerated retirement of existing buses), another important question is how the costs of full fleet replacement differ, given uncertainty in how costs vary across agencies of different characteristics. Table provides an estimate of the costs of replacing the entire fleet for E-buses in both the current and next replacement cycle. This type of analysis ignores the intertemporal cost changes (i.e. exchanging capital for operating costs), but provides a rough estimate for the direction and magnitude of expected changes in replacement costs over the near term.

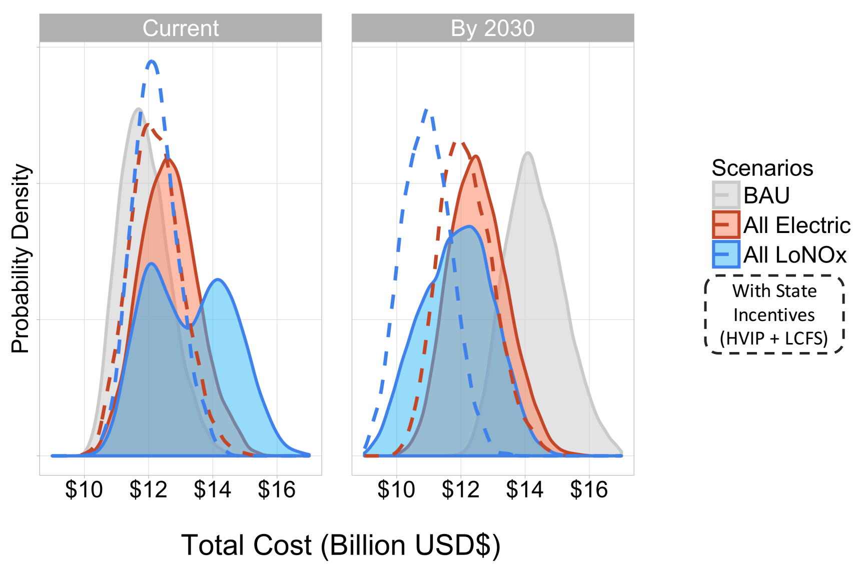
The mean lifetime cost for replacing and operating the current fleet is $7.7 billion dollars (Table). The lifetime cost of replacing the current fleet with 100% electric buses with current prices increases net costs for agencies by $1.24 to $1.28 billion dollars (~17%). Electrification increases total costs by $2.92-$2.97 billion dollars, of which $1.67 to $1.71 billion dollars is offset by HVIP and LCFS subsidies. By 2030, replacing the fleet with 100% electric is estimated to decrease net lifetime costs by $730 to $768 million dollars, with $1.21 to $1.25 in HVIP and LCFS subsidy.

Table 8 Total System Replacement Costs (Billion USD$)

	period	***mean***	*sd*	*min*	*max*
BAU	Current	**$11.87**	$0.77	$10.01	$14.59
	By 2030	**$14.32**	$0.92	$11.79	$17.99
All LoNOx	Current	**$13.03**	$0.80	$10.86	$16.16
	By 2030	**$12.85**	$0.84	$10.50	$15.93
All Electric	Current	**$14.37**	$0.77	$12.11	$17.62
	By 2030	**$12.57**	$0.83	$9.78	$15.56

Figure 23 shows the expected changes in likely system cost outcomes over the next two vehicle replacement cycles. As evident, the likelihood of an all-electric fleet increasing or decreasing costs is not necessarily well-represented by a comparison of average (mean) costs. There is also a significant difference in the total subsidies required to bring costs for E-buses in line with business as usual replacement costs across the two periods. By 2030, both the cost difference between BAU replacement and the value of subsidies offered to E-buses appear to decline significantly.

Figure 23 Statewide Bus Transition Costs



Another important consideration regarding costs of a statewide bus electrification goal is the variability in costs experienced by different agencies. In particular, small and rural agencies have orders of magnitude smaller fleets, operate fewer high density routes (e.g. a higher percentage of low stop density/high speed routes), and smaller reserve fleets compared to urban agencies. For these reasons, they are likely to experience higher fixed infrastructure costs and more problems with accommodating E-bus range and service issues in the near term.

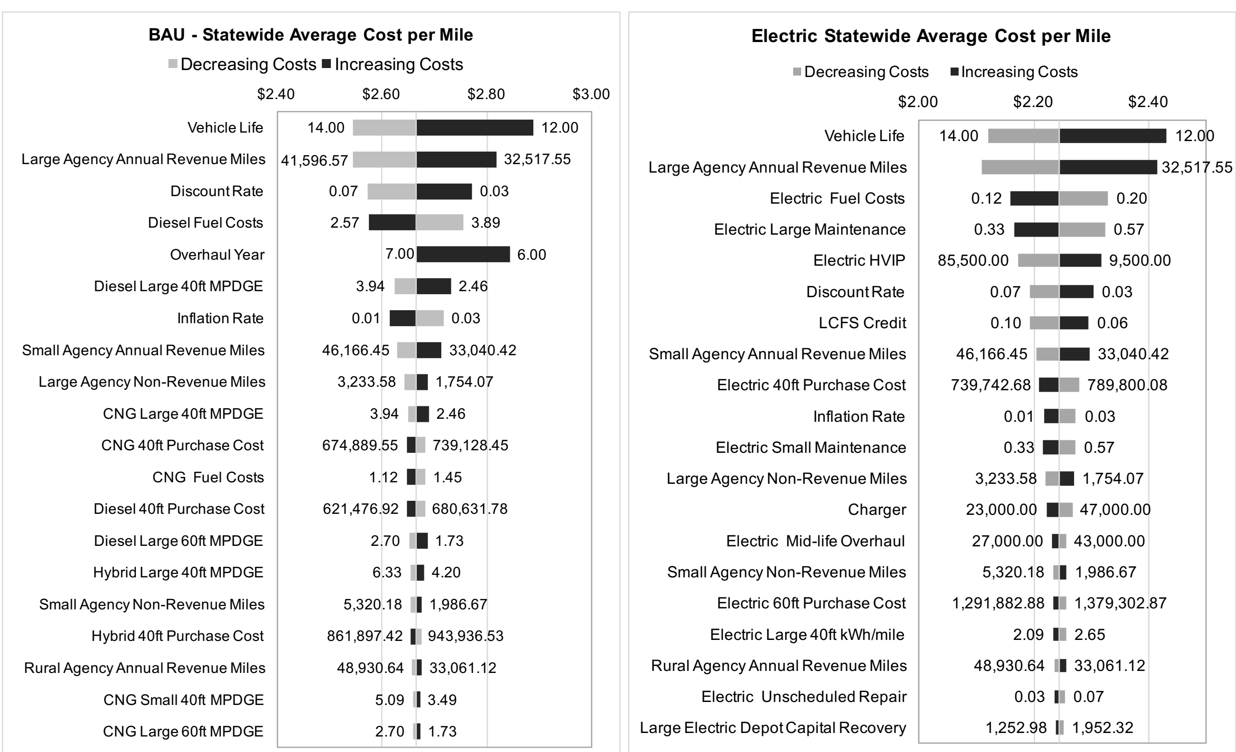
Figure 25 shows how these factors can contribute to differences in TCO for buses. Smaller agencies have higher lifetime ownership costs for transit buses on average, but some smaller agencies are likely to have costs for electric buses 7.5% higher than larger agencies. At the extremes, a small rural agency could experience 75% higher adoption costs compared to the largest urban fleets.

Diesel powertrains are a notable exception to the general cost trend for large vs. small agencies; this is in part due to lower per-mile maintenance costs for diesel vehicles at small agencies compared to large agencies. The group of small, rural agencies may operate 5% of active buses, but represent more than half of transit agencies in the state. Including these agencies in the scope of an electrification target significantly increases the uncertainty of predicting the costs of the regulation with regard to the costs of system-wide replacement for a given powertrain.

Drivers of Variance in Current Vehicle Costs

As illustrated above, uncertainty can be a confounding factor when comparing the lifetime cost of transit bus ownership. The variance in TCO for both conventional diesel and CNG buses is primarily driven by the annual miles, purchase costs, fuel efficiency, and vehicle life (Figure 24). Total spending on fuel over the vehicle life is a significant operational cost, but its contribution to uncertainty is reflected across vehicle fuel efficiency, annual miles, vehicle life, and fuel costs. In Figure 25, bar width shows range of per mile costs, values are minimum and maximum range of parameter considered, ordered by contribution to variance.

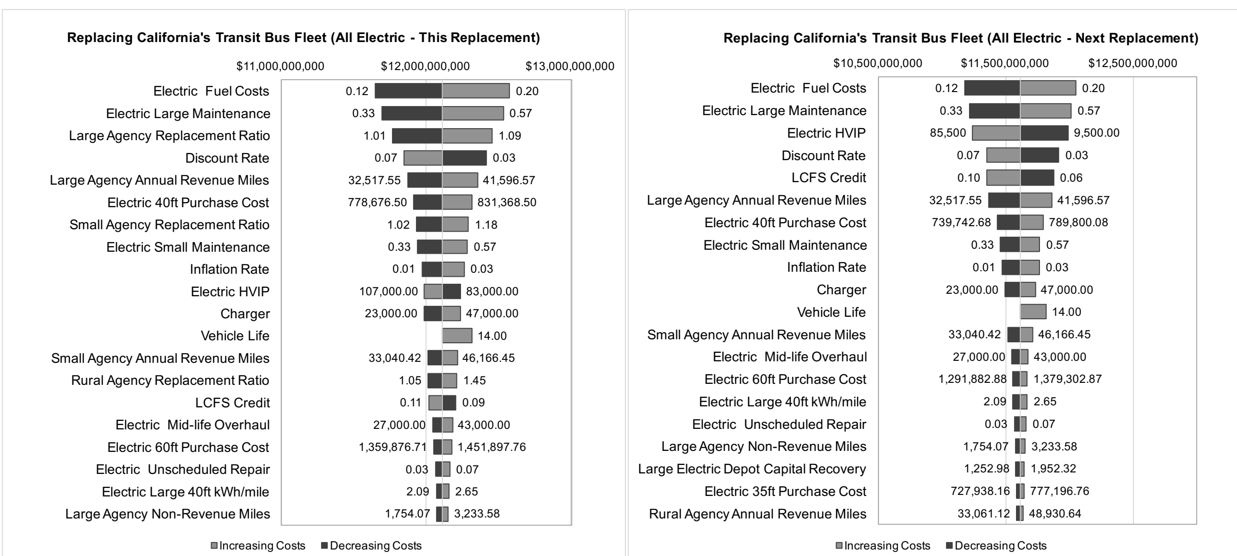
Figure 24 Screening Sensitivity Analysis of Parameters Affecting TCO of Transit Buses by 2030



 A change of $0.10/kWh in the cost of electricity for E-buses represents approximately $72,000 dollars in net present value. At $0.12/kWh, the upper end of expected LCFS subsidy for E-bus charging, the LCFS subsidy decreases the total cost of ownership of e-buses by almost 10%. While overall, electricity costs are likely to be contractually predictable, a lack of empirical data contributes to increased uncertainty about e-bus maintenance costs. Despite the low costs suggested by initial demonstrations, the maintenance costs, including training and capital investments, will remain a potentialt concern.

E-buses represent a different value proposition for transit agencies transitioning from conventional buses; diesel buses and CNG buses historically have relatively low fixed upfront costs and high variable operations costs. Given the variability in purchase prices for conventional buses, upfront costs have a significant effect on the uncertainty in lifetime costs. If agencies transition to a fleet that has higher fixed upfront costs and lower operations costs, the uncertainty in a question of whether total costs are equivalent becomes one about variable costs. Maintenance, fuel costs, purchase and fuel subsidies are all primary sources of uncertainty for E-bus lifetime costs.

Figure 25 Screening Analysis of Statewide Fleet Replacement with 100% Electric Buses



At the state level, uncertainty in transition costs for electric buses in the current term are driven in large part by bus range limitations and technology replacement issues (Figure 25 - Left). Replacement ratios for large and small agencies will be a key concern in transition costs. By 2030 (Figure 27 – Right), the effects of range mismatch and replacement ratio is signfiiantly reduced.   Over both periods, uncertainty in fuel costs, state incentives, and maintenance costs, are signficant hurdles to accurately predicting transition costs.

Discussion

A key limitation of this study is the assumption of independent costs between the first and subsequent purchase periods. E-buses currently represent a new market entry, and will face continued barriers to widespread commercialization. Near-term adoption of E-buses may be critical to ensuring long term viability (i.e. lower costs and improved technology performance) of E-buses. Any deterministic projection of medium to long term costs that does not consider near-term rates of adoption may overestimate potential improvements to the economics of E-buses. A "purchase period" scenario model was chosen in this study to illustrate how expected cost changes between now and the next time an agency replaces the same bus could affect TCO. It is unclear what levels of E-bus deployment are necessary to ensure that E-bus prices continue to fall. But, the costs of owning and operating a conventional bus has been increasing steadily. The results of this study suggest that if conventional bus prices continue to increase, E-buses will quickly become the most cost effective alternative given current policy.

The current purchase price of an E-bus can be more than 40% *higher* than what agencies have paid for conventional alternatives. But the economics of E-buses are improving rapidly, in part due to spillover effects from widespread deployment of electric powertrains and lithium batteries in light duty vehicle applications. E-bus battery costs are expected to decline by $85,000 or more, while the per-kW costs of electric motors and power electronics are expected to fall by almost 40%.[15] This study adopts a conservative assumption that all cost reductions over the next decade will enable further performance improvements for E-buses, not price reductions. In turn, E-buses in the next replacement period offer little to no mismatch in technical service potential, but still have slightly higher purchase costs. The assumption is notably conservative as some E-buses available today can replace conventional buses over a variety of duty cycles. A key exception to this price assumption is the possible replacement of lithium batteries before the end of its service life; these costs are assumed to fall dramatically in the second replacement period.

Even with this conservative assumption on pricing, E-buses are likely to become the most cost effective choice for transit agencies within their next two major replacement cycles. While increased capital costs may be offset by lower operating expenses, whether all agencies are able to realize these lower lifetime costs is still in question. At the system level, significant cost reductions are realized from full replacement with E-buses. However, there is heterogeneity, and small rural agencies may be forced to increase costs or decrease service to electrify their fleets. Perhaps equally important, purchase costs for diesel and CNG fueled buses have and are expected to continue to increase over time. This is driven in part by increasingly stringent emissions regulations, but also by a range of performance improvements.

---

[15] The Department of Energy, Electric Drive Program expects the cost of electric motor and power electronic costs to fall from $12/kW to $8/kW by 2022
https://energy.gov/sites/prod/files/2016/06/f32/edt000_rogers_2016_o_web.pdf

It is also important to consider whether agencies will be able to achieve equivalent technical performance and maintain current service levels without additional capital outlays on E-buses. Agencies may require additional buses if the effective range a bus can travel per charge is insufficient to meet the distance required by the duty cycle, and the agency does not have sufficient schedule flexibility to reassign these buses. The number of buses that must be purchased will depend on the route structure, the vehicle range per charge, and the charging system.

In the real world, electric vehicle efficiency and range will depend on several factors, including driver behavior, route, environmental conditions, and traffic conditions. The average vehicle range and efficiency may also not be the appropriate metric for design of an electric bus system, as it may reflect suboptimal operation of the battery system with respect to maximizing its service life, or may increase the risk of adverse service events due to inadequate battery capacity. Nevertheless, fuel costs over the lifetime of a bus are more than 2-3 times greater than costs for midlife overhauls and battery replacement, which are expected to cost less than $100,000 over 14 years (for more discussion, see the section on Midlife Overhaul).

E-buses available in 2016 are assumed to have an effective range of 120 miles per charge, increasing linearly to 250 miles per charge by 2035. Proterra[16] currently markets XR and E2 series Catalyst buses, respectively listed with 130-190 and 250-350 miles of range per charge. Proterra is a small, start-up manufacturer and the E2 is not yet available (Proterra has delivered 100 buses into service,[17] equivalent to less than 5% of the LACMTA fleet). Regardless, it is widely expected that longer range power systems will become available in the coming decade. This will be due to improvements in battery technology, decreasing battery costs, and improvements to vehicle efficiency. Average vehicle range may also not be the appropriate metric for design of an electric bus system; average range may reflect suboptimal operation of the battery system with respect to maximizing its service life. To minimize the risk of adverse service events due to inadequate battery capacity, buses may be purchased to meet a minimum daily range.

Depending on the route structure, on-route charging can decrease the number of additional buses needed by facilitating a longer daily service range. However, on-route charging systems can currently cost more than three times as much as depot charging systems. On-route charging systems come in multiple varieties. Fast-charging systems can cost as much as $500,000 for a 500 kW system, while smaller 60 to 80 kW systems have been installed at much lower costs. Depot systems are typically $20,000 to $60,000 per charger for 20 to 80 kW.[18] The costs of additional buses and charging systems and the route-specific logistics of charging

[16] https://www.proterra.com/products/catalyst-40ft/
[17] https://www.proterra.com/press-release/proterra-continues-north-american-market-leadership-with-milestone-deployment-to-san-joaquin-rtd/
[18] For further discussion of charging system costs, please see the ACT working group discussion documents or data assumptions at https://www.arb.ca.gov/msprog/bus/actmeetings.htm.

would need to be evaluated in more detail to determine whether on-route of depot charging is more suitable, and what the overall costs of buses and chargers would be.

As agencies increase the size of their electric fleets, each may also be able to optimize charging infrastructure and decrease the number of additional chargers required per additional bus acquired. In addition, E-bus ranges are improving rapidly even as the costs of energy storage fall and the market for electric buses is growing. This suggests that capital costs for electric may fall faster than other conventional technologies that have already achieved learning and scale economies.

Agencies face clear tradeoffs between expanding service and increasing investments into existing services, like electrifying routes. Historically, route and service planning and maintenance operations separate decision-making processes. Preparing for an all-electric fleet will likely require better integration of maintenance and planning departments. Future route and system planning should consider the performance characteristics of electric vehicles and strategic build-out of electric bus depots. In addition, fuel costs may vary across prospective charging facilities by location; route planning could also consider how routes might be reorganized to improve service without requiring the purchase of additional buses.

Battery Replacement

Lithium-ion batteries have become the preferred choice for electric vehicles because of high-energy densities, long cycle life, robust operating range, and low cost. Charge and discharge cycles progressively degrade the performance of lithium batteries in electric buses, eventually resulting in the need for replacement.[19] Electric battery warranties typically cover a range of service with a guaranteed percentage of the new capacity; for instance, a typical electric bus warranty might guarantee a battery to deliver a minimum of 80% of its initial discharge capacity after 12 years. Discharge capacity or depth of discharge (DOD) is commonly used to rate the functional capacity of a battery over a duty cycle. A 12 year to 80% DOD schedule translates to a loss in effective vehicle range of approximately 1.5% per year.

Capacity degradation has clear impacts on vehicle range, but the combination of resistance-induced power fade and diminished capacity will ultimately determine battery end-of-service. Increases to battery internal resistance reduce round-trip efficiency and will gradually render the battery inoperable in high-power applications. While both phenomena reduce the battery's capabilities, resistance increases make stored energy inaccessible.

While stored energy is rendered inaccessible for the high-power output typical of heavy-duty electric vehicle duty cycles, batteries could be functional in lower-power applications. A retired

[19] See Schaltz, E., Khaligh, A., & Rasmussen, P. O. (2009). Influence of battery/ultracapacitor energy-storage sizing on battery lifetime in a fuel cell hybrid electric vehicle. IEEE Transactions on Vehicular Technology, 58(8), 3882-3891; Cooney, G., Hawkins, T. R., & Marriott, J. (2013). Life cycle assessment of diesel and electric public transportation buses. Journal of Industrial Ecology, 17(5), 689-699.

electric bus battery could retain upwards of 70% of its new capacity in some applications. A growing body of research has pointed to the opportunities for potential secondary-use of retired electric vehicle batteries in stationary applications.[20] Unfortunately, this research has also indicated that there may be limited economic viability in repurposing electric vehicle batteries, primarily due to consistently improving performance and lower costs from newer batteries, as well as uncertain performance from degraded batteries. Nevertheless, given the large size and capacity of electric bus batteries (>300 kWh compared with ~25 kWh for passenger electric vehicles), repurposing may prove a viable revenue stream in the presence of policies promoting the provision of additional grid-tied storage (e.g. California's AB 2514).

Uncertainty in State-Wide Adoption Costs

When considering total compliance costs for the state (given a goal to transition to 100% E-buses), it is also important to consider the structure of existing fleets. Fleets that have already transitioned to CNG have likely made significant investments in CNG refueling infrastructure and maintenance facilities. As such, there is a significantly different change in costs for CNG compared to diesel fleets. As the majority of the state's CNG fleet operates in the Southern portion of the state, this creates a divide between incentives for Northern and Southern California Transit Agencies, although there are also a number of large, urban fleets in the South Coast that may be well positioned to electrify some of their routes.

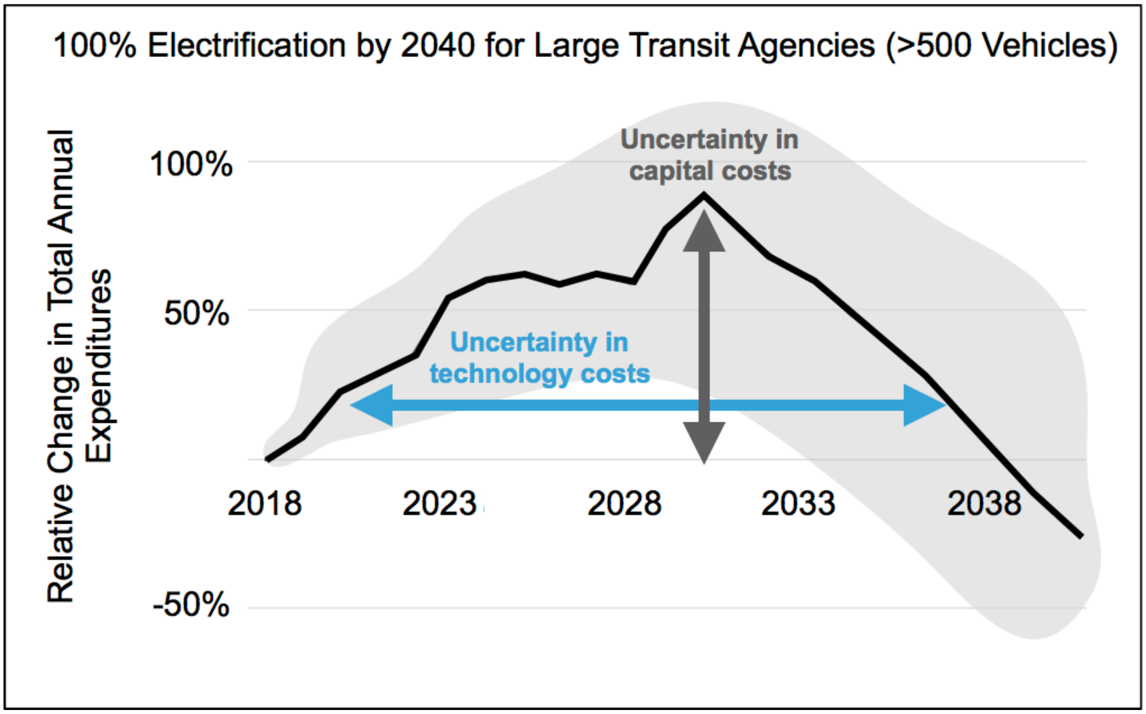
Another interesting finding of the screening analysis depicted in Figure 25 is that given the wide range of potential depot improvement costs considered ($15,000-$40,000 dollars per bus), capital cost improvements were not the most important factor when considering uncertainty in statewide adoption costs. While this range of assumed costs did not include some of the most extreme estimates, it seems unlikely that infrastructure improvements are the biggest source of uncertainty for whether a transition to electric buses would decrease costs on the whole and on average for California transit agencies.

Finally, another consideration is how annual expenditures will change over time given a move to adopt electric buses. Given a 2040 target for transit fleet electrification, we might expect agencies to delay the majority of purchases of E-buses till ~2030, and instead focus early efforts on small demonstration or pilot projects while waiting for E-bus technology and prices to improve. This type of purchase or replacement schedule is consistent with the likely costs reflected in Figure 28. Transitioning to electric buses increases annual expenditures as new investments in infrastructure are made. Over time, E-buses deliver lower operating costs and overall decrease total expenditures. The time required for agencies to realize savings from electrification (blue arrow) is due to uncertainty in technology and policy; namely fuel costs and

[20] See H. Ambrose, D. Gershenson, A. Gershenson, D. Kammen, Driving rural energy access: a second-life application for electric-vehicle batteries. *Environmental Research Letters* **9**, 094004 (2014); S. J. Tong, A. Same, M. A. Kootstra, J. W. Park, Off-grid photovoltaic vehicle charge using second life lithium batteries: An experimental and numerical investigation. *Applied Energy* **104**, 740-750 (2013); J. Neubauer, A. Pesaran, B. Williams, M. Ferry, J. Eyer, paper presented at the 2012 SAE World Congress and Exhibition, Detroit, Michigan, 2012.

subsidies. The overall investment required to achieve the lower operating costs suggested by E-buses is driven by uncertainty in capital costs.

Figure 26 Change in Annual Expenditures for Large Agency with 100% Electric by 2040



Emissions Benefits

A shift to E-buses can effectively eliminate tailpipe emissions, potentially leading to local air quality improvements. These air quality benefits may accrue to pedestrians, cyclists, drivers and passengers as well as to individuals living, working, and traveling near transit routes. These local air quality improvements are likely to be of particular interest to communities currently experiencing air pollution burdens from other mobile and stationary sources. Even when considering the lifecycle emissions associated with electricity generation, the high penetration of renewables and other low-emitting generators in the California grid mean that E-buses have lower per-mile emissions rates than buses using other fuels (Ercan & Tatari, 2015; Lajunen & Lipman, 2016). In addition to air quality benefits, electric buses also significantly reduce GHG emissions (Table 7). An 85% reduction in per-mile emissions of GHGs could avoid more than a million metric tonnes of CO_2-equivalent per year.

Any comparison of emissions rates should take into account potential changes in the technology used to generate the electricity. California's strong target for renewable generation suggests E-buses will continue to deliver reliably low emissions electricity.

Table 7 Per Mile Emissions Comparison for E-buses and CNG (grams/mile)[21]

	2018 Electric	2030 Electric	CNG (Conventional)
VOC	0.14	0.10	2.01
CO	0.78	0.56	4.97
NO_X	0.87	0.63	2.74
PM_{10}	0.08	0.07	0.03
$PM_{2.5}$	0.06	0.05	0.03
SO_X	0.52	0.43	0.57
CH_4	2.16	1.50	22.26
N_2O	0.02	0.02	0.24
CO_2	742.07	524.61	2898.65
CO_2e (GWP_{100})	802.40	566.55	3527.24

The reduction in NO_X emissions and local pollutants (VOC and CO) will also have significant economic benefits in terms of reduced public health impacts. While these costs are not considered here, they entail a potentially substantial economic benefit in addition to those associated with carbon abatement.

[21] This estimate is based on the CAGREET2016 model for electricity and CNG production emissions. Combustion emissions are estimated from EMFAC. Assumes a vehicle efficiency of 0.475 Therms/mile for CNG, and 2.1 kWh per-mile for Electric). The electricity mix assumption can be found the Appendix. All units are in grams per-mile.

Appendix 1: In-Depth Discussion of Methods

This study compares the net present costs of transit bus ownership across fuel pathways for composite and conventional steel buses. Two methodologies for TCO uncertainty analysis are compared: one, screening methods; and two, Monte Carlo analysis (Saltelli, Chan, & Scott, 2000). Changes to operational costs for composite vehicles are simulated by way of impacts to collision repair costs, overhaul costs, and vehicle lifetimes. Historical operations data and other published sources are used to derive parameter distributions for cost analysis. For all scenarios, a 5% discount rate was used and a 2% inflation rate was assumed for future costs.

Two types of global sensitivity analysis (GSA) are used in this study to illustrate uncertainty in potential cost estimates for transit buses. Screening analysis is a variable-based importance method for GSA and equates the change in output variance to on one at a time elimination of uncertainty in random input parameters (Tang, Zhenzhou, Zhiwen, & Ningcong, 2015). In the presence of correlated inputs, sampling methods may be superior as they offer the ability to asses expected shifts in the probability density function of the output (Borgonovo & Peccati, 2006). Sampling allows for direct calculation of a contrast between posteriors of cost distributions, which in turn enables estimates of probability or confidence intervals on expected outcomes, as well as formal statistical testing (i.e. analysis of variance).

Monte Carlo Simulation (MCS) was used to estimate scenario cost distributions. MCS involves estimating a set of probability density functions for parameter values and exploring the posterior probability of an output function using a Markov Chain algorithm. MCS is widely applied in physical, computation, and statistical sciences to estimate models and analyze complex systems (Blum & François, 2010; Frangopol, Kallen, & Van Noortwijk, 2004; Raftery, 1996; Zeger & Karim, 1991). MCS allows for a graphical comparison of stochastic dominance. Stochastic dominance describes the superiority of one alternative compared to another with respect to a set of performance objectives. Let us assume P(AsB) is the probability that *A* is superior to *B* for any cost driver Z_i:

The probabilistic dominance or superiority of A over B could be described as,

Equation 1

$$P(AsB) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(P_A(Z_1,Z_2)\int_{Z_1}^{\infty}\int_{-\infty}^{Z_2} P_B(z_1,z_2 \mid A(Z_1,Z_2))dz_2 dz_1 \right) dZ_1 dZ_2,$$

where $P_B(z_1,z_2 \mid A(Z_1,Z_2))$ is the probability distribution of B's performance given A's performance at Z_1, Z_2. For the purposes of this study, we assume independence of costs across both purchase periods and fuel pathways, thus vastly simplifying this comparison. Given the assumption that each probabilistic scenario is independent, we can simplify Equation 1 to:

Equation 2

$$P(AsB) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(P_A(Z_1, Z_2)\int_{Z_1}^{\infty}\int_{-\infty}^{Z_2} P_B(z_1, z_2)dz_2dz_1 \right)dZ_1dZ_2,$$

Through the independence assumption, we can compare each scenario probabilistically with the BAU through Equation 2.

Next, we evaluated the one-way route length and the number of trips taken on a route over the course of a day. Each trip on each route can have a different one-way travel distances because buses do not always service the entire range of stops on a route. Individual buses may have a mix of "shorter" and "longer" assignments over the course of a service period. We estimated the full length over each route from stop to stop using Google Maps. Buses were then aggregated based on median and maximum number of trips per route. The distance requirements for these categories, 150 miles per day, less than 200 miles per day, and less than 250 miles per day respectively, were then estimated based on the average number of trips in each category and average route mileage for the entire system.

Only depot based charging of electric buses was considered. All buses are assumed to return to a depot facility for a single charge event, and can only delivery their fully charged range once per day. The average replacement ratio represents the number of electric buses required to meet the daily range requirement for a route divided by the effective electric range. In other words, a bus that runs a 25 mile route 5 times per day has a daily range requirement of 125 miles. An electric bus with an effective range of 100 miles would have a replacement ratio of 1.25 for this route.

Vehicle Fuel Economy

Vehicle fuel economy or fuel efficiency was investigated through a number of directions. Both simulated drive cycle fuel economies and real world fuel efficiencies were estimated and compared before a final method was adopted. For conventional powertrains, we can easily simulate the fuel economy of vehicles using the standard road load equation (Table A1: Comparing Simulated Fuel Efficiency of Buses).

Table A1: Comparing Simulated Fuel Efficiency of Buses

	Diesel	Hybrid	CNG	BEB
AFLEET 2016	3	4	3	*8.5*
MAN Cycle	2.8	3.4	4.8	*18.2*
OCC Cycle	4.1	5.0	5.9	*20.5*
UDDS Cycle	6.5	7	7.2	22.7

Vehicle energy demands, or average fuel consumption per unit distance-mass travelled (SFC), can be estimated from the physical forces affecting the bus:

$$SFC = \frac{C_{aero} * v_{aero}^2 + C_{rolling} + \overline{\alpha}(1 - \eta_{regen})}{\eta_{powertrain}} + \frac{E_{auxfuel}}{M_{veh} * Dist}$$

$$C_{aero} = \frac{\frac{1}{2} * \rho C_D FA}{M_{veh}}$$

$$C_{rolling} = RRC * g$$

Where:

$$v_{aero} = aerodynamic\ speed$$

$$\overline{\alpha} = characteristic\ acceleration$$

$$SFC = \frac{Fuel}{Mass * Distance}$$

$$C_{aero} = aerodynamic\ resistance$$

$$C_{rolling} = rolling\ resistance$$

$$RRC = coefficient\ of\ rolling\ resistance$$

$$\rho = air\ density$$

$$C_D = coefficient\ of\ aerodynamic\ resistance$$

Excepting for auxiliary loads, energy required to power a vehicle can be attributable to the need to overcome primary physical forces including inertia, aerodynamic resistance, friction at the wheels, and internal friction (e.g. transmission). Both speed and acceleration are important for estimating fuel consumption for a given duty cycle. Aerodynamic resistance is a significant driver of fuel consumption at higher speeds. Acceleration forces, which urban transit buses experience more often, have high power demands and translate to energy fuel consumption different depending on powertrain.

The following model was used to estimate fuel economy based on the route regression:

$$v_{aero} = \beta * average\ driving\ speed$$

$$\overline{\alpha} = \beta_1 * \frac{Stops}{Mile} + \beta_2 * \left(\frac{Stop}{Mile}\right)^2$$

Table A2: Coefficient Estimates for SFC Regression

	Average Speed	Stops per Mile	Stops per Mile^2
Aerodynamic Effect	0.59	-	-
Acceleration Effect	-	0.17	-0.03

Powertrain efficiency assumptions were drawn from literature estimates and are contained in table A3, in particular see: (Schwertner & Weidmann, 2016)

Table A3: Assumed Powertrain Efficiencies for Each Powertrain

	Powertrain Efficiency	Regen Efficiency
Diesel	38%	0%
CNG	38%	0%
Series	38%	54%
Parallel	42%	52%
Fuel Cell	44%	54%
Electric	89%	72%

Data from fuel economy testing of current E-buses was used to calibrate the model. These data were obtained primarily from the Altoona bus testing center database (Table A2).

Table A2: Fuel Efficiency of Electric Buses from Altoona Testing

	Proterra 40' Catalyst	BYD 40' ebus	New Flyer 40' Xcelsior
Curb Weight (lbs)	27500	31890	32770
Arterial Phase (MPDGE)	17.9	14.8	16.5
Commuter (MPDGE)	26.7	26.4	25.1
Overall Average (MPDGE)	22.2	18.9	20.5

Table A2: MAN – Manhattan/New York City Test Cycle, OCC – Orange County Test Cycle, UDDS – Urban Dynamometer Drive Cycle, AFLEET estimated fuel economy

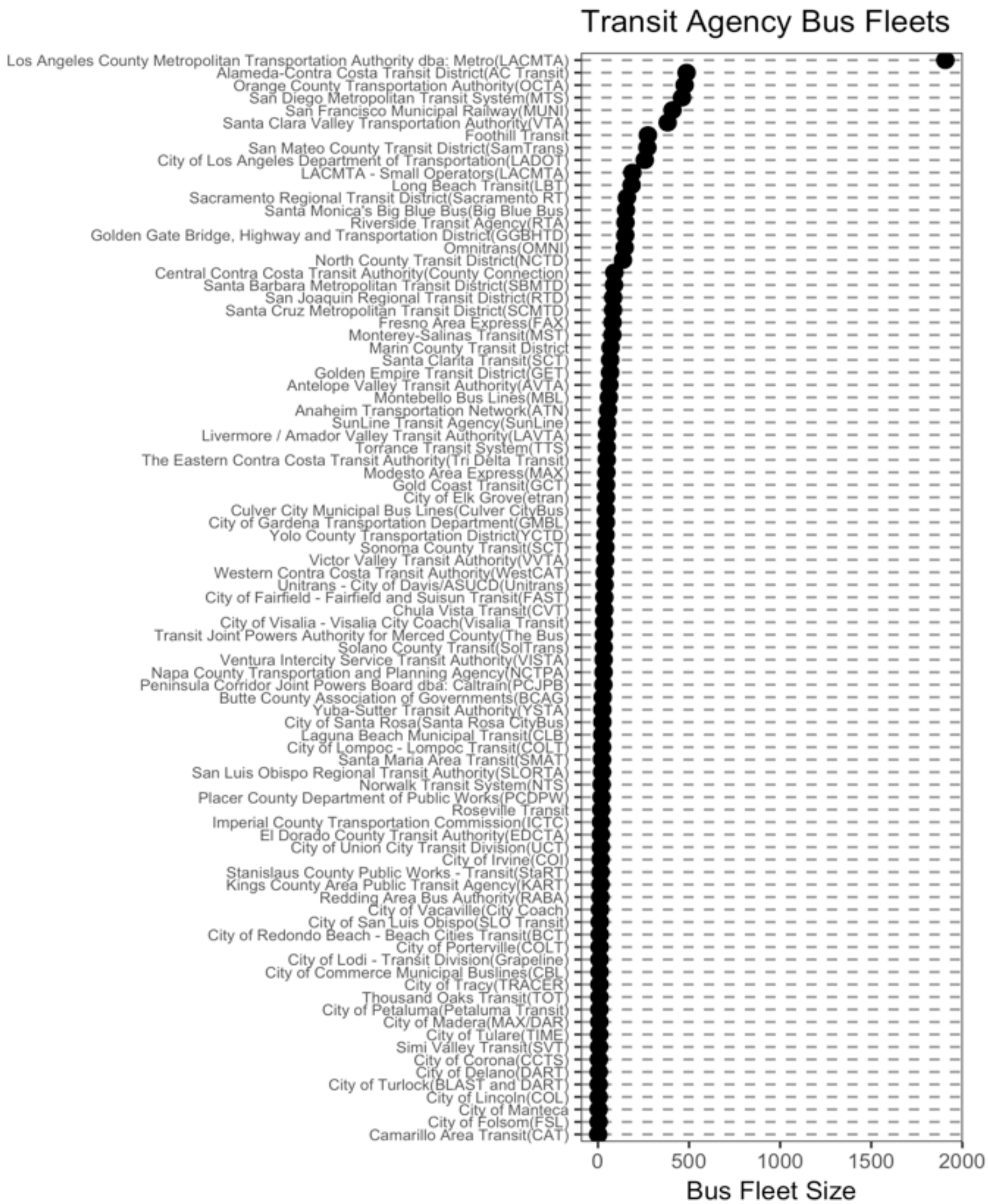
Average travel speeds for scheduled daily route trips were determined using the Google Maps distance matrix API. Travel times and average speeds included expected dwell times for stops based on GTFS data. Parameter estimates were also compared with a TCRP report,[22] and validated against drive cycle data in the NREL Fleet DNA Database. The TCRP report analyzed both real world and chassis dynamometer fuel economies for several technologies of transit bus powertrains, including hybrid and CNG systems. The report did not include examples of electric buses, so the models were supplemented with data from the NREL fleet DNA database.

Estimating emissions from E-buses requires assumptions about the sources of electricity generation for the utility. The following projection was based on the EIA reference case scenario for generation in California, which are generated using the National Energy Modelling System (NEMS).

Table A3: Generation Mix Assumption for Emissions Reduction Comparison

	2018	2030
Coal	5%	5%
Oil	0%	0%
Natural Gas	59%	40%
Nuclear	8%	7%
Renewables	26%	47%
Biomass	2%	2%

[22] Clark, N. N. (2009). *Assessment of hybrid-electric transit bus technology* (Vol. 132). Transportation Research Board.



Transit Agency Bus Fleets
Los Angeles County Metropolitan Transportation Authority dba: Metro(LACMTA)
Alameda-Contra Costa Transit District(AC Transit)
Orange County Transportation Authority(OCTA)
San Diego Metropolitan Transit System(MTS)
San Francisco Municipal Railway(MUNI)
Santa Clara Valley Transportation Authority(VTA)
Foothill Transit
San Mateo County Transit District(SamTrans)
City of Los Angeles Department of Transportation(LADOT)
LACMTA - Small Operators(LACMTA)
Long Beach Transit(LBT)
Sacramento Regional Transit District(Sacramento RT)
Santa Monica's Big Blue Bus(Big Blue Bus)
Riverside Transit Agency(RTA)
Golden Gate Bridge, Highway and Transportation District(GGBHTD)
Omnitrans(OMNI)
North County Transit District(NCTD)
Central Contra Costa Transit Authority(County Connection)
Santa Barbara Metropolitan Transit District(SBMTD)
San Joaquin Regional Transit District(RTD)
Santa Cruz Metropolitan Transit District(SCMTD)
Fresno Area Express(FAX)
Monterey-Salinas Transit(MST)
Marin County Transit District
Santa Clarita Transit(SCT)
Golden Empire Transit District(GET)
Antelope Valley Transit Authority(AVTA)
Montebello Bus Lines(MBL)
Anaheim Transportation Network(ATN)
SunLine Transit Agency(SunLine)
Livermore / Amador Valley Transit Authority(LAVTA)
Torrance Transit System(TTS)
The Eastern Contra Costa Transit Authority(Tri Delta Transit)
Modesto Area Express(MAX)
Gold Coast Transit(GCT)
City of Elk Grove(etran)
Culver City Municipal Bus Lines(Culver CityBus)
City of Gardena Transportation Department(GMBL)
Yolo County Transportation District(YCTD)
Sonoma County Transit(SCT)
Victor Valley Transit Authority(VVTA)
Western Contra Costa Transit Authority(WestCAT)
Unitrans - City of Davis/ASUCD(Unitrans)
City of Fairfield - Fairfield and Suisun Transit(FAST)
Chula Vista Transit(CVT)
City of Visalia - Visalia City Coach(Visalia Transit)
Transit Joint Powers Authority for Merced County(The Bus)
Solano County Transit(SolTrans)
Ventura Intercity Service Transit Authority(VISTA)
Napa County Transportation and Planning Agency(NCTPA)
Peninsula Corridor Joint Powers Board dba: Caltrain(PCJPB)
Butte County Association of Governments(BCAG)
Yuba-Sutter Transit Authority(YSTA)
City of Santa Rosa(Santa Rosa CityBus)
Laguna Beach Municipal Transit(CLB)
City of Lompoc - Lompoc Transit(COLT)
Santa Maria Area Transit(SMAT)
San Luis Obispo Regional Transit Authority(SLORTA)
Norwalk Transit System(NTS)
Placer County Department of Public Works(PCDPW)
Roseville Transit
Imperial County Transportation Commission(ICTC)
El Dorado County Transit Authority(EDCTA)
City of Union City Transit Division(UCT)
City of Irvine(COI)
Stanislaus County Public Works - Transit(StaRT)
Kings County Area Public Transit Agency(KART)
Redding Area Bus Authority(RABA)
City of Vacaville(City Coach)
City of San Luis Obispo(SLO Transit)
City of Redondo Beach - Beach Cities Transit(BCT)
City of Porterville(COLT)
City of Lodi - Transit Division(Grapeline)
City of Commerce Municipal Buslines(CBL)
City of Tracy(TRACER)
Thousand Oaks Transit(TOT)
City of Petaluma(Petaluma Transit)
City of Madera(MAX/DAR)
City of Tulare(TIME)
Simi Valley Transit(SVT)
City of Corona(CCTS)
City of Delano(DART)
City of Turlock(BLAST and DART)
City of Lincoln(COL)
City of Manteca
City of Folsom(FSL)
Camarillo Area Transit(CAT)
0
500
1000
1500
2000
Bus Fleet Size

References Cited

Ahluwalia, R., Wang, X., & Kumar, R. (2012). Fuel Cell Transit Buses. *Argonne National Laboratory, Argonne, IL*.

Ambrose, H., & Jaller, M. (2016). *ELECTRIFICATION OF DRAYAGE TRUCKS: ON TRACK FOR A SUSTAINABLE 1 FREIGHT PATH 2.* Paper presented at the Transportation Research Board 95th Annual Meeting.

Blum, M. G., & François, O. (2010). Non-linear regression models for Approximate Bayesian Computation. *Statistics and Computing, 20*(1), 63-73.

Borgonovo, E., & Peccati, L. (2006). Uncertainty and global sensitivity analysis in the evaluation of investment projects. *International Journal of Production Economics, 104*(1), 62-73.

Bubna, P., Brunner, D., Gangloff, J. J., Advani, S. G., & Prasad, A. K. (2010). Analysis, operation and maintenance of a fuel cell/battery series-hybrid bus for urban transit applications. *Journal of Power Sources, 195*(12), 3939-3949.

CARB. (2015). *Draft Discussion, Advanced Clean Transit Regulation*. Retrieved from http://www.arb.ca.gov/msprog/bus/actdiscussiondocument.pdf.

Center, A. B. T. a. R. (2014). *BYD Electric Bus*. Retrieved from

Center, A. B. T. a. R. (2015a). *New Flyer, Model XE40*. Retrieved from

Center, A. B. T. a. R. (2015b). *Proterra, Inc. Model BE-40*. Retrieved from

Clark, N. N. (2009). *Assessment of hybrid-electric transit bus technology* (Vol. 132): Transportation Research Board.

Cooney, G., Hawkins, T. R., & Marriott, J. (2013). Life cycle assessment of diesel and electric public transportation buses. *Journal of Industrial Ecology, 17*(5), 689-699.

Ellram, L. M., & Siferd, S. P. (1998). Total cost of ownership: a key concept in strategic cost management decisions. *Journal of Business Logistics, 19*, 55-84.

Ercan, T., & Tatari, O. (2015). A hybrid life cycle assessment of public transportation buses with alternative fuel options. *The International Journal of Life Cycle Assessment, 20*(9), 1213-1231.

Eudy, L., Prohaska, R., Kelly, K., & Post, M. (2016). *Foothill Transit Battery Electric Bus Demonstration Results*. Retrieved from

Ferrin, B. G., & Plank, R. E. (2002). Total cost of ownership models: An exploratory study. *Journal of Supply chain management, 38*(2), 18-29.

Frangopol, D. M., Kallen, M. J., & Van Noortwijk, J. M. (2004). Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. *Progress in Structural Engineering and Materials, 6*(4), 197-212.

Jang, Y. J., Ko, Y. D., & Jeong, S. (2012). *Optimal design of the wireless charging electric vehicle.* Paper presented at the Electric Vehicle Conference (IEVC), 2012 IEEE International.

Jørgensen, F., Pedersen, P. A., & Solvoll, G. (1995). The costs of bus operations in Norway. *Journal of Transport Economics and Policy*, 253-262.

Karlaftis, M. G., & McCarthy, P. (2002). Cost structures of public transit systems: a panel data analysis. *Transportation Research Part E: Logistics and Transportation Review, 38*(1), 1-18.

Kassel, R., & Leonard, J. H. (2016). Gladstein, Neandross & Associates, Game Changer for CNG.

Lajunen, A. (2014). Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies, 38*, 1-15.

Lajunen, A., & Lipman, T. (2016). Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy, 106*, 329-342.

Lowell, D., Seamonds, D., Park, D., & Turner, G. (2015). *Composite Structure Buses: Current Experience & Recommendations For Future Bus Purchases*. Retrieved from

Nykvist, B., & Nilsson, M. (2015). Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change, 5*(4), 329-332.

Raftery, A. E. (1996). Approximate Bayes factors and accounting for model uncertainty in generalised linear models. *Biometrika, 83*(2), 251-266.

Saltelli, A., Chan, K., & Scott, E. M. (2000). *Sensitivity analysis* (Vol. 1): Wiley New York.

Schwertner, M., & Weidmann, U. (2016). Comparison of Well-to-Wheel Efficiencies for Different Drivetrain Configurations of Transit Buses. *Transportation Research Record: Journal of the Transportation Research Board*(2539), 55-64.

Shirazi, Y., Carr, E., & Knapp, L. (2015). A cost-benefit analysis of alternatively fueled buses with special considerations for V2G technology. *Energy Policy, 87*, 591-603.

Tang, Z.-C., Zhenzhou, L., Zhiwen, L., & Ningcong, X. (2015). Uncertainty analysis and global sensitivity analysis of techno-economic assessments for biodiesel production. *Bioresource technology, 175*, 502-508.

Tong, F., Hendrickson, C., Biehler, A., Jaramillo, P., & Seki, S. (2017). Life cycle ownership cost and environmental externality of alternative fuel options for transit buses. *Transportation Research Part D: Transport and Environment, 57*, 287-302.

Zeger, S. L., & Karim, M. R. (1991). Generalized linear models with random effects; a Gibbs sampling approach. *Journal of the American statistical association, 86*(413), 79-86.