ANL/ESD-21/4

Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains

Energy Systems Division

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Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains

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by
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April 2021

Erratum to accompany “*Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains*” (Argonne National Laboratory report ANL/ESD-21/4)

July 2021

After initial publication of this report, the authors were made aware of some minor typographical errors and omissions. As these mistakes can potentially confuse the results, they have been corrected in the present version.

- In the executive summary on page xxiii, “HEV” (hybrid electric vehicle) was once written as “BEV” (battery electric vehicle), contrary to the findings shown in the accompanying figure.

- Tables B.5 and B.6 previously stated the incorrect all-electric ranges for the battery electric vehicle and plug-in hybrid electric vehicle for the class 8 day cab tractor and class 4 delivery truck, respectively. These ranges have been corrected. Additionally, two sentences were added to Appendix B on page 143 to explicitly state the correctly modeled all-electric range for all medium- and heavy-duty vehicles.

- Several stakeholders have been added explicitly to the acknowledgments section.

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ACKNOWLEDGMENTS

This research was supported by the Vehicle Technologies Office in the Office of Energy Efficiency and Renewable Energy at the U.S. Department of Energy, and the authors express their thanks to VTO, and in particular Jacob Ward, Raphael Isaac, and Mark Smith, for guidance and helpful discussion. The authors thank members of the U.S. DRIVE government-industry partnership Integrated Systems Analysis Technical Team for insightful discussions. The authors also thank attendees and panelists of the Total Cost of Ownership workshops for medium- and heavy-duty vehicles, held in April 2020, for their valuable insights and perspectives. In particular, the authors would like to thank Mike Tunnell (American Transportation Research Institute), Mike Roeth (North American Council for Freight Efficiency), Scott Phillippi (UPS), Dawn Fenton (Volvo Group NA), Alan Mace (Ballard Power Systems), and Randal Kaufman (Black & Veatch) for being panelists. The authors especially thank Sandra Loi of NREL for her invaluable assistance in reorganizing and hosting the workshops as virtual events after the implementation of nationwide travel restrictions due to COVID-19. The authors also thank Douglas Cheung and Kenneth Levin of Edmunds, Chris Harto of Consumer Reports, Paul Milner of Utilimarc, Bob Boundy and John Thomas of Oak Ridge National Laboratory, and Anant Vyas of Argonne National Laboratory for helpful discussions.

LIST OF ACRONYMS

AAA	Automobile Association of America
AEO	Annual Energy Outlook
AFDC	Alternative Fuel Data Center
AFV	alternative fuel vehicle
APR	annual percentage rate
APU	auxiliary power unit
ARR	adjusted retention rate
ATRI	American Transportation Research Institute
AVCEM	Advanced Vehicle Cost and Energy-use Model
BEA	Bureau of Economic Analysis
BEV	battery electric vehicle
BLS	Bureau of Labor Statistics
CARB	California Air Resources Board
C&C	comprehensive and collision
CD	charge depleting
CE	Consumer Expenditures
CI	compression ignition
CNGV	compressed natural gas vehicle
CPI	consumer price index
CR	Consumer Reports
CS	charge sustaining
dge	diesel-gallon equivalent
DOE	Department of Energy
DPF	diesel particulate filter
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EVSE	electric vehicle supply equipment
FCEV	fuel cell electric vehicle
FET	federal excise tax
FRB	Federal Reserve Board
FRIA	final regulatory impact analysis
GDP	gross domestic product
gge	gasoline-gallon equivalent
GVWR	gross vehicle weight rating
HDV	heavy-duty vehicle
HEV	hybrid electric vehicle

HFTO	Hydrogen and Fuel Cell Technologies Office
HOS	hours of service
HVUT	Heavy Vehicle Use Tax
ICEV	internal combustion engine vehicle
IPD	implicit price deflator
IRS	Internal Revenue Service
ISG	integrated starter generator
KBB	Kelley Blue Book
LCOD	levelized cost of driving
LDV	light-duty vehicle
LRR	low rolling resistance
LTL	less-than-truckload
MHDV	medium-duty vehicle
MHDV	medium- and heavy-duty vehicles
MPG	miles per gallon
mpgge	miles per gasoline-gallon equivalent
M&R	maintenance and repair
MSRP	manufacturer suggested retail price
MY	model year
NADA	National Automobile Dealers Association
NAIC	National Association of Insurance Commissioners
NAS	National Academies of Science
NHTS	National Household Travel Survey
NHTSA	National Highway Traffic Safety Administration
NIPA	National Income Product Accounts
NRC	National Research Council
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PEV	plug-in electric vehicles
PHEV	plug-in hybrid electric vehicles
PHIS	public highway infrastructure and services
PTO	power take-off
RIA	regulatory impact analysis
RPE	retail price equivalent
SAFE	Safer Affordable Fuel-Efficient Vehicles rule
SI	spark ignition
SUV	sport utility vehicle
SWA	sales-weighted average

TCO	total cost of ownership
TL	truckload
TMV	True Market Value
TRB	Transportation Research Board
VIUS	Vehicle Inventory Use Survey
VMT	vehicle miles traveled
VTO	Vehicle Technologies Office

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EXECUTIVE SUMMARY

In order to accurately compare the costs of two vehicles, the total cost of ownership (TCO) should consist of all costs related to both purchasing and operating the vehicle. This TCO analysis builds on previous work to provide a comprehensive perspective of all relevant vehicle costs of ownership. In this report, we present what we believe to be the most comprehensive explicit financial analysis of the costs that will be incurred by a vehicle owner. This study considers vehicle cost and depreciation, financing, fuel costs, insurance costs, maintenance and repair costs, taxes and fees, and other operational costs to formulate a holistic total cost of ownership and operation of multiple different vehicles. For each of these cost parameters that together constitute a comprehensive TCO, extensive literature review and data analysis were performed to find representative values in order to build a holistic TCO for vehicles of all size classes. The light- and heavy-duty vehicles selected for analysis in this report are representative of those that are on the road today and expected to be available in the future. Table ES-1 summarizes the main parameters in this study, including the cost components which comprise TCO, the sizes and vocations of vehicles which are analyzed, the powertrains of these vehicles, and the model year for analysis of both current and future vehicles.

TABLE ES-1 Study scope: cost components and other key parameters used in this study

Cost Components
Purchase Cost
Depreciation
Financing
Fuel
Insurance
Maintenance
Repair
Taxes
Registration Fees
Tolls and Parking
Payload Capacity
Labor

Sizes and Vocations
Compact Sedan
Midsize Sedan
Small Sport Utility Vehicle
Large Sport Utility Vehicle
Pickup Truck
Class 4 Delivery
Class 6 Delivery
Class 8 Bus
Class 8 Refuse
Class 8 Vocational
Class 8 Tractor – Day Cab
Class 8 Tractor – Sleeper Cab

Powertrains
Internal Combustion Engine
Hybrid Electric Vehicle
Plug-in Hybrid Electric Vehicle
Fuel Cell Electric Vehicle
Battery Electric Vehicle

Timeframe
2020
2025
2030
2035
2050

Previous analyses of TCO, particularly those dealing with alternative fuel vehicles (AFVs), have often focused on the purchase cost and the fuel cost. While these are two of the most important factors making up the cost of the vehicle, we find sizeable variations in other operational costs across powertrains, size classes, and usage parameters. We use vehicles modeled in Autonomie to estimate vehicle costs and fuel economy along with fuel price projections from the Energy Information Administration (EIA), and focus on developing internally consistent estimates for other relevant cost parameters. Important additive analyses in this study include systematic analysis of vehicle depreciation, in-depth examination of insurance premium costs, comprehensive maintenance and repair estimates, analysis of all relevant taxes and fees, and considerations of specific costs applicable to commercial vehicles. This study, which considers these additional cost components, provides a more holistic and comprehensive perspective of TCO for a wider range of vehicle sizes, types, and vocations than have previously been analyzed.

TCO can be presented in aggregate terms over the entire span of the analysis timeframe, on an annualized basis, or on a per-mile basis as a levelized cost of driving (LCOD). Figure ES-1 shows the discounted lifetime costs of owning and operating two representative vehicles: a small sport utility vehicle (SUV) with a gasoline-fueled internal combustion engine (ICE) for 15 years and a heavy-duty battery electric truck (BEV) for 10 years in model year (MY) 2025. Many of our cost components, including vehicle cost and depreciation, financing, taxes, insurance, and repair, scale with manufacturer suggested retail price (MSRP). As such, all of these cost components will continue to decrease in the future as retail prices for AFVs are projected to decrease, contributing to significantly more competitive TCOs.

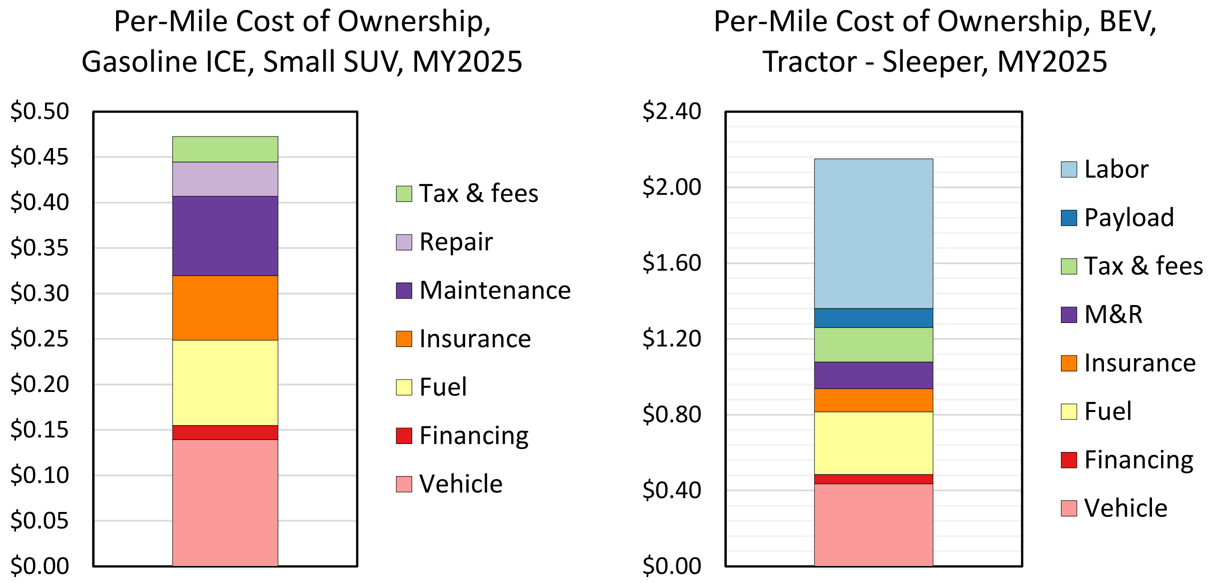


FIGURE ES-1 Levelized cost of ownership of a model year 2025, small ICE SUV (left), and a model year 2025, class 8 sleeper cab BEV (right)

To populate the data for these graphics, we undertook a thorough literature exploration on each of the cost components listed in Table ES-1. The following bullet points summarize our prior knowledge for the major additive cost components in our analysis as well as the new review, analysis and findings of our study which identify and fill what were previously gaps in our understanding of TCO, for both light-duty vehicles (LDV) and medium- and heavy-duty vehicles (MHDV) as well.

Depreciation

- New analysis: Systematic analysis of depreciation by powertrain (LDVs), development of multi-variable HDV depreciation model.
- Key findings: Cars depreciate faster than light trucks. MY13-16 electric vehicles have a greater depreciation rate than newer PEVs.

Insurance

- New analysis: In-depth analysis of liability, comprehensive and collision insurance costs for LDVs by powertrain for selected size classes, development of simple MHDV insurance cost model from several sources for a range of vocations.
- Key findings: LDV insurance costs show comparable costs for different powertrains, lower costs for larger size classes. MHDV insurance costs vary significantly by vocation.

Maintenance and Repair (M&R)

- New analysis: Systematic analysis of LDV maintenance and repair costs: maintenance schedule for LDVs by powertrain for selected size classes, model for LDV repair costs by powertrain for selected size classes. Developed estimates for MHDV M&R costs.
- Key findings: Electric and electrified powertrains have lower maintenance and repair costs than ICE powertrains for all vehicle sizes, relative to vehicle price. MHDV M&R costs depend heavily on vocation and duty cycle.

Taxes, fees, parking, tolls, etc.

- New analysis: Development of consistent costs for both LDVs and MHDVs by size class and powertrain, covering a comprehensive range of relevant taxes and fee-related costs.
- Key findings: LDV taxes and fees are comparable across powertrain types and size classes; marginally higher registration fees for AFVs. MHDV costs depend on the vocation, weight rating, and state.

Costs unique to commercial vehicles

- New analysis: Models developed to estimate labor costs of BEV charging and heavy-duty payload capacity costs.
- Key findings: Many vehicles would be affected by additional battery weight, reducing the available payload capacity, and this cost can be substantial. BEV charging can be time-consuming; labor rates can cause this cost to dominate TCO. Auxiliary Power Units to minimize idling are cost effective ways to minimize fuel consumption.

Financial analysis

- New analysis: Examination of discount rates, inflation rates, and loan terms.
- Key findings: Real loan terms of 4% for 5.25 years are appropriate for analysis along with a 1.2% discount rate for households, 3% for businesses.

Our study builds on previous work to provide a more comprehensive analysis of depreciation trends based on various vehicle attributes using resale values for a larger number of makes and models than previously investigated. We analyzed residual value of 98 vehicle models across a variety of powertrain types, size classes, and other characteristics for MYs 2013–2019 to derive a systematic model of LDV depreciation trends based on key characteristics of the vehicle. We also performed regression modeling on MHDV used vehicle listings to derive a model of MHDV depreciation as a function of vehicle type, age, and mileage driven. Figure ES-2a shows these trends by powertrain type for LDV, indicating that both PHEVs and BEVs maintain their value better than conventional counterparts in recent years, but depreciate more quickly when considering all seven MYs. Figure ES-2b shows a sample class 8 sleeper cab depreciation for three mileage cases: default, low, and high.

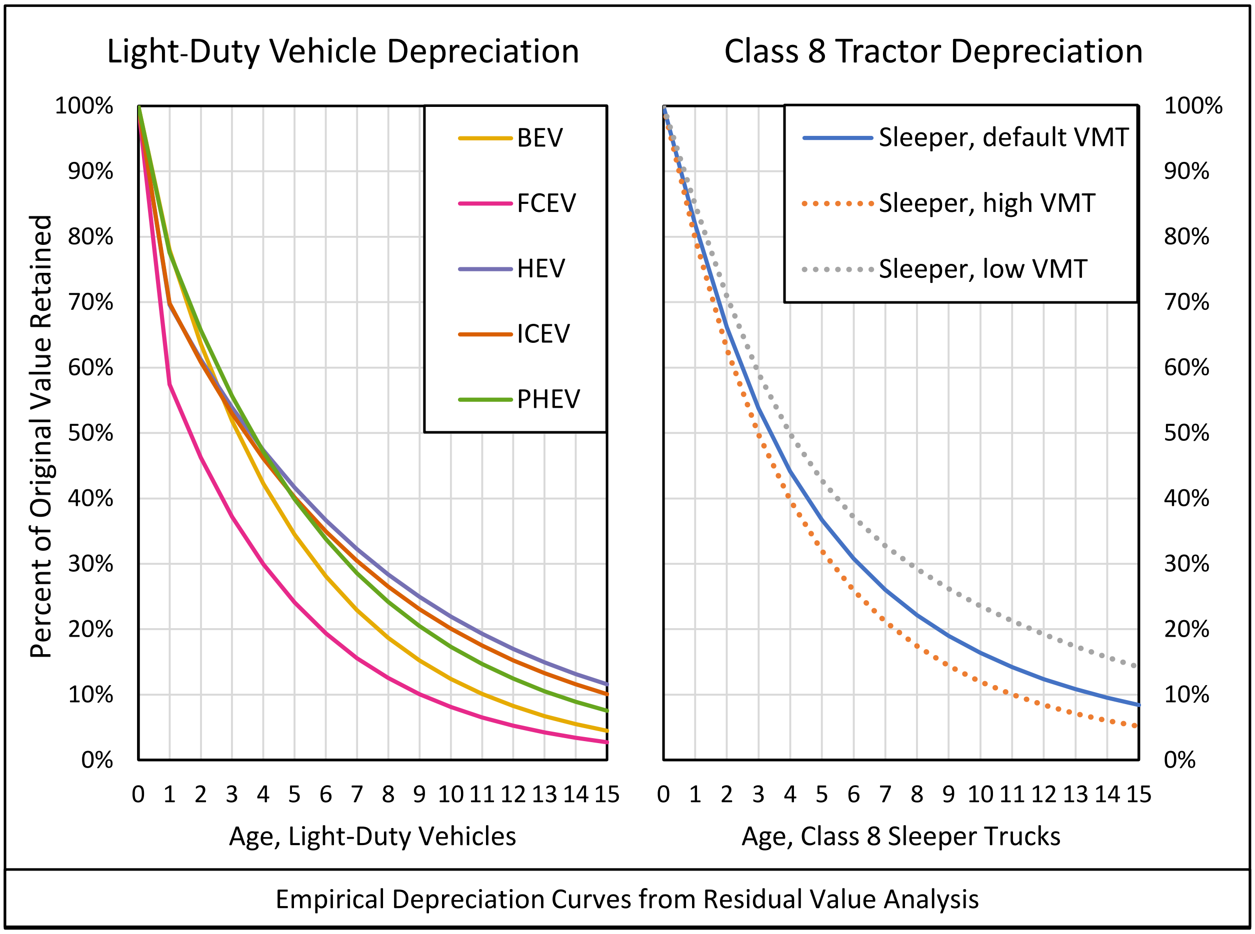


FIGURE ES-2 Depreciation trends by powertrain and size class (Car, Light truck)

Prior knowledge on insurance-related costs was limited to quotes for LDVs and some information for MHDVs. In this study, we provide a holistic analysis of insurance premiums for a wide variety of vehicles ranging in powertrain type, size class, and other vehicle characteristics. We find that the national average liability coverage premium is $600 annually for all powertrain types and size classes. However, we also analyze differences in comprehensive and collision coverage premiums across these vehicle characteristics. As shown in Figure ES-3, we find small differences by powertrain type, but do find systematic differences in insurance premium costs by size class. For most MHDV, we use average insurance costs from Utilimarc. For tractor trailers, we supplement average liability insurance costs from ATRI with information about physical damage insurance which exhibit differences by vehicle residual value (and thus powertrain).

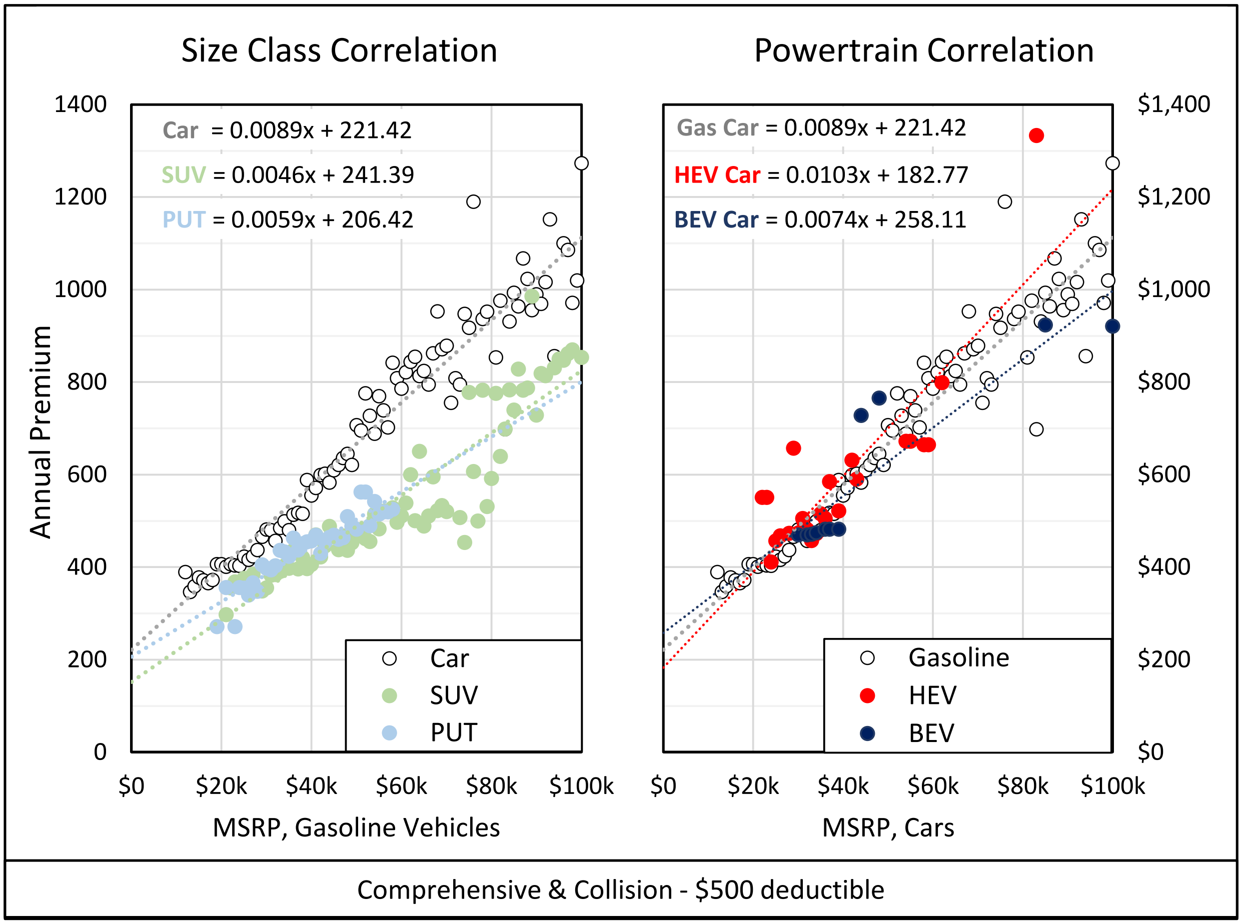


FIGURE ES-3 Annual premium for comprehensive and collision insurance by size class and by powertrain

Previous TCO studies largely omitted consideration of maintenance and repair (M&R) costs or used estimates which were assumption-based. Our TCO also includes a comprehensive analysis of M&R cost data for both LDVs and MHDVs. In addition to reviewing a wide variety of literature on combined M&R costs, we construct a generalized maintenance service schedule for each of the powertrain types. Many services have different schedules for the different powertrains (14 of the 24 in Figure ES-4, indicated by asterisks), as advanced powertrains can either extend service intervals (e.g. spark plugs for HEVs and PHEVs) or eliminate the service (e.g. oil changes for BEVs). We find that AFVs, especially BEVs, systematically have lower maintenance costs than ICEVs, as illustrated by Figure ES-4.

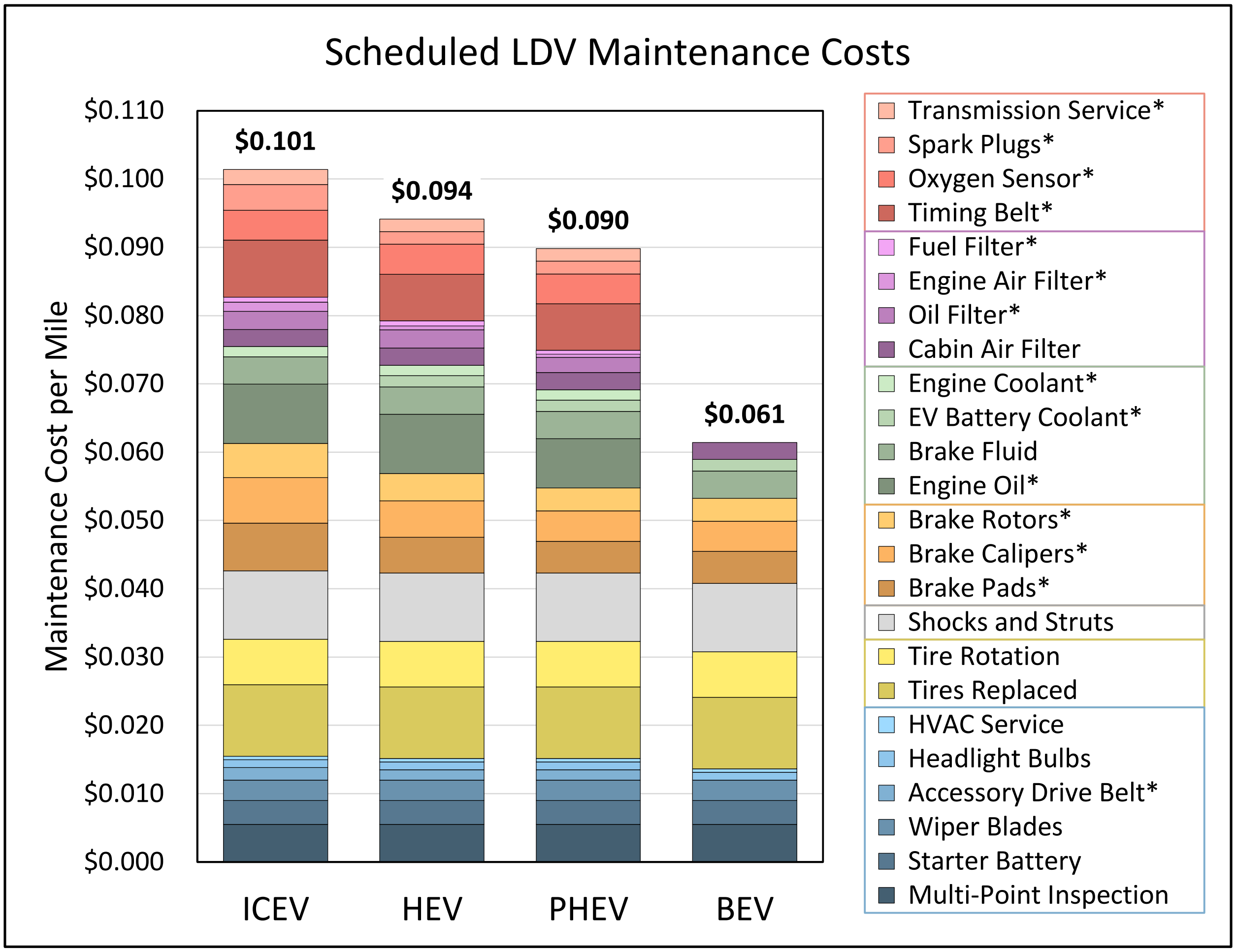


FIGURE ES-4 Per-mile maintenance costs by powertrain (*Service intervals that vary by powertrain)

Our analysis also included in-depth examination and modeling of repair cost data for real-world vehicles for a variety of powertrain types and size classes. We find that repair cost is an increasing exponential function of MSRP and varies significantly by vehicle characteristics; scaling factors for the powertrain type and size class of the vehicle of interest are shown in Table ES-2. The percent in each cell indicates the ratio of the repair costs for a vehicle with the given size class and powertrain to the repair costs of an ICE car with the same MSRP. Larger vehicles and AFVs both systematically tend to have lower repair costs as a percentage of MSRP. For MHDV, no size class dependence was found, but a difference in M&R costs by powertrain was observed, shown in the final row of Table ES-2.

TABLE ES-2 Repair cost scaling factors by powertrain and size class, relative to ICE car or MHDV truck with same MSRP

LDV	ICEV	HEV	PHEV	BEV / FCEV
Car	100%	89%	86%	67%
SUV	91%	81%	78%	61%
Pickup	70%	62%	60%	47%
MHDV	100%	87%	83%	60%

While information was previously available on taxes, fees, and other miscellaneous costs such as parking, tolls, etc., prior TCO work did not consistently synthesize or include these data. We analyzed the most important tax- and fee-related expenses for different powertrains, size classes, and states of purchase and registration. We find little variation in taxes and fees across different powertrain types, though find that this cost component is not insignificant in the TCO.

Prior TCO work has largely focused on LDVs, leaving a lack of thorough analysis of TCO for MHDVs. In addition to collecting and analyzing the available data for MHDVs for each of the above components, we also examine several cost components specific to these commercial vehicles that are important to a comprehensive analysis of MHDV TCO. We developed models to quantify the value of payload capacity loss resulting from heavy batteries, which can increase total TCO by over 10% for large batteries. We also explore labor costs, and particularly labor costs incurred during BEV charging. If vehicle fueling qualifies as working, the driver could spend more time charging than driving, causing the TCO for BEVs to increase dramatically.

The above results demonstrate the most important new knowledge in each of the additive cost components of our comprehensive and holistic TCO. We then aggregate each of the cost components in Table ES-1 to calculate a lifetime TCO for comparison across vehicles of different types and attributes. Figure ES-5 shows TCO results from this study comparing the LCOD of six different powertrains for a small SUV in 2025, modeled using Autonomie. Based on the assumptions chosen, the hybrid electric vehicle (HEV) has the lowest cost, followed by the conventional gasoline-fueled spark-ignition internal combustion engine (ICE-SI). The fuel cell electric vehicle (FCEV), the diesel-fueled compression-ignition internal combustion engine (ICE-CI) vehicle, and the plug-in hybrid electric vehicle (PHEV) have similar costs, while the BEV is the most expensive. The lower operating cost (especially fuel and maintenance) is not sufficient to offset the higher incremental cost of purchasing the BEV. For the non-combustion vehicles, the cost of ownership is high due to batteries (for plug-in electric vehicles) or the cost of hydrogen fuel for fuel cell electric vehicles (FCEV).

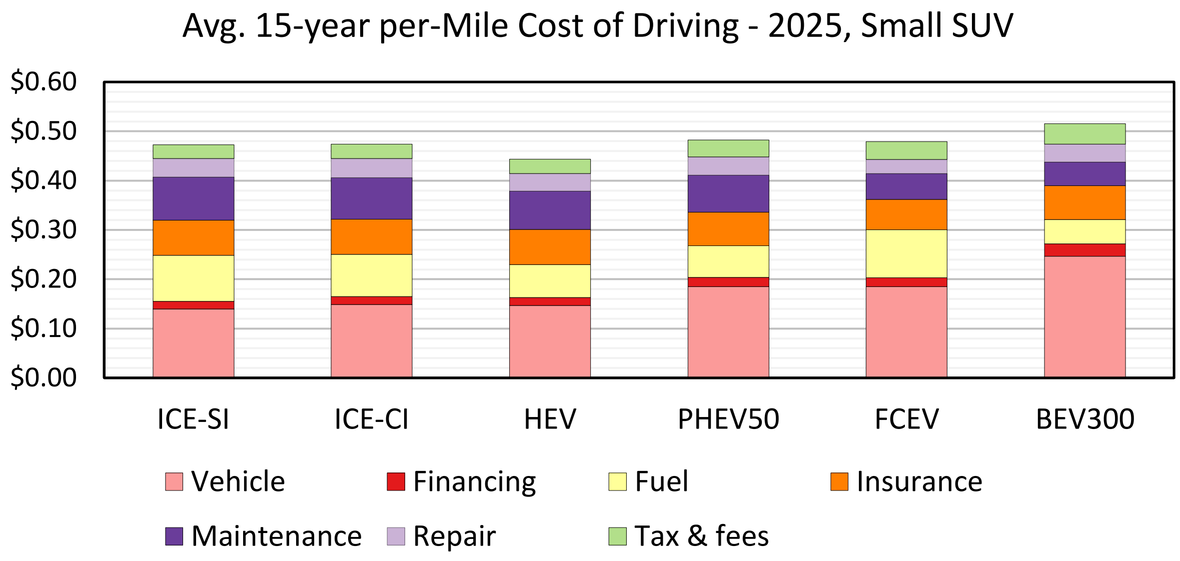


FIGURE ES-5 LCOD across powertrains for light-duty SUV, MY2025

In the case of MHDV, Figure ES-6 shows how TCO can be drastically different depending on the vocation. Typical 10-year TCOs are presented for conventional diesel ICE vehicles of seven different heavy-duty applications, ranging from a medium-size delivery truck to a long-haul tractor trailer. In this case, the class 8 sleeper cab has one of the highest lifetime costs, due to its high mileage, but has the lowest per-mile costs. On a per-mile basis, class 8 day cabs have the second-lowest TCO. TCO for medium-duty delivery trucks are the lowest on a lifetime basis, due to the reduced lifetime driving mileage relative to the other vehicles. However, they have one of the highest costs on a per-mile basis. Excluding labor costs, the class 4 delivery has a comparable TCO to the day cab. Likewise, on a total cost basis, vocational trucks are both comparatively low, but on a per-mile basis, this is one of the most expensive segments, owing to low annual mileage. Due to high M&R costs and comparatively low annual mileage, refuse trucks have higher operating cost than other vehicles. For all of these vehicles, the cost of operating the vehicle is heavily weighted by the labor of the driver, followed by the fuel costs.

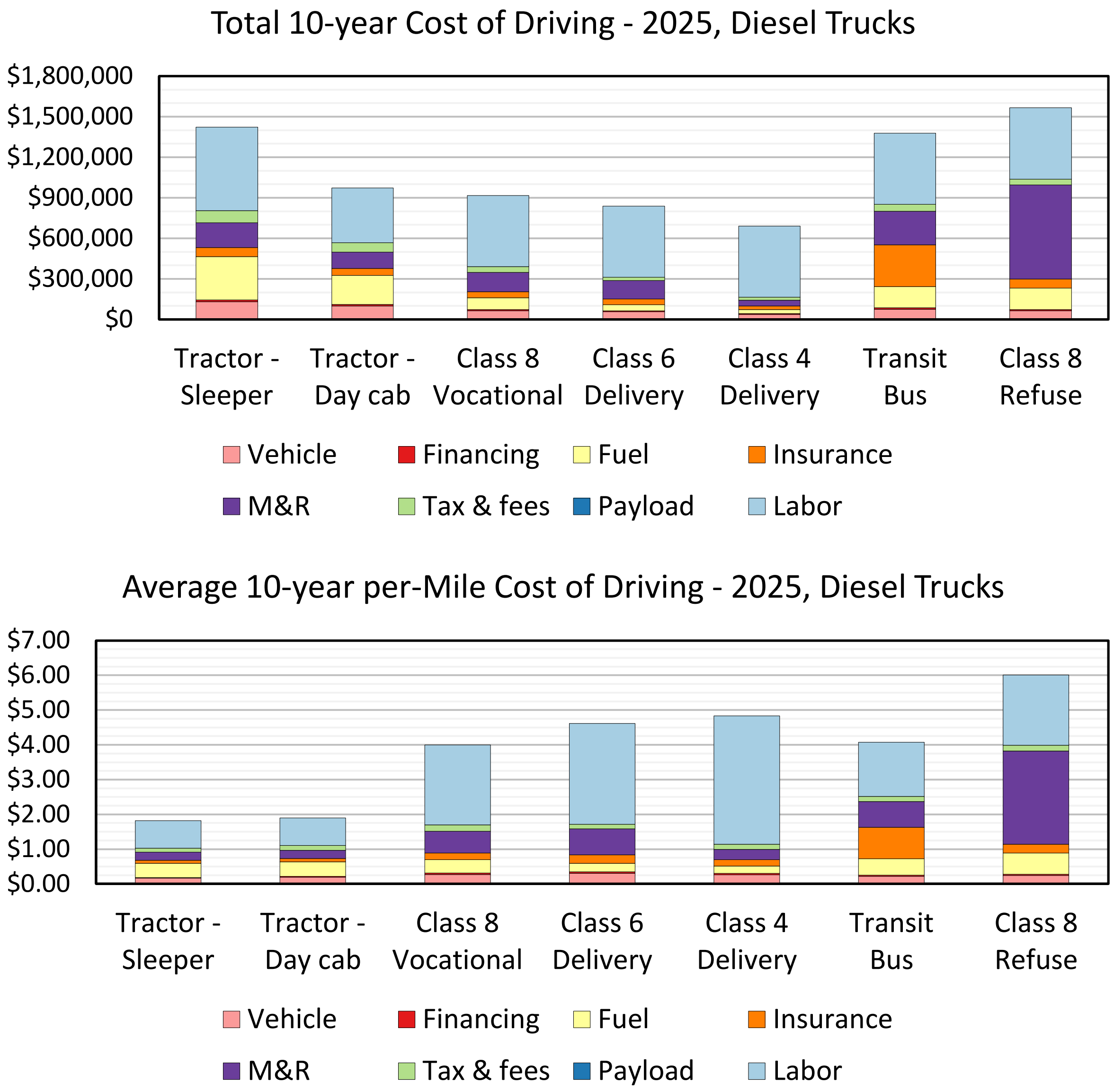
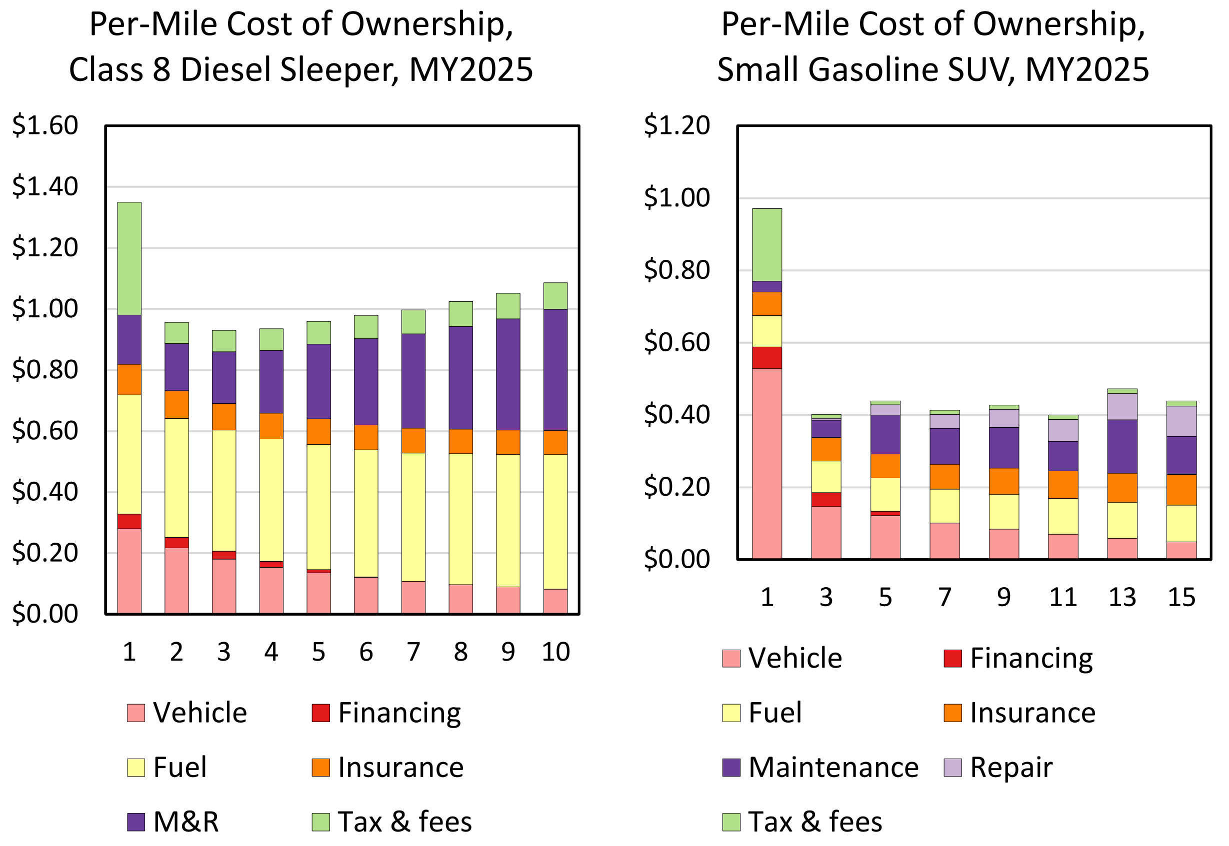


FIGURE ES-6 TCO and LCOD across MHDV vocations, MY2025

Figure ES-7 shows how the cost of vehicle ownership varies throughout a vehicle's lifetime for a typical diesel-fueled class 8 sleeper cab and for a small SUV fueled by gasoline. In the first year, ownership costs for each vehicle are at their highest due to vehicle depreciation and the cost of registering the vehicle. Vehicle costs gradually decrease as the vehicle loses residual value, while operating costs of M&R grow sharply as the vehicle ages. Insurance costs decline modestly on a per-mile basis due to the decreased residual value later in the analysis window. For the light-duty vehicle, ownership costs are mostly steady, gradually rising late in the vehicle's life due to increased maintenance and repair while vehicle deprecation diminishes.


Per-Mile Cost of Ownership, Class 8 Diesel Sleeper, MY2025

Per-Mile Cost of Ownership, Small Gasoline SUV, MY2025

FIGURE ES-7 TCO across vehicle lifetime for class 8 diesel truck and gasoline SUV

Figure ES-8 shows how TCO is forecast to change over time and by powertrain. This figure shows the modeled reduction in TCO for the small SUV and the class 8 day cab tractor for different powertrains from 2020 through 2050 as vehicle technology improves, using modeling results from Autonomie. While the HEV begins as the lowest cost powertrain for small SUV, FCEV are forecast to reach cost parity by 2030 when hydrogen prices reach $5/kg while BEV reaches cost parity by 2035 at a battery cost of $98 per usable kWh of capacity, with these two technologies being the lowest cost in 2050. For the class 8 day cab tractor, the HEV and ICEV begin as the lowest cost powertrains, and the BEV250 reduces in cost from the most expensive to the least expensive by 2030. Due to the comparatively high cost of hydrogen in this analysis, the FCEV never reaches cost parity in this modeling. Cost modeling for the class 8 sleeper cab shows the same trends as the day cab, except that the BEV becomes the cheapest option by 2035. Cost modeling for the class 4 delivery truck finds the 150-mile BEV the least cost option in 2025, while the conventional diesel ICEV is the most expensive powertrain by 2030.

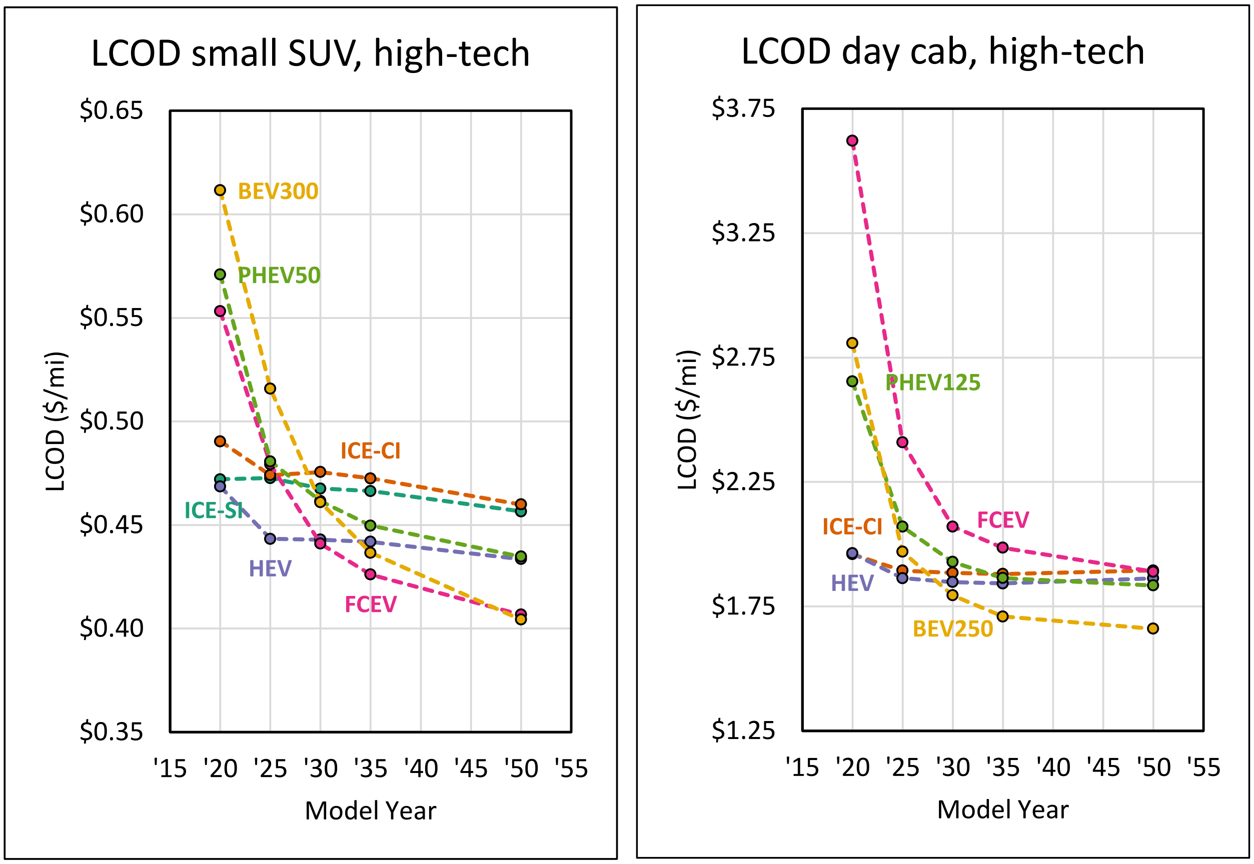


FIGURE ES-8 TCO for small SUV and class 8 day cab from MY2020 to MY2050

These results summarize some of the broad range of analyses that are presented in the body of this report. In many cases, the highest costs are for the vehicle and the fuel, but this is not always true. We find that insurance and M&R both play an important role in TCO and contribute toward differences between powertrains. In the case of MHDVs, payload capacity costs and especially labor costs both affect TCO and contribute to key differences between the powertrain types. In both cases, while taxes and fees are small contributors to TCO, they nonetheless are important to consider.

Given the breadth of cost elements presented in this report, we believe that these results can be broadly to fill gaps in analyses by other researchers. Our single-vehicle-focused analysis can be used within segmentation-type analyses which aim to identify market opportunities for specific technologies and in market adoption analyses which estimate future sales shares of different vehicle technologies.

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1. INTRODUCTION

This report documents a comprehensive analysis of vehicle ownership costs, yielding a total cost of ownership (TCO). The purpose of this study is to estimate all of the components of the national-average TCO from the perspective of an individual or firm doing an explicit, complete, internally consistent, data-based estimation of the TCO of vehicles having a range of vehicle fuels and powertrain technologies. Our findings can be used by analysts, researchers, and policymakers when determining the relative ownership costs of alternative fuel vehicles (AFVs) and deciding directions for future research, and by consumers and fleet operators to select cost-effective vehicles. A detailed literature review supplemented by discussions with subject matter experts shows the need for a more consistent, comprehensive approach to vehicle ownership costs and for sufficient data to support a comprehensive analysis. The costs listed in Table 1.1 were quantified for the light-duty passenger vehicle size classes and powertrains in 2020 and future years shown in the table.

TABLE 1.1 Private passenger vehicle cost components quantified and vehicle size classes, powertrains, and years modeled

Cost Components	Size Classes	Powertrains	Years
Purchase & Depreciation	Compact Sedan	Internal Combustion Engine	2020
Financing	Midsize Sedan	Hybrid Electric Vehicle	2025
Fuel	Small Sport Utility Vehicle	Plug-in Hybrid Electric Vehicle	2030
Insurance	Large Sport Utility Vehicle	Fuel Cell Electric Vehicle	2035
Maintenance & Repair	Pickup Truck	Battery Electric Vehicle	2050
Taxes & Fees			

For commercial vehicles, we included the same cost components as for passenger vehicles as well as direct operational costs, including both labor expenses and the marginal payload expenses relative to a conventional engine. The cost components listed in Table 1.2 were quantified for commercial vehicles of selected combinations of size classes and vocations with powertrains in the years listed.

In this analysis, direct costs were quantified at a national level (averages or representative values) from the perspective of a rational vehicle owner. Of particular interest here are direct, monetary costs incurred by owners of light-duty passenger vehicles and owners/operators of light-, medium- and heavy-duty commercial vehicles with different powertrains. No “soft” costs, such as value of driver preferences for comfort, performance, styling etc., and no costs external to purchasing and operating the vehicle, such as costs due to congestion, pollution, or noise impacts were included. Because this analysis focuses on the ownership and operation costs of an individual vehicle, it is distinct from segmentation-type analyses which aim to identify market opportunities for specific technologies (e.g. Morrison et al. 2018; Hunter et al. 2021 forthcoming). Likewise, this analysis does not attempt to model market adoption to estimate

TABLE 1.2 Commercial vehicle cost components quantified and vehicle size classes, powertrains, and years modeled

Cost Components	Size Classes	Powertrains	Years
Purchase & Depreciation	Class 4 Delivery	Internal Combustion Engine	2020
Financing	Class 6 Delivery	Hybrid Electric Vehicle	2025
Fuel	Class 8 Transit Bus	Plug-in Hybrid Electric Vehicle	2030
Insurance	Class 8 Refuse	Fuel Cell Electric Vehicle	2035
Maintenance & Repair	Class 8 Vocational	Battery Electric Vehicle	2050
Taxes & Fees	Class 8 Tractor – Day Cab		
Payload Capacity	Class 8 Tractor – Sleeper Cab		
Labor			

future sales shares of different vehicle technologies, as these analyses depend on consumer behavior which is not completely tied to vehicle cost of ownership (e.g. Stephens et al. 2020; Brooker et al. 2021 forthcoming). That noted, the results from this output can be used to supplement those types of analyses, as this report includes rigorous and self-consistent analysis of many of the costs that comprise a TCO calculation.

Previous ownership cost analysis supported by the Department of Energy Vehicles Technology Office (DOE VTO) has focused on vehicle manufacturing cost (and the resulting vehicle retail price, typically represented as the manufacturer suggested retail price, or MSRP) and fuel cost. In this study, we expand upon this work by focusing on other cost components and use the vehicle cost and fuel economy modeling from existing VTO-supported work, specifically vehicle modeling by the Argonne Autonomie team and documented in Islam et al. (2020), and Vijayagopal et al. (2019), as discussed in Section 3.2.

While vehicle and fuel costs are two of the largest factors in the TCO for many vehicles, examining solely these two components does not fully capture the differences in total costs between powertrain types. Initial vehicle retail price is the largest cost in early years, but over a longer analysis window of 15 years, recurring costs such as maintenance, repair, insurance, registration fees, and others become increasingly important. As such, establishing more scientifically-sound bases for these cost components is crucial for gaining a more holistic understanding of lifetime TCO. We find that costs for maintenance, repair, taxes and fees, and, to an extent, insurance, all vary significantly between powertrains and are systematically lower for AFVs. This indicates that past work, which has focused primarily on vehicle and fuel costs, may have misrepresented differences in TCO between powertrain types.

We developed estimates of the cost components listed above by collecting and analyzing data to establish a firmer basis for costs such as maintenance and repair, insurance, depreciation, and some operating costs for commercial vehicles. Such data were available for specific makes and models, but had not been systematically and consistently analyzed in a manner sufficient to support general comparisons of these costs across powertrains for different vehicle size classes. We also provided a firmer basis for economic and financial assumptions, including appropriate rates for discounting, inflation, and vehicle loans. As discussed in the literature review (Section 2), previous studies of ownership costs have made different assumptions about many of these factors, often without a firm technical basis. We establish a comprehensive conceptual framework for defining and estimating the TCO, and identify and begin to fill critical data gaps in estimates of the TCO of both light-duty vehicles (LDV) and medium- and heavy-duty vehicles (MDV and HDV, together MHDV).

We modeled depreciation of cars and light trucks of model years (MY) 2013–2019 with different powertrain types capturing the dependence on model year, powertrain, market segment (luxury and mass market), and size class. Our results indicate that, on average, battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), and fuel cell electric vehicles (FCEV) depreciate somewhat more quickly than their hybrid electric vehicle (HEV) and internal combustion engine vehicle (ICEV) counterparts do, but recent model year plug-in electric vehicles (PEV), especially luxury BEVs, hold their value about as well as if not better than ICEVs. We also analyzed depreciation of MHDV, capturing the dependence on age and cumulative mileage for each size class, though data limitations prevented analysis of the depreciation of MHDV with different powertrains.

We collected and analyzed insurance cost information on LDV and modeled these costs for cars, sport utility vehicles (SUV), and pickup trucks. We found that insurance costs depend on MSRP and size class, but are similar across powertrains. The available data on insurance costs for commercial vehicles is more limited, but we could estimate annual costs for each of the size classes listed in Table 1.2. We also estimated insurance costs as a function of vehicle value for tractor trailers, giving an implicit variation as a function of powertrain.

Analyzing maintenance costs of LDVs of different powertrains as a function of vehicle age, vehicle mileage and time (maintenance schedule), we found that on average electrified powertrains (HEVs, PHEVs, BEVs, and FCEVs) all have lower scheduled maintenance costs than ICEVs. We also analyzed LDV repair (not including scheduled or unscheduled maintenance or costs covered by warranties), and estimated costs for cars, SUVs, and pickup trucks by powertrain. We found that average repair costs, as a percentage of MSRP, were lower for HEVs, PHEVs, and BEVs than for ICEVs, ranging from 11% to 33% lower. For MHDV, we found expected annual costs for maintenance and repair (M&R) as a function of vehicle age for each of the size classes in Table 1.2, and adjusted these for AFVs, as informed by data for maintenance and repair for transit buses.

We collected information on taxes, fees, parking, tolls, inspection, licensing, and other costs and found modest differences between these costs for passenger vehicles with different powertrains, largely due to state-level differences in vehicle registration. For MHDV taxes and fees, we found no explicit powertrain dependence, but we did account for changes in highway use tax related to the heavier weight of AFVs.

We compiled data on the additional costs incurred for operating commercial vehicles. We also identified important data gaps for labor costs associated with charging PEVs and costs for battery electric freight trucks from to the loss of payload weight capacity due to the increased weight of the large battery itself. The payload capacity cost was estimated by comparing the distribution of real-world freight truck operating weight with the estimated weights of class 8 tractor trailers trucks from Autonomie simulations. The labor cost for time spent recharging a commercial electric vehicle was estimated based on the difference in time required to charge a PEV and the time required to refuel an ICEV and typical driver wages. Recharging labor costs can be quite high, depending on assumptions about expected charging power rates, and whether personnel are required for the full time spent recharging.

Our contributions to knowledge of TCO are summarized in Table 1.3. Our work resulted in improved estimates of cost components that have not been well addressed in previous work, and our results support a more comprehensive assessment of ownership costs for a wide range of vehicles of different size classes and powertrain types, including commercial vehicles. Further, the calculations in this analysis are internally consistent, in spite of pulling from a disparate set of data sources.

TABLE 1.3 New knowledge of TCO cost components delivered by the present study

Cost component	Prior knowledge	New knowledge
Depreciation	Resale values by make & model	Systematic analysis of depreciation by powertrain (LDVs). Developed simple HDV depreciation model.
Maintenance and Repair	Estimates from different sources available, but no consistent analysis. Previous TCO work largely assumption-based	Analysis of LDV maintenance and repair, model for LDV maintenance by powertrain for selected size classes. LD PEV M&R costs lower or comparable to ICEV M&R costs. Developed estimates for HDV M&R costs.
Insurance	Quotes for LDVs available, some information for HDVs available	Analyses of LDV insurance costs show comparable costs for different powertrains. Developed simple HDV insurance cost model
Taxes, fees, parking, tolls, etc.	Information available, but not consistently synthesized	Consistent estimates developed for LDVs by size class and powertrain. Developed estimates for HDV costs.
Costs unique to commercial vehicles	Labor costs associated with BEV charging, lower payload capacity, not well understood	Models developed to estimate labor costs of BEV charging and HDV BEV payload capacity costs

The literature on TCO was reviewed to inform our analytic approach, and the approaches taken in previous studies and findings of selected studies are reviewed in Section 2, along with a discussion of the method for calculation and core analytical assumptions. Section 3 presents the data necessary to calculate each cost component, including vehicle cost and fuel economy, residual value, fuel costs, insurance costs, maintenance and repair costs, taxes and fees, commercial vehicle operational costs, and labor costs. Literature relevant to these specific cost components is also presented in the section on each cost component. Section 4 presents results for our core modeling cases, as well as sensitivity analyses to show the most impactful and most uncertain cost components. We conclude with a discussion on the implications of these results in Section 5. Appendix A has additional information about alternative methods for calculating TCO. Appendix B presents results for TCO calculations in tabular form. Appendix C explores sensitivity analyses for the TCO calculations in greater detail, while the references are a comprehensive documentation of the many studies which supplied data for this analysis.

2. TCO CALCULATION METHODOLOGY AND BACKGROUND

2.1. CONCEPTUAL FRAMEWORK FOR VEHICLE COSTS

The total lifetime cost of owning and operating a vehicle comprises a set of mutually exclusive and collectively exhaustive elements, which are usefully delineated according to the *perspective* from which lifetime cost is viewed and the *general approach* to estimating lifetime cost. At the most general level we distinguish between: i) the perspective of *private* individuals or firms and the perspective of *society,* and ii) a completely *quantitative* approach to estimating vehicle costs and an approach that is *not* 100% quantitative, which for convenience we designate "*(partially) qualitative."* (A "partially qualitative" approach thus can include some quantification.) This gives four over-arching categories:

1) *Private* perspective, *100% quantitative* approach: an explicit, mathematical accounting of the costs and benefits for a private individual or firm. This study is in this category.

2) *Private* perspective, *(partially) qualitative* approach: an informal and at least partially subjective consideration of costs and benefits for a private individual or firm.

3) *Societal* perspective, *100% quantitative* approach: an explicit, mathematical accounting of all of the costs and benefits for the whole society, over many generations.

4) *Societal* perspective, *(partially) qualitative* approach: an informal and at least partially non-quantitative assessment of the costs and benefits for society.

The four categories comprise different cost *elements* and use different detailed *methods* to estimate lifetime cost. As mentioned above, the purpose of this study is to estimate all of the components of the national-average TCO with the approach and perspective of category 1: an explicit, complete, internally consistent, data-based estimation of all of elements of the TCO of advanced-technology vehicles for private individuals or firms. Although category 1 (private-quantitative) has the same perspective as category 2 (private-qualitative), and the same general approach as category 3 (societal-quantitative), it actually comprises substantially different cost elements and involves different estimation methods than do the other categories (Table 2.1). Analysts should understand these differences to avoid mistakenly applying category-1 estimates, such as in this study, to category-2 or category-3 estimates. In particular, the classification of Table 2.1 and the extended related discussion in Appendix A show that, common practice notwithstanding, it is *not* correct to estimate societal costs simply as the sum of private costs and external costs (e.g., of air pollution or climate change). Appendix A provides a complete delineation of the differences between categories 1, 2, and 3, and explains in detail how the societal-quantitative costs are not merely private-quantitative plus external costs. Table 2.1 and Appendix A do not discuss category-4 costs, societal-qualitative, because these share nothing in common with the private-quantitative costs that are the subject of this report.

TABLE 2.1 Cost elements and methodological comments for the private-quantitative, private-qualitative, and societal-quantitative categories on lifetime cost of motor vehicles

Perspective→	***Private***			***Societal***
General approach →	***(Partially) qualitative***		***100% quantitative***	
Scope of the cost analysis	Whatever private individuals or firms *perceive* as costs in the context		Market/financial costs to private individuals or firms,	Effects on everyone and everything in large-scale social, economic, and environmental systems
What is as a "cost"			Actual price-times-quantity payments, which *include* transfer payments (e.g., taxes, producer surplus), but *exclude* external costs	Only true economic resource cost, which is the area under the long-run marginal cost curve, *including* external costs, but *excluding* transfer payments
How costs are estimated	Consumer: subjective judgement	Analyst modeling consumers: econometric analysis; surveys	Explicit financial accounting	Social cost-benefit or welfare analysis; damage-function analysis
How estimates are used	Consumer: making own decisions	Analyst: to understand and model consumer behavior	To evaluate and compare the full private costs and benefits of vehicle ownership and use	To evaluate and compare the full social costs and benefits of transportation projects, policies, and scenarios
Time frame, analysis window	The period of initial vehicle ownership (implicitly)		The period of initial vehicle ownership (explicitly)	For vehicle: lifetime to scrappage For effects of vehicle use: many generations into the future
Financial parameters: discount rate, loans, risk	Considered qualitatively, typically with budget constraints, very short time horizons, and aversion to loss and uncertainty		Included quantitatively, based on actual interest payments and financial opportunity costs	The social discount rate includes only a national productivity component; the social cost of a loan is the administration cost

Note: The green-shaded column is the private-quantitative perspective/approach in this project.

2.2. REVIEW OF TCO LITERATURE

This section assesses literature related to a holistic TCO calculation. More detailed examination of the literature for each of the individual cost elements are described in the relevant portions of Section 3. In order to assess the state of knowledge of the TCO of conventional and alternative-powertrain vehicles (mainly electric vehicles), we reviewed and evaluated nearly 200 TCO studies published between 2000 and 2020. Our main objective was to determine which aspects of the TCO of motor vehicles were well researched and well analyzed, and which aspects were less well researched and analyzed and accordingly would benefit most from a new, focused research effort. In some cases, data sources, results, and methods from the literature informed the development of our own estimates of the TCO. About 15% of the reviewed studies estimated the TCO of MHDV (including buses); the remainder estimated the TCO of LDV. The vast majority of the studies were journal articles, relatively short reports, or sections of larger reports. As discussed next, only a handful were comprehensive and detailed.

We developed a template to evaluate the rigor and level of detail of these TCO studies. The template lists all of the main elements in a TCO analysis. For each study, we evaluated the quality of each TCO element. In order to have a consistent evaluation of the TCO elements across the studies, we created standardized quality ratings. Table 2.2 summarizes the quality ratings from the review templates. In general, few studies are *comprehensive* (cover all components of the TCO), *original* (as opposed to reliant on other work), and *detailed* (as opposed to making simple assumptions). For example, as shown in Table 2.2a, few studies have a quality rating of “A1” or “A2” for most of the cost elements. Many studies omit cost elements or make simple assumptions with little or no in-depth analysis. A spreadsheet accompanying this report evaluates all of the studies in greater detail (Delucchi 2021, ANL 2021a).

TABLE 2.2a Summary of quality of studies reviewed

	Number of studies with quality rating of:						
Cost aspect	*A1*	*A1**	*A2*	*B*	*C*	*D*	*n.e.*
Major new components	12	15	11	15	58	1	78
Vehicle manufacturing cost	5	10	6	5	26	3	135
Vehicle retail cost	2	8	5	10	41	3	121
Energy use	16	16	7	13	32	9	97
Energy price	2	7	5	11	45	9	111
Non-energy operating costs (e.g. insurance, M&R, and other costs such as tolls and fees)	2	6	3	4	25	5	145
External costs (in physical units)	8	23	12	6	21	1	119
External costs (in dollars)	1	7	2	2	14	0	164
Other factors affecting lifetime cost	1	2	6	8	25	4	144

TABLE 2.2b Explanation of quality of studies reviewed

Rating	Explanation of quality rating
A1	A comprehensive, detailed and original analysis or model, with complete documentation (e.g., a study that features original models of manufacturing cost, energy use, air pollution damages, or emissions).
A1*	Same as A1, but based on use of models developed by others (e.g., a study that uses the GREET model to estimate life-cycle emissions or the BatPaC model to estimate battery manufacturing cost).
A2	Similar to A1 – an original analysis – but significantly less detailed and comprehensive.
B	Estimate based on a very simple calculation or function. Whereas A1 studies have detailed models, and A2 studies have several functions, B studies have only a single calculation or function.
C	Estimate based on review and analysis of the literature, without any original calculations or modeling of any kind.
D	Assumption based on a literature citation with no analysis or review of the literature, or no citation at all.
n.e.	not estimated.

TABLE 2.2c List of studies with A1 or A1* ratings in three or more cost aspects

Study	Year
Delucchi and Lipman	2001
Electric Power Research Institute (EPRI)	2001
Lipman and Delucchi	2006
Goedecke et al.	2007
U.S. Environmental Protection Agency (EPA)	2009
Sun et al.	2010
Camus and Farias	2012
National Research Council (NRC)	2013
Stephens et al.	2016
Lee and Thomas	2017

Our review indicates the need for a more rigorous, comprehensive, detailed, up-to-date, internally consistent, transparent TCO study. Table 2.3 summarizes the research needs based on our review of the literature. Section 2.2.1 details the studies which merit particular discussion in this report, including several from Table 2.2c. An external report (Delucchi 2021) details findings from many other studies related to TCO calculations.

TABLE 2.3 Discussion of research needs

Cost aspect	Research need	Discussion
Major new components	Modest	Detailed models of costs of batteries and fuel cells are available for LDVs and have been used in or developed for TCO studies, but need to be extended to MHDVs. More work is needed to develop cost data and models for electric powertrains and for gaseous fuel tanks, for LDVs and MHDVs.
Vehicle manufacturing cost	Significant	Relatively little work has been done on estimating manufacturing cost and retail cost, apart from modeling the cost of new components. More work is needed on cost of new materials for gliders, body, etc.
Vehicle retail cost		
Energy use	Minor	Detailed energy-use models for conventional and electric-powertrain vehicles are available and have been used in prior TCO studies.
Energy price	Modest	Very few TCO studies have developed original estimates of energy price, but detailed energy-price estimates and projections are available from the Energy Information Administration (EIA) and other organizations. More work is needed on the cost of PEV charging infrastructure.
Non-energy operating costs	Significant, especially for insurance, M&R	Very few studies have made original, detailed estimates of the main non-energy operating costs, insurance and maintenance and repair.
External costs (in physical units)	Minor/ modest	Few TCO studies have developed original estimates of emissions of pollutants or greenhouse gases, but some studies have used detailed models developed by others.
External costs (in dollars)	Modest	Very few TCO studies have developed original estimates of external costs, but some studies have used detailed models developed by others.
Other factors	Significant, especially for depreciation	Few studies have developed or used detailed estimates of other factors affecting lifetime costs.

2.2.1. Highlights from Specific Studies

As shown in Table 2.2, studies generally do not develop a proper conceptual framework for estimating the TCO. General discussions of cost-benefit analysis can be found in any number of texts and papers (e.g., Johansson and Kriström 2018; Carolus et al. 2018). Van Velzen et al. (2019) propose a framework for estimating the future total cost of ownership of electric vehicles. They state that the main purpose of their framework is to focus on a few factors that can significantly affect future EV costs, such as the mark-up from manufacturing cost to retail price and the effects of scale economies and learning-by-doing. While they propose an influence diagram showing connections between factors and the TCO of electric vehicles, they do not develop a general *conceptual* framework.

Delucchi and Lipman (2001) developed a detailed, integrated model of the performance, energy use, manufacturing cost, retail cost, and lifecycle cost of electric vehicles and comparable gasoline internal-combustion engine vehicles (ICEVs). The integrated model has three major parts: a sub-model of vehicle cost and weight; a sub-model of vehicle energy use; and an assessment of periodic ownership and operating costs. The sub-model of vehicle cost and weight consists of a model of manufacturing cost and weight, and a model of all of the other costs – division costs, corporate costs, and dealer costs – that compose the total retail cost of a vehicle. The manufacturing cost is the materials and labor cost of making the vehicle, estimated for each of the nearly 40 sub-systems that make up a complete vehicle. This sub-model also performs detailed analyses of the manufacturing cost of batteries and electric drivetrains. The lifecycle cost aspect of the model handles insurance payments in some detail, establishing a relationship between the liability and physical-damage insurance premiums, and the value and annual travel of a vehicle. The maintenance and repair cost analysis is based mainly on the comprehensive data on sales of motor-vehicle services and parts reported by the Bureau of the Census.

The Electric Power Research Institute (EPRI 2001) estimated the vehicle manufacturing cost using Component-Based Cost Analysis. This method estimates glider costs, engine costs, transmission costs, electric traction costs, accessory costs, storage system costs, battery module cost, other battery component costs and charger costs. To estimate Retail Price Equivalents (RPE) of the vehicle components, they examined both the cost of labor and materials for each component as well as what a manufacturer would pay to build the component itself or buy it from a supplier. Operating costs, including costs for fuel and maintenance, are calculated using label-adjusted fuel economies and representative driving patterns based on survey results.

Lipman and Delucchi (2006) analyzed the manufacturing costs, retail prices, and lifecycle costs of five hybrid gasoline-electric vehicle types in high-volume production. Updating and major modifications were made to a detailed motor vehicle retail and lifecycle cost spreadsheet model that had previously been used to analyze the costs of conventional vehicles, electric-drive vehicles, and other alternative-fuel vehicles (Delucchi and Lipman 2001). This cost model was combined with a hybrid vehicle design and performance analysis using the ADVISOR vehicle simulation model. The U.S. Environmental Protection Agency (EPA 2009) published an extremely detailed cost analysis for hybrid electric vehicles, plug-in hybrids, and full electric vehicles. The report considers several vehicle classes: subcompact, compact, midsize, large passenger car, large multi-purpose vehicle, small truck and large truck. In general, the costing methodology employed in this analysis is based on the development of detailed production process flow charts and the transferring and processing of key information from the process flows into standardized cost worksheets.

Sun et al. (2010) estimated the societal lifetime cost of hydrogen FCEVs and conventional gasoline internal combustion engine vehicles. They used AVCEM (Advanced Vehicle Cost and Energy-use Model), a vehicle performance and design model, to design a vehicle to exactly satisfy performance and range specification with no more power and storage than is needed (Delucchi 2005). They used the Steady State City Hydrogen Infrastructure System Model to estimates regional hydrogen infrastructure costs, emissions and primary energy requirements, and used the Lifecycle Emissions Model to estimate energy use, criteria pollutant emissions, and CO2-equivalent greenhouse-gas emissions from a variety of transportation and energy lifecycles (Delucchi 2003). Sun et al. estimate the external costs of oil use, air pollution, climate change and vehicle noise. The external costs of oil use per mile are calculated simply as the external cost per gallon of petroleum divided by the fuel economy. The fuel economy is calculated within AVCEM; Sun et al. use the results. The external cost per gallon is based upon a base-year value and an assumed rate of change.

The National Resource Council (NRC 2013) assessed the potential of alternative fuels and alternative powertrains to reduce oil use and GHG emissions from the US LDV fleet by 80% by the year 2050. The report uses four models to estimate future vehicle characteristics, vehicle penetration into the market, and the impact on petroleum consumption and GHG emissions. To estimate energy use, the NRC used an ICEV model developed by a consultant that projects vehicle efficiency out to 2050 by focusing on the reduction of energy losses from vehicle use. To estimate the costs of vehicle technologies, the NRC developed a spreadsheet model of technology costs. To estimate GHG emissions and oil use, the NRC modified and updated ANL's VISION model (Singh et al. 2004). The NRC then reviewed the literature and applied estimates of the social cost of carbon and the social cost of petroleum use. To model consumer demand for vehicles, the NRC used the LAVE-Trans model.

Stephens et al. (2016) estimated the benefits of successfully developing advanced vehicle technologies, including battery-electric, hybrid, and fuel-cell vehicles. The incremental costs associated with advanced powertrains were estimated based on DOE cost and performance targets and cost models developed by Ricardo Engineering and the ANL Autonomie group (ANL 2019). The Autonomie model also was used to simulate vehicle energy use. The fleet mix was modeled using several consumer vehicle choice models, and GHG emissions and oil use were estimated using the GREET model (ANL 2020) and the VISION model (Singh et al. 2004). The researchers concluded that their analysis demonstrates that "successful VTO and FCTO programs will significantly reduce (1) oil consumption and oil dependence, (2) GHG emissions, and (3) consumer energy expenditures…[and that] these programs offer American drivers [other] benefits…including increased mobility, and reduced exposure to potential oil price shocks."

Lee and Thomas (2017) focused on medium- and heavy-duty vehicles to analyze ownership costs for diesel, hybrid electric compressed natural gas, biofuel and electric class 6 freight trucks, including vehicle purchase, fuel, maintenance, diesel emission fluid, and electric vehicle supply equipment (EVSE). Fuel economy was based on vehicle simulations, and costs were estimated from a variety of publicly available estimates.

Beyond the conceptual framing of the above studies, several reports have presented TCO from a consumer-focused perspective. The Automobile Association of America (AAA) and Consumer Reports have published reports for LDV, while the American Transportation Research Institute has published an annual series of papers for tractor trailers. Every year, AAA releases its *Your Driving Costs* report, which estimates of the cost of owning a new vehicle for five years, including depreciation, fuel, maintenance, insurance and other fees for several light-duty passenger vehicle size classes (e.g. AAA 2020). The latest version of this report found that HEV are cheaper to own than most ICE sedans and SUVs, and that BEV and HEV had the lowest operating costs but BEV have the highest depreciation costs. The representative proportions of each of the cost components (for a small gasoline-fueled SUV) are presented in Figure 2.1a. The CR white paper compared costs of electric vehicles with conventional vehicles (Harto 2020a). They found that BEV and PHEV can be cost-competitive with gasoline-fueled ICE after accounting for reduced maintenance and fuel costs. Relatedly, Runzheimer and Company (now part of Motus) has historically quantified the cost of driving in terms of business reimbursements for the Internal Revenue Service (IRS). In 2021, the business mileage standard rate is 56 cents per mile (Motus 2020).

Likewise, a number of recent papers on ownership costs of heavy-duty vehicles cite the annual report issued by the American Transportation Research Institute (ATRI) on the operational cost of trucks (Murray and Glidewell 2019). The annual ATRI reports provides valuable data on current and historical costs of long-haul diesel trucks. These reports include both average annual labor and vehicle costs as shown in Figure 2.1b. Labor and fuel costs are the two largest costs for commercial freight carriers, with labor costs increasing sharply since 2012. Although fuel costs have often been volatile, though have been relatively low the past few years due to a drop in diesel prices and improvements in truck fuel economy. Truck payments are the third highest cost-category and have been rising since 2013.

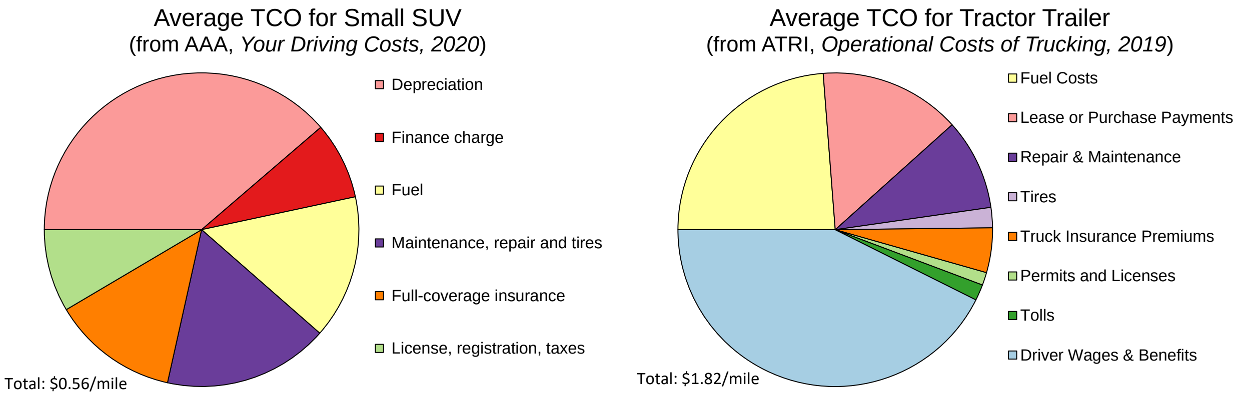


FIGURE 2.1 Left: Costs for driving medium SUV, data from AAA (2020). Right: Costs for driving class 8 tractor trailer, data from ATRI (Murray and Glidewell 2019).

Murray and Glidewell (2019) report that maintenance and repair costs have declined from $0.17 per mile in 2008 to $0.10 per mile in 2018, while tire costs have been fairly consistent, $0.04 per mile in 2018, as shown. Given an average freight truck VMT of 88,250 in 2018, maintenance and repair and tire costs were $12,400. Finally they note that the EPA 2007 emission standards required the installation of a diesel particulate filter (DPF) to meet particulate matter emissions requirements. This DPF must be “regenerated” occasionally to remove accumulated material from the filter. While this increased M&R costs for fleets with urban duty-cycles, it did not significantly impact the commercial trucking industry as highway duty-cycles enable passive regeneration, which limits DPF clogging.

Although vehicle ownership costs have been the subject of a number of studies, particularly light-duty vehicles, gaps remain that make it difficult to comprehensively assess ownership costs of vehicle of a wide range of powertrain types and size classes. Purchase and fuel costs of currently available vehicles can be estimated, though some costs and factors influencing costs remain uncertain and insufficiently well documented in the literature. Other costs, such as taxes and fees, are well-known, but variable from state to state and across vehicle classes. Operational costs and factors that influence these vary significantly, especially for commercial medium- and heavy-duty vehicles and studies vary in assumptions about these (neglecting them in some cases). A synthesis of available data and modeling results for future vehicles and systematic analysis of ownership costs is needed to enable assessment of these costs for a range of vehicle with different powertrain types under a variety of assumptions.

2.3. QUANTIFICATION OF TCO

For the private-quantitative cost analysis described in Section 2.1, we have identified the most relevant cost elements for a total cost of ownership analysis in this study. With the inputs from Section 3, we can combine the values of each of these cost elements in a cohesive total cost of ownership calculation. In this analysis, TCO is split into nine components (see Table 2.4):

- Vehicle cost
    - The vehicle cost includes the cost of purchase less the residual value of the sale of the vehicle at the end of the analysis window.
- Financing
    - Financing represents the cost of interest payments beyond the retail price of the vehicle.
- Fuel
    - Fuel cost is proportional to the driving distance, the fuel efficiency of the vehicle, and the cost of the specific fuel needed by the vehicle.
- Insurance
    - Insurance costs cover both liability and vehicle replacement or repair, using national average of costs for light-duty drivers, and all typical costs for each MHDV vocation.
- Maintenance and repair
    - Maintenance includes the cost of scheduled vehicle repairs as the vehicle ages, as well as unscheduled services for inspection and replacement of vehicle parts that do not have set replacement intervals.
- Repair
    - Repair accounts for unexpected costs to operate a vehicle, after accounting for regular maintenance and fixes made while under warranty.
    - For heavy-duty vehicles, maintenance and repair are combined due to lack of data distinguishing the two categories.
- Taxes & fees
    - Taxes and fees include taxes on vehicle sales as well as any recurring annual costs, such as registration fees, parking, and tolls.
- Payload capacity expenses
    - Payload capacity expenses are additional costs from adjustments in fleet vehicle operation due to the increased weight of new vehicle technologies.
- Labor
    - Labor costs are representative of the typical wages and benefits for drivers. This also includes additional time for charging or fueling vehicles. For light-duty vehicles used as household vehicles, operational and labor costs are both zero.

In this TCO calculation we account for the relationships between individual components, using a consistent set of underlying assumptions. For example, while maintenance and repair costs come from numerous different sources, these sources are all harmonized to have the same usage profile in this study, accounting for variations in size class, powertrain, travel behavior, and economic assumptions. Where possible, functional forms have been generated for each component to account for variability in these assumptions. The details for each specific cost element are described in greater detail in Section 3 of this report.

The core underlying assumptions about vehicle sizes and powertrains directly influence nearly every calculation. Vehicle characteristics depend on the model year (MY) of the vehicle – future alternative vehicles are expected to experience technological and production progress which results in in lower cost and higher fuel efficiency. The incumbent technologies on the other hand experience an increase in cost and efficiency reflecting cost of investments for incremental efficiency improvements. Key vehicle parameters such as the vehicle manufacturing cost, fuel economy, and weight are all taken from Autonomie simulation results (Islam et al. 2020; Vijayagopal et al. 2019); a comparison of Autonomie simulation with real-world vehicles is presented in Section 3.2.3. Table 2.4 shows the inputs that influence each cost component. Most cost elements depend on vehicle parameters such as the size class and powertrain. Many of them are proportional to the total vehicle miles traveled (VMT) and related to the vehicle MSRP.

TABLE 2.4 Cost components and interdependencies

Cost components	Key inputs
Vehicle	MSRP, Powertrain, Size class, Incentives, Battery size, VMT, Performance
Financing	MSRP, Finance terms
Fuel	Powertrain, MY, VMT
Insurance	MSRP, Size class, VMT
Taxes & Fees	MSRP, VMT, Powertrain, Size class, Weight
Maintenance	Powertrain, Size class, VMT
Repair	MSRP, Powertrain, Size class
Labor	VMT, Fuel
Payload	VMT, MSRP, Weight, all others
Non-Cost components	**Key inputs**
MSRP	Powertrain, Size class, MY, Retail markup
Fuel Economy	Powertrain, Size class, MY
Weight	Powertrain, Size class, MY
VMT	Size class, Payload

In this analysis, we find a total cost of ownership based on discounted cash flow. This is presented in Equation 2.1, where i is the year of the cash flow (positive or negative), N is the total length of the analysis window, d is the discount rate accounting for opportunity cost, and C_i

represents a cash flow in year *i*, in real (not nominal) dollars, adjusted for inflation, but not discounted.

$$TCO = \sum_{i=1}^{N} \frac{C_i}{(1+d)^i} \qquad \text{Eq 2.1}$$

The present value of expenses in each year are added, i.e., values beyond the first year are discounted using the relevant real discount rate, described in greater detail in Section 2.3.1. For LDVs, we assume a discount rate of 1.2% while for MHDVs we use a discount rate of 3.0%. We treat all cash values as 2019 dollars. Figure 2.2 shows the discounted cash flow for a conventional gasoline-fueled spark-ignition (SI) internal combustion engine SUV, simulated for MY 2025. In this calculation, we assume that the vehicle cost includes a down payment of 12% in the first year and loan payments in the first through fifth years, and that the vehicle is sold or scrapped in year 15. We also assume the miles driven per year decreases from 16,000 mi in the first year to under 11,000 in year 15 for a total of 201,400 miles, based on NHTSA and EPA regulatory analysis (NHTSA and EPA 2020), see Section 2.3.3 for more detail. Over this time window, the vehicle is the most expensive single component, followed by the fuel, maintenance, and insurance. In years 2 through 5, vehicle and financing costs sum to a constant value, representing fixed monthly loan payments, while year 1 has additional incurred costs from the vehicle downpayment along with sales tax and vehicle titling. The negative cash flow for vehicle cost in Year 15 is the residual value from the vehicle being sold.

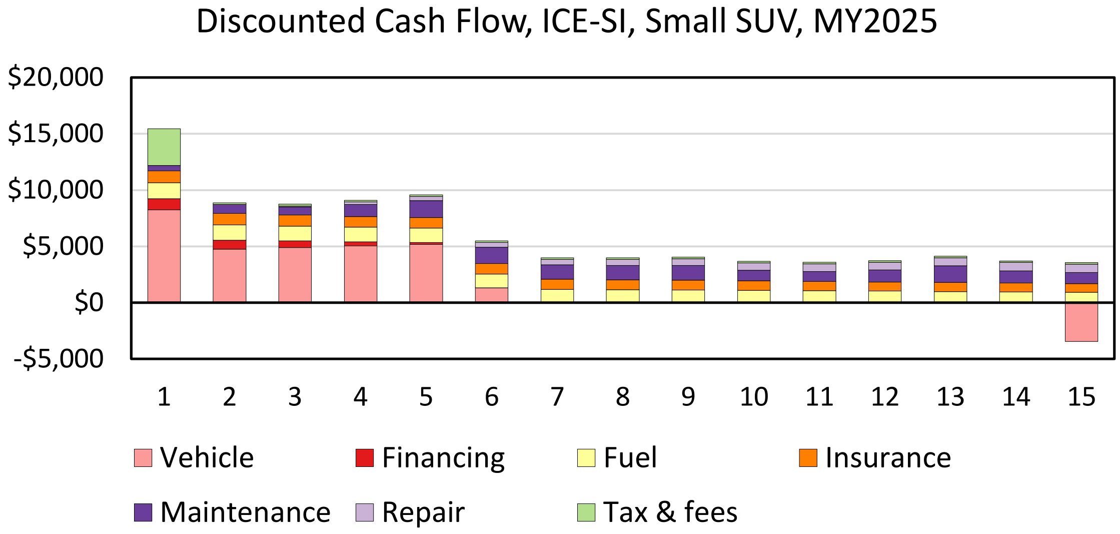


FIGURE 2.2 Discounted cash flow graphic, MY2025 small SUV example

While this cash flow analysis is straightforward, an alternative to showing vehicle purchase and resale/salvage cash flows is to show the vehicle costs as depreciation of the vehicle, i.e., to amortize the vehicle cost over its life. Vehicle costs are then given by depreciation, as shown in Figure 2.3. In the example shown in Figure 2.3, the large cost incurred in the first year is due to the large depreciation in the first year, the difference between a “new” and “used” car, along with sales taxes. While these figures may look different, it is worth noting that the total costs are identical, after accounting for the discounted residual value of the cash flow in the year that the vehicle is sold, and the use of the format in Figure 2.3 is largely for clarity of presentation.

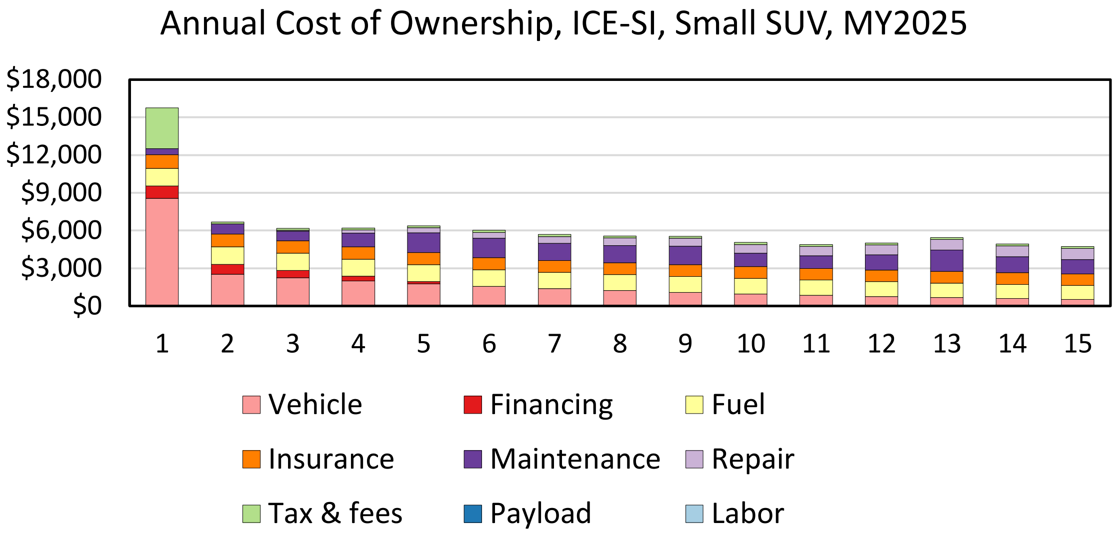


FIGURE 2.3 Annual cost of ownership graphic, MY2025 small SUV example

In addition to a calculation of total costs over the life of a vehicle (or over some period), it can be insightful to amortize the total cost over the distance the vehicle is driven. The most common way is to calculate costs on a per-mile basis, presenting a levelized cost of driving (LCOD), though other related metrics such as cost-per-ton-mile, cost-per-passenger-mile, and cost-per-revenue-mile can be useful for specific applications. We calculate the cost per mile in each year as the ratio of real costs to miles driven in each year. Figure 2.4 presents the same data as in Figures 2.2 and 2.3 as a levelized cost of driving. As with Figure 2.3, vehicle costs are amortized. In order to quantify the LCOD, we need to amortize the cost over the miles driven in each year, or equivalently, “discount” the miles along with the costs, as described in greater detail in Section 2.3.3. This gives Equation 2.2:

$$LCOD = \sum_j LCOD_j = \sum_j \left(TCO_j / \sum_{i=1}^{N} \frac{VMT_i}{(1+d)^i} \right) \qquad \text{Eq 2.2}$$

where the subscript *j* represent each of the individual cost elements comprising the TCO calculation.

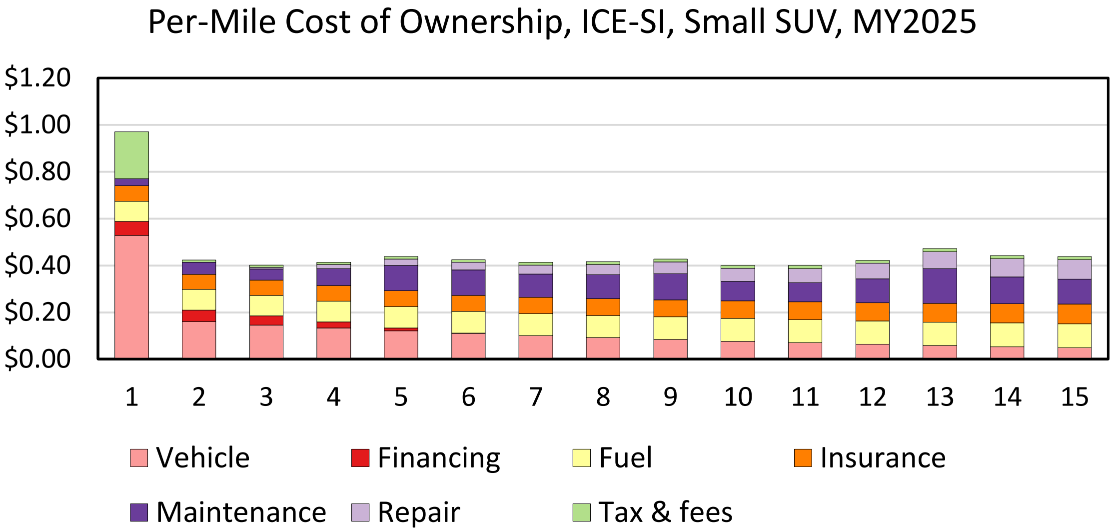


FIGURE 2.4 Cost per mile as a function of vehicle age graphic, MY2025 small SUV example

While Figures 2.2 – 2.4 show cost on an annual basis, it can also be informative to see costs on a mileage basis. An observant reader will note that while the total annual costs (shown in Figure 2.3) decrease over time, the *per-mile* annual costs increase slightly (Figure 2.4), as maintenance and repair costs grow. Figure 2.5 presents the same data, using cumulative lifetime VMT as the horizontal axis. Some of the specific component costs are proportional to mileage driven, but others depend on the age of the vehicle, so the per-mile cost is still an implicit function of the vehicle vintage and the specific VMT schedule being modeled.

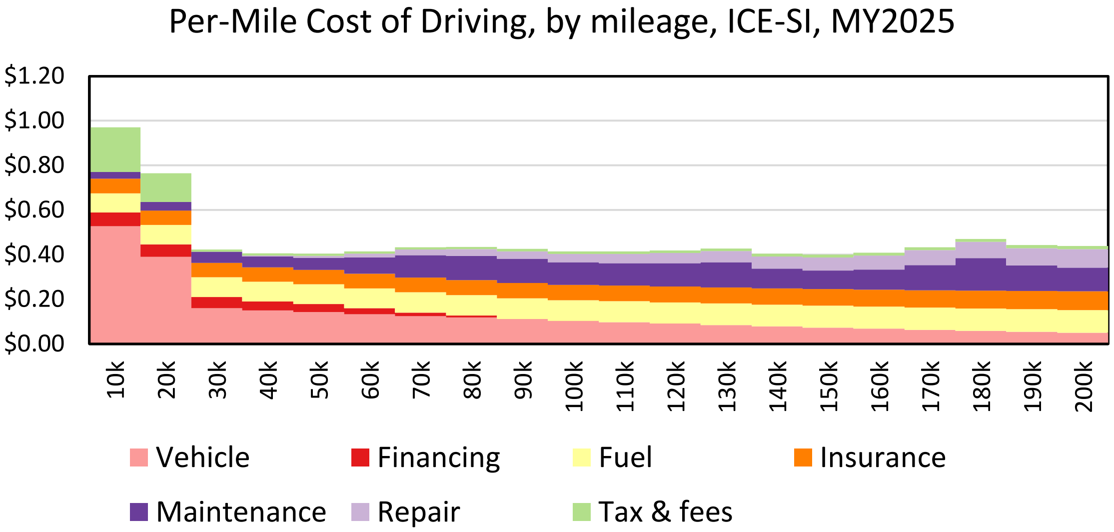


FIGURE 2.5 Cost of driving as a function of cumulative lifetime mileage, small SUV example

Finally, when comparing across multiple vehicles, it is often convenient to aggregate across the entire analysis timeframe. Figure 2.6 shows the total cost of ownership and average cost per mile for these graphics.

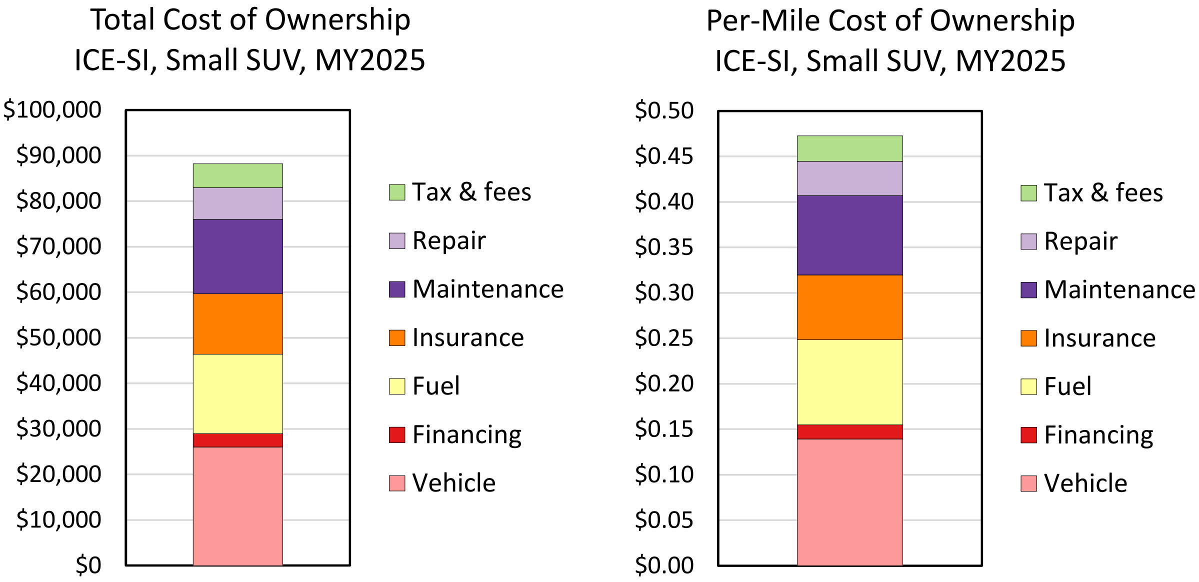


FIGURE 2.6 Lifetime costs for operating a gasoline-powered MY2025 small SUV

The remainder of this section addresses the core analytical assumptions which are necessary for a quantification of TCO, namely the underlying assumptions for financial analysis, analysis timeframe, and vehicle travel and survival.

2.3.1. Financial Analysis

TCO calculations involve an extensive set of financial parameters. Among these, interest rate, inflation, and discount rate parameters are the most important for calculating a private-quantitative TCO based on real prices. We estimate private interest and discount rates relevant to estimating costs and benefits from an economically rational perspective. As noted above, whereas the social perspective considers *all* costs of any kind, including so called “external” costs; the private-quantitative perspective considers only those costs relevant to a quantitative full-cost accounting from the perspective of a private individual or firm. The TCO is the sum of the discounted cash flows as presented earlier in Equation 2.1.

2.3.1.1. Discount Rate

The discount rate mathematically represents the opportunity costs of cash flows at different times. We distinguish between upfront costs and ongoing costs, as future costs are discounted. For the vehicle purchase, we further distinguish between paying cash up front and financing. For an up-front cash payment, the opportunity cost is the alternative use of the money, which may be represented, for example, by an interest rate for ordinary saving accounts or safe short-term investments. Thus, an initial cash payment can be annualized at the real after-tax interest rate on investments or savings foregone by paying cash for transportation.

In the case of a loan, the actual cost to the borrower is not the initial cost of the vehicle, but rather the periodic cash loan payment. Hence, for a borrower, one first must calculate the actual loan payments, which depend on the amount of the loan, the life of the loan, and the interest rate on the loan, measured as an annual percentage rate (APR). The resulting loan payment series then is treated as an ordinary annuity; one finds the present value of the loan payment series, on the basis now of the *discount rate:* the interest rate for consumer savings or similar safe short-term investments. Finally, this present value can be annualized over the entire life of the vehicle, again on the basis of the discount rate *qua* personal opportunity cost of money. This procedure is necessary because the interest rate that pertains to loans is different from discount rate – the interest rates that express consumers' opportunity cost of money – and because the life of the loan is different from the life of the vehicle financed with the loan. (Note that it is standard practice to calculate the lifetime cost on the basis of monthly interest rates and monthly travel, rather than annual interest rates and annual travel. There is a slight difference between the two methods. The monthly interest rate is 1/12th of the assumed annual rate, and the monthly mileage rate is 1/12th of the estimated annual mileage.) If the discount rate is lower than the interest rate on the loan, such as with low-APR purchase incentives, it can be financially advantageous to finance a vehicle in spite of the nominal increase in cost. In general, however, loan rates are higher than the discount rate.

The opportunity cost can be viewed as a foregone reasonable investment over the given timeframe. For large, infrequent purchases, this can be assumed to be comparable to interest rates on treasury notes, which have historically averaged about 3.2% (FRB 2021b, table H.15). For ongoing expenses, this can be compared to a savings account, which generally offers lower interest rates than longer-term certificates of deposit. For businesses, a nominal cost of capital of 5% is assumed. This is necessarily higher than for individual consumers, as otherwise a business would solely invest in bonds rather than into the company itself.

2.3.1.2. Loans and Financing

Data from Experian notes that 87% of new vehicle purchases were financed, and approximately 40% were from banks and 60% from financing companies (Zabritski 2020). According to Experian, the average loan rate in 2019 was 5.9%. Personal loan rates can range as a function of creditworthiness and loan terms, with higher interest rates typical of consumers with lower credit ratings. The average loan for a new vehicle in the highest credit tier was just under 4% APR in 2019, while the average APR in the lowest credit tier was nearly 15%. The

Federal Reserve Board (FRB) also publishes information about average loan characteristics: the average APR on a 48-month bank loan was 5.4%, the average APR on a 60-month bank loan was 5.3%, and the average interest rate from a finance company was 6.4% on a 67-month term (FRB 2021a, table G.19). Historically, the typical APR is somewhat volatile year-over-year. Since 2000, the FRB data notes that the annual average APR for a prime bank loan has ranged from 3.25% to 9.23%, with an average of 4.79% (FRB 2021b, table H.15).

As noted above, finance rates on personal loans are a function of credit score, which in turn is moderately correlated with income (Beer et al. 2018). However, vehicle purchase choices are also a function of income, and so real-world interest rates may vary across vehicles, because of differences in the populations buying them (Cox 2021). In this analysis, we present an analysis from the perspective of a private individual or firm doing a comprehensive, quantitative, data-based estimation of the TCO, rather than an analysis across a broad population. Therefore, we do not account for differences in national-average loan rates across vehicles (or consumers) outside of sensitivity analyses.

Interest rates for commercial vehicles are even less uniform than for LDV. The FRB prime rate, or the average majority prime rate charged by banks on short-term loans to business, was 5.3% in 2019 (FRB 2021b, table H.15). Data from Nav shows traditional commercial bank loans ranged from 2–13% APR in 2020 (Luthi 2020), while other funding sources such as online loans and invoice financing extend even beyond that range of interest rates (Brex 2020). In this analysis, we use the same default loan parameters for MHDV as for LDV.

The average loan term has increased over the last decade. Experian reports that the average loan term for new vehicles was 69 months in 2019, while the average loan term for the highest credit tier was 63 months. The FRB reports an average loan time of 67 months for loans from finance companies, but does not present a weighted average loan term for loans from banks and credit unions. Value Penguin reports the average loan term of 63 months (Wamala 2020) while Credit Karma reports the average loan term of 71 months (Clarke 2020). In this analysis, we will use 63 months (5.25 years) as the default loan term.

The average down payment on a vehicle loan is approximately 12% (Montoya 2019). This is similar to historical data from the FRB of a 90% loan-to-value ratio, though this data set has been discontinued (FRED 2012). In this analysis, we use 12% as our default value.

2.3.1.3. Inflation and Real Discount and Interest Rates

Prices can change because of general price inflation, whereby prices throughout the economy rise for a given level of total output – i.e., a fixed level of costs. Since our purpose is to estimate changes in actual costs, we account for changes in prices due to general inflation.

To avoid mistaking price inflation for changes in actual cost, we want to express and compare all cost estimates in terms of the same price level – the same amount of money per unit of output. Implicit Price Deflators (IPD) can be used to account for general price inflation. We call the designated year of price/output level *the price year*. Dollar values expressed with respect to a single price year are called “constant” or “real” dollars (because they are based on prices at a constant output level). In this analysis, we use dollar year 2019$ for all costs. Given that different data sources may have different assumptions, we convert all prices to 2019$.

To estimate the rate of inflation we use the Gross Domestic Product (GDP) Implicit Price Deflator from the U.S. National Income Product Accounts (NIPA) compiled by the U.S. Bureau of Economic Analysis (BEA, 2020). This expresses the yearly change in the relationship between prices and output. Thus, we can pick a single price/output year upon which to base all of our cost estimates, and use the GDP IPDs to convert all estimates to this particular year. The “real” GDP is calculated with base-year prices but also with a “chained dollar” *current*-year quantity index known as a Fisher index. The chained-dollar Fisher quantity index is calculated by compounding the year-over-year changes between the base year and the current year (Landefeld et al. 2003).

Alternatively, the Consumer Price Index (CPI) from the Bureau of Labor Statistics (BLS) is a weighted average of the prices of a fixed bundle of goods and services purchased by wage earners in urban areas (BLS 2021). It thus differs from GDP IPDs in several ways: it is based on a subset of goods and services in the economy, whereas the IPDs pertain to all goods and services that make up GDP; CPI is based on a *fixed* bundle of goods and services, whereas the IPDs are based on the actual mix of goods and services in the economy year to year; it is limited to purchases by wage earners in urban areas, whereas the IPDs cover all economic activity; and it is referenced to prices in a base year, whereas IPDs are not.

We compiled inflation forecasts by experts from surveys from 1990 to 2019 (Federal Reserve Bank of Philadelphia 2020), the historical general CPI from 1990 to 2019, historical GDP IPDs from 1990 to 2019, and the average of all three. We believe that the full data series (1990 to 2019) is most representative, because it includes periods of relatively high and low inflation. In general, the GDP IPDs give a broader measure of inflation than does the CPI. Also, Dotsey et al. (2003) argue that IPDs are more consistent than are CPIs. Therefore, we use GDP IPDs for evaluating macroeconomic parameters such as the discount rate and rate of inflation. In this study, we assume an annual inflation rate of 2% for future costs, similar to recent historical data from the IPDs (BEA 2021). By subtracting this rate of inflation from nominal discount rates and APR (OMB 1992), we find real discount rates and APRs, as shown in Table 2.5.

TABLE 2.5 Key economic parameters for financial analysis

Parameter	**LDV**	**MHDV**
Inflation rate	2.0%	2.0%
Discount rate (nominal)	3.2%	5.0%
Discount rate (real)	1.2%	3.0%
APR (nominal)	6.0%	6.0%
APR (real)	4.0%	4.0%
Loan maturity term	5.25 years	5.25 years
Down payment	12%	12%

Our recommended values can be compared with others. Bekdache (1999) develops a model of ex ante real interest rates that depends on economic variables other than just historical values. Bekdache (1999), Chen (2001), and Dotsey et al. (2003) estimate that from 1960 to the mid 1990s real rates were in the range of 2 to 4% for government notes, excluding the period of relatively volatile inflation from about 1972 to 1987. This is comparable to, but somewhat higher than, the discount rates in Table 2.5 because those data include several years of estimated *negative* real returns. Bekdache concludes that "short term movements in nominal interest rates are more closely related to changes in real borrowing costs than they are to changes in inflationary expectations" (Bekdache 1999, 188).

2.3.2. Analysis Timeframe and Survivability

As mentioned above, the lifetime cost of motor-vehicle use is some aggregation of the costs related to owning and operating motor vehicles *over some period*. We can compare the costs of individual vehicles over some analysis period, or the cost of vehicle fleets that evolve over some period of time. In either case, the basic method is to estimate the present value of all the pertinent cost streams (i.e., those that differ across vehicles) over a given analysis period. In this analysis, we choose a fixed analysis window as an exogenous input to our TCO calculations. In actuality, it is quite possible that the vehicle ownership period is affected by operational costs, such as the need for major repairs or unaffordable fuel prices. In this analysis, a sudden vehicle retirement (such as if a vehicle crashes and is scrapped) would change the analysis window, but also necessitate the purchase of a replacement vehicle. Such a dynamic model for a multi-vehicle TCO is a particularly interesting research topic, but outside the scope of this report.

Two common choices for the analysis window are over the entire lifetime of a vehicle, and over the assumed ownership time of the first owner of the vehicle. In either case, we must be careful to properly treat cost streams that actually continue past the analysis period. At the end of the analysis window, the vehicle will have some residual value. The vehicle can be sold to a new owner based on its market value, or salvaged for parts or scrap at the end of its life. Calculations for vehicle depreciation assume that the vehicle is in good, drivable condition, and so innately account for repairs throughout the vehicle life. However, the calculation may underestimate residual value for vehicles with major M&R expenses to replace components late in the vehicle's life. Some repairs or components that are replaced during the life of a vehicle (assuming for the moment that the analysis period is to the end of vehicle life), such as the battery pack in electric vehicles, still have value at the end of vehicle life, beyond what would be typically expected by depreciation. Generally, for an investment in a vehicle near the end of the analysis window, N, there will be substantial residual value for investment made in year N, less residual value for investments made in year $N-1$, and so on back to the initial vehicle purchase. The present value of the sum of these residual values in year Y should be deducted from the present value of the cost streams. Therefore, in this analysis, we assume that major repairs (e.g. engine rebuild, battery replacement) do not occur late in the vehicle's life in the baseline scenario, and that minor repairs are incorporated into the model for residual value.

In this analysis, we use a default timeframe of 15 years for light duty vehicles. While this is longer than the first owner typically holds possession of the vehicle, it is representative of the costs that will be incurred over the ownership of the vehicle. We analyzed survivability rates from data published by the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation (Lu 2006) and by the EPA (EPA 2016), finding the average lifetime of a vehicle in the United States was approximately 14 years in 2006 and just under 16 years in 2016. Independent analysis by Bento et al. also found an average lifetime of just under 16 years as well, which has grown over time (Bento 2018). The ultimate ownership period of the vehicle is often determined by if a vehicle is cost effective to operate for the owner. Using a 15-year lifetime allows for exploration of the growth of maintenance and repair costs as the vehicle ages. An analysis published by the US DRIVE industry-government partnership assessed multiple time periods ranging from 3 to 15 years (Elgowainy et al. 2016): "The shorter time periods capture the perspective of the typical first purchaser. The longer time period, chosen to cover the entire life of the vehicle, provides a societal perspective. Both perspectives are important in comparing different vehicle-fuel technology combinations." (Elgowainy et al. 2016, 98)

For medium- and heavy-duty vehicles, a default analysis window of 10 years is assumed. For vocational vehicles, the analysis window is related to a payback period. Ricardo found that the typical desired payback is not over the vehicle's full useful life. "Based on the data that was collected, the typical desired payback period is half of a vehicle's useful life… class 8 long haul trucks will replace their trucks after about 3 years and desire an 18-month payback period… Class 7 & 8 vocational trucks and class 4-6 urban delivery vehicles have longer useful life, so customers can accept a 3- to 5-year payback window." (Ricardo 2017, 7)

Many of these vehicles go through multiple owners over a 10- or 15-year time window. The VMT schedules that are used in this study are representative of average vehicles for a given vintage, as these are broadly representative of fleet usage. Because of this, it makes sense to consider an analysis window beyond a first owner for these fleet vehicles. However, a shorter analysis window increases the relative importance of depreciation rates early in a vehicle's life, therefore we consider a shorter window in some sensitivity cases.

2.3.3. Vehicle Travel and Mileage

In this analysis, our default assumption for driving behavior comes from vehicle mileage schedules published by NHTSA and EPA for LDV (NHTSA and EPA 2020) and by the U.S. Census Bureau for MHDV (U.S. Census 2004), which are reproduced in Figure 2.7. The baseline mileage schedules for VMT for passenger cars and for light-duty trucks are from the Final Regulatory Impact Analysis (FRIA) from the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule published by NHTSA and EPA. We note that these mileage schedules are derived by averaging across vehicles which have different ownership patterns as opposed to focusing on a single owner. These mileage schedules show higher mileage early in a vehicle's life, gradually decreasing as the vehicle ages. For cars and SUVs, initial VMT is approximately 16,000 which drops to approximately 10,000 by year 15. Pickup truck VMT decreases from 19,000 to 10,000 over the same time window. Vehicle driving behavior is assumed to be independent of powertrain. Short-range BEVs have been found to drive less than comparable ICEV, but on average a 300-mile range BEV is expected to be driven within 4% of the average distance that a typical ICEV is driven (Gohlke and Zhou 2020).

VMT schedules for MHDV come from the Vehicle Inventory Use Survey (VIUS), last performed by the U.S. Census Bureau in 2002 (U.S. Census 2004). Like LDV, MHDVs also exhibit a decrease in mileage over time, and have a very large variance in annual miles across each of the different MHDV vocations and size classes. These range from medium-duty delivery trucks which drive comparably to passenger LDV to heavy-duty tractor-trailers which can drive over 100,000 miles per year early in their lives. Sleeper-cab tractors represent long-haul trucks, while day-cab tractors represent regional and local trucking, and so sleeper-cab tractors drive approximately 50% more than day-cab tractors. A class 8 vocational truck can have many different configurations; in this analysis we use a VMT representing a single-unit heavy-duty freight truck, which is aligned with the underlying modeling assumptions from Autonomie. The class 8 vocational and refuse trucks each drive more than 30,000 miles per year early in their lifetimes, dropping below 20,000 after 15 years. Transit buses drive consistent distances throughout their lifetime, approximately 40,000 miles per year. For nearly all MHDV mileage schedules, the annual VMT increases in the second year; this is likely a quirk in the underlying sampling for the VIUS data including partial-year driving, as opposed to an increase in daily VMT.

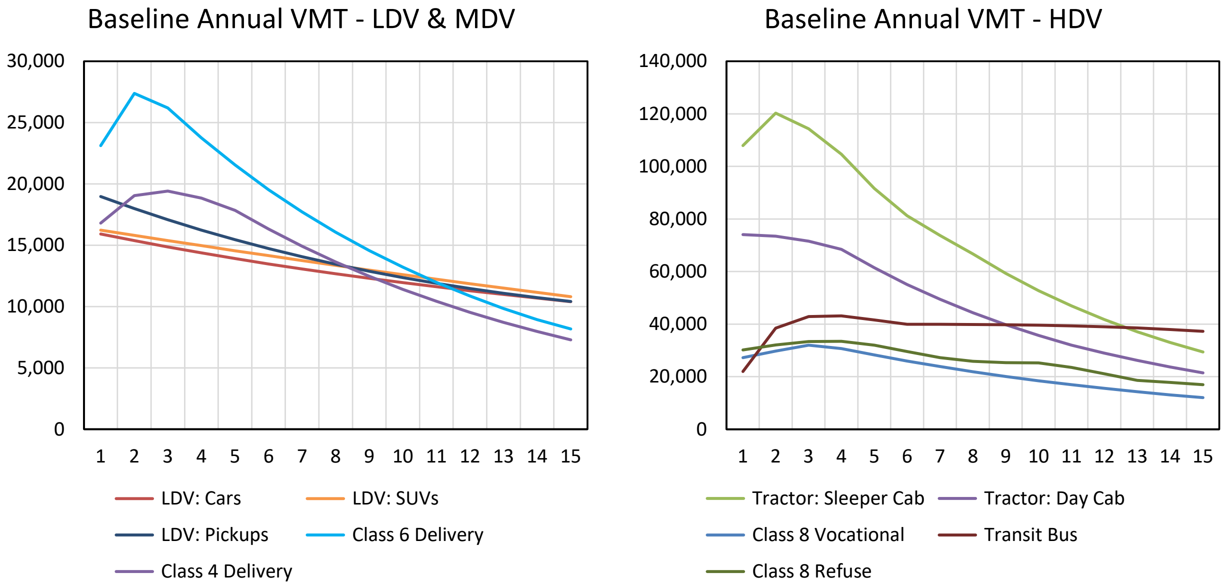


FIGURE 2.7 Left: VMT schedules for LDV and medium-duty delivery vehicles. Right: VMT schedules for heavy-duty vehicles.

Using a monotonically decreasing mileage schedule accounts for variations in travel behavior and for changes in vehicle use over its lifetime. An analysis of the National Household Travel Survey (FHWA and ORNL 2019) shows that even within a household, older vehicles are driven less than newer vehicles. However, a common alternative for VMT is to use a fixed mileage, as that would supply a constant utility to a household. Using a constant mileage instead of a monotonically decreasing mileage schedule would result in fewer miles in the first year and more miles in future years. In a discounted cash flow analysis, future costs are given less weight than earlier costs. Using a constant mileage schedule would delay many variable costs until later years, reducing the overall cost of these miles by a small factor. At a real discount rate of 1.2% over an analysis window of 15 years, a constant mileage schedule would reduce the discounted fuel cost by 0.7% and lifetime maintenance costs by 1.3%.

Use of these mileage schedules is conditional upon vehicle survivability. Subtly, the mileage schedules generated by NHTSA and EPA are intrinsically based on observed VMT, representing "the usage of vehicles on the road at the time of the sample" (NHTSA and EPA 2020). More directly, eventually every vehicle will be removed from service, and their VMT will be zero. A survivability-weighted VMT will account for this fraction of vehicles no longer in use, resulting in a reduced average VMT. This analysis implicitly accounts for vehicle survivability by use of a 15-year analysis window for LDV, and 10-year analysis window for MHDV, as described in Section 2.3.2. With this truncated lifetime, the total VMT is comparable to a much longer analysis window with a survivability-weighted VMT.

Quantification of a levelized cost of driving, in \$/mi, requires careful consideration of the cumulative vehicle miles traveled (EPA 2014, OMB 2003). Intuitively, it can seem that there can be no such thing as discounted VMT, because discounting applies to money or money-denominatable flows over time, and VMT is not in money units. Nonetheless, it turns out that cumulative VMT must be discounted in order to obtain the correct estimate of the *lifetime* cost per mile (in \$/mi). Formally, this can be demonstrated using annuities. The basic reason is that the lifetime cost is a function of the cost per mile in year t, and we should discount the annual cost values themselves. That is, we should value a given \$/mi cost in a later year less than we value the same \$/mi cost in an earlier year – and this effectively discounts miles as well as dollars. The conceptual or intuitive difficulty in understanding that we should discount VMT probably stems from the fact that while we are used to discounting time streams of money, we are not used to discounting \$/mi values over time, perhaps because \$/mi value itself *seems* like it is time-independent. In any case, the proper accounting for LCOD on a per-mile basis uses discounted cash flows as well as "discounted" VMT, as shown in Equation 2.2 in Section 2.3.

In Table 2.6, VMT corresponds to the access benefits of travel in the current conventional petroleum-fuel vehicle baseline. This baseline, fundamental benefit of travel is the same for all vehicles. Table 2.6 lists ways in which VMT can vary by vehicle type and affect costs but not baseline benefits. These changes in VMT are outside of the scope of this analysis, which looks at broadly representative mileage schedules, but could be important in TCO and LCOD quantification for households and individual fleets.

TABLE 2.6 Changes in VMT related to vehicle powertrain technology not accounted for in this study that affect the costs but not the baseline benefits of travel

Factor affecting VMT	Direct effect on cost	Other effects
Fewer refueling/recharging stations	Increase in VMT and in all costs in any way related to VMT; increase in time and search costs	Adaptation can result in trip-chaining and new trips, with some compensating benefits (costs will decrease over time as number of stations increases)
Availability of dedicated parking/charging stalls at some stores	Possibly very small decrease in VMT and in all costs in any way related to VMT; very small decrease in time and search costs	
Availability of home recharging	Small decrease in VMT and in all costs in anyway related to VMT; small decrease in time and search costs	Reduced exposure to pollution, danger at refueling stations
Lower maintenance & repair needs (EVs)		Reduced stress associated with dealing with repair shops
No need for emissions testing (EVs)		Reduced scheduling anxiety
Access to HOV lanes	Small change in any costs related to vehicle speed; decrease in travel time costs	Reduced stress associated with congestion
Change in travel by supporting vehicles (e.g., tanker trucks)	No direct *additional* effect on internalized private costs because the cost of the supporting VMT is reflected in the price of the transportation goods (e.g., fuel) it transports	Changes in external costs associated with the supporting vehicles, because by definition these are not reflected in prices

3. COST ELEMENT DATA AND ASSUMPTIONS

This section examines the data available for calculating the cost of vehicle ownership for each TCO cost element. Section 3.1 summarizes general data sources important for calculating TCO, with further explanation in the relevant sections. Section 3.2 presents information about the vehicle, including both modeling of the cost and residual value, along with the fuel economy. Section 0 presents information about energy prices and fuel costs. Section 0 presents insurance. Section 3.5 presents maintenance and repair. Section 3.6 discusses taxes and fees. Section 3.7 presents costs and considerations unique to commercial vehicles.

3.1. DATA SOURCE SUMMARY

Characteristics of the vehicles in this analysis came from Autonomie modeling, validated against real-world vehicle sales data from Wards Auto and fuel economy data from FuelEconomy.gov. Depreciation rates for LDV were obtained from Edmunds from their “True Market Value” (Edmunds TMV 2020), based on historical sales, which included average resale value (private party sale) for used vehicle models up to 7 years old. Depreciation rates for MHDV came from used vehicle listing data from Commercial Truck Trader and TruckPaper.com, validated against data from PriceDigests. Fuel prices for these vehicles came from EIA forecasts for regular gasoline, diesel, and electricity. Premium gasoline prices were extrapolated from regular gasoline prices, while hydrogen prices were set to match DOE Hydrogen and Fuel Cell Technologies Office (HFTO) targets.

For LDV insurance costs, we combined information from the National Association of Insurance Commissioners (NAIC), The Zebra, Progressive, and Edmunds to find average insurance rates for liability, collision, and comprehensive insurance coverage. For MHDV insurance, we used information from Progressive, ATRI, Commercial Truck Insurance HQ, Bus Insurance HQ, and Trusted Choice to find insurance rates for each of the size classes and vocations in this study. Maintenance and repair costs come from many different sources, including the Consumer Expenditure Survey, YourMechanic, Utilimarc, ATRI, Consumer Reports, Edmunds, RepairPal, MIT, and prior studies published by Argonne National Laboratory and Oak Ridge National Laboratory.

As described in Section 2.3.1, default financial parameters and analytical parameters were informed by a thorough literature review, and specifically by data from the U.S. Department of Commerce, the Federal Reserve Board, Experian, Nav, and Edmunds. Travel and ownership behavior is derived largely from prior analyses by NHTSA, EPA, and the U.S. Census Bureau. Key economic parameters are summarized in Table 2.5.

As will be discussed in greater detail in Section 4.3, we considered the influence of uncertain inputs on TCO and individual cost components. For cost components for which we had sufficient data, we used data one standard deviation higher and lower than the median value, representing the variability of uncertainty of the respective inputs. For data where distributions exist, but not clear statistics, we used the 15th and 85th quantiles for the lower and upper bounds, which corresponds to one standard deviation (in a normal distribution). We chose these as robust statistics, i.e., not influenced much by outliers. Our sensitivity analysis therefore assessed the uncertainty in TCO due to the uncertainty in the inputs where possible, rather than to an arbitrary variation in inputs.

3.2. VEHICLE

In this section, we discuss all data, methods, and assumptions related to the vehicle. We begin with a short discussion on Autonomie-simulated vehicle retail prices, both for current and future MY vehicles. We then consider battery pack manufacturing and retail costs as well as salvage value, which is used in several sensitivity cases as discussed later. The following section discusses vehicle fuel economy findings for both LDV and MHDV. Finally, we consider vehicle depreciation, which is the direct vehicle-related costs. We examine retail price and residual value to determine the depreciation of the vehicle, which is interpreted as the Vehicle Cost in our TCO and LCOD calculations.

3.2.1. Vehicle Retail Prices

Projected future LDV and MHDV retail prices were obtained from the results of Argonne Autonomie modeling (Islam et al. 2020; Vijayagopal et al. 2019). These prices were estimated from a bottom-up estimate of manufacturing costs of major components, including battery packs in hybrid and plug-in electric vehicles, and fuel cells and hydrogen storage tanks in fuel cell vehicles (Islam et al. 2020; Vijayagopal et al. 2019). These prices were estimated using a combination of cost models from Ricardo and inputs from experts from Argonne, DOE, and industry, based on assumptions about technological progress in electrification, lightweight materials, fuel cell and hydrogen storage, and engine technologies. Future vehicle and component costs were estimated for two cases, one assuming high technology progress, consistent with DOE technology targets, and one assuming slower technology progress, with higher costs for batteries, fuel cells and hydrogen tanks, and other vehicle components. These two sets of projections were intended to represent technology progress with and without continued technology research and development investment by the DOE Vehicles Technologies Office and the Hydrogen and Fuel Cells Technologies Office. Autonomie models vehicles in terms of “lab year”; this analysis adds five years to the lab year for the model year to account for a technology being deployed. In this analysis, we use model year 2025 (lab year 2020) as the baseline vehicle.

We estimated future vehicle retail prices from vehicle manufacturing costs (i.e. the ratio of vehicle retail price to manufacturing cost) using a factor of 1.5 for LDV. This retail price equivalent factor is based on Vyas et al. (2000). We applied this factor to LDVs of all powertrain types, even though this may not be accurate for some powertrains. Other estimates of this factor, and an alternate approach using indirect cost multipliers, have been reviewed (see, e.g., Kelly 2020; NRC 2013), but no adequate basis for a more refined estimate is available. The influence of production volumes on costs was not considered for LDV, with the reasoning that only vehicles being produced at scale would be broadly of interest and available to consumers.

Vijayagopal et al. (2019) included a retail price markup in their MDHV cost calculations; this markup factor varies by powertrain.

Figure 3.1 shows modeled prices for MY2020 and MY2025 small SUV for spark-ignition (SI) ICEV, compression-ignition (CI) ICEV, HEV, PHEV, BEV, and FCEV. The default all-electric range for PHEV was 50 miles, and the default all-electric range for BEV was 300 miles (i.e., BEV300), though a BEV200 was also modeled. Figure 3.2 shows similar modeling for MDV delivery trucks, while Figure 3.3 shows the same for HDV regional-haul day-cab tractors. The BEV range was 150 miles for the class 4 delivery truck and the BEV range was 250 miles for the class 8 day-cab tractor. The simulated PHEV range for each MHDV was one-half the BEV all-electric range in all cases. Between 2020 and 2025, the prices drop for most AFV due to reduction in technology costs, while prices increase for ICEVs (both SI and CI) due to required increases in fuel economy. For MY2025 vehicles, both low technology progress and high technology progress cases are shown, underscoring how research and development can minimize consumer costs when purchasing a vehicle for all powertrains. All of the cost modeling for MY2020 and MY2025 is summarized in Tables 3.1 and 3.2 for all five LDV size classes and all seven MHDV vocations.

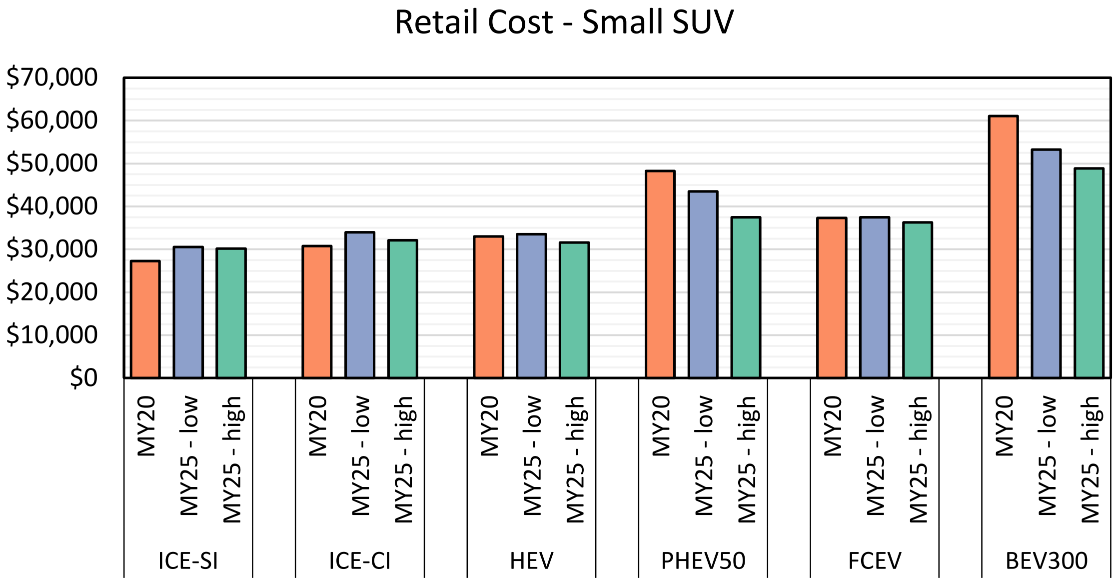


FIGURE 3.1 Cost modeling for Autonomie LDV for small SUV in MY2020 and MY2025

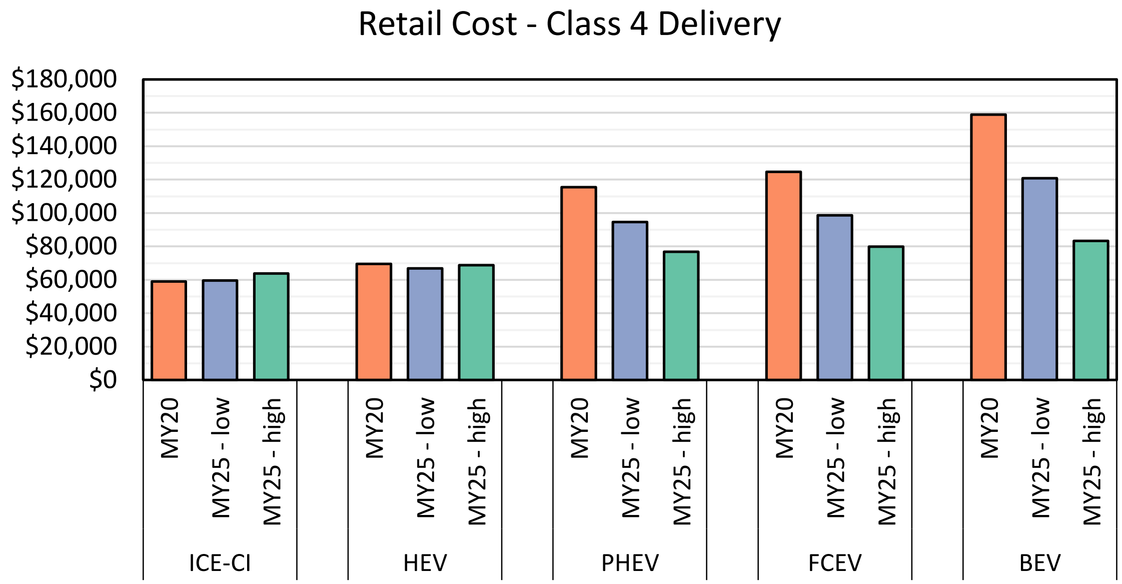


FIGURE 3.2 Cost modeling for Autonomie MDV in MY2020 and MY2025

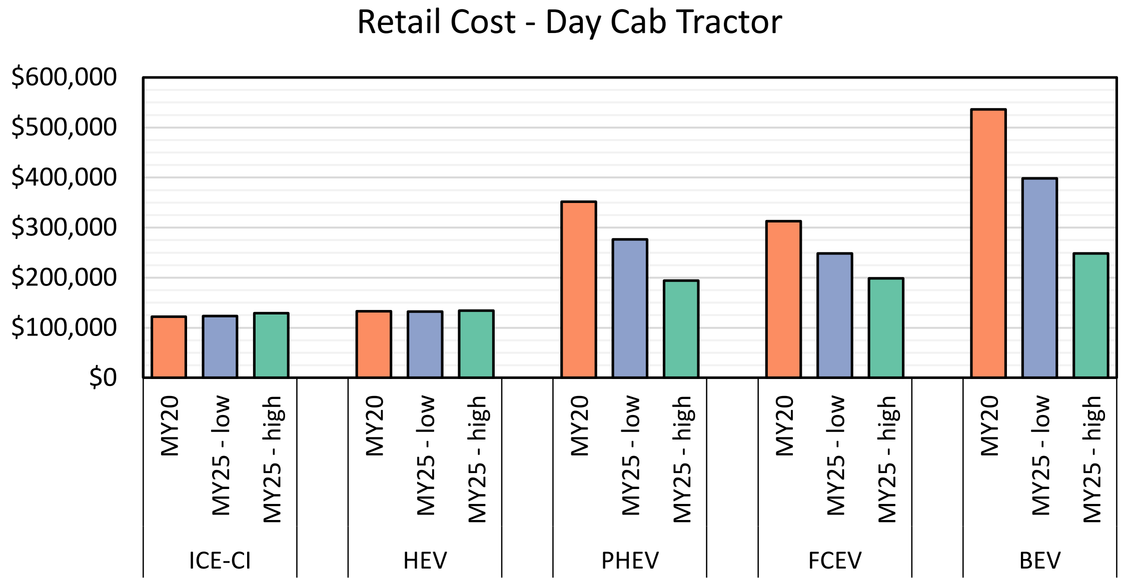


FIGURE 3.3 Cost modeling for Autonomie HDV in MY2020 and MY2025

TABLE 3.1 Cost modeling for Autonomie LDV for all size classes in MY2020 and MY2025

		ICE-SI	ICE-CI	HEV	PHEV	FCEV	BEV
Compact sedan	MY20	$19,095	$22,945	$24,166	$37,147	$26,578	$45,566
	MY25 – low	$21,496	$25,136	$24,031	$32,686	$26,246	$39,023
	MY25 – high	$21,486	$23,855	$22,736	$27,982	$25,724	$35,948
Midsize sedan	MY20	$24,068	$27,697	$29,391	$43,342	$33,261	$52,827
	MY25 – low	$27,783	$31,170	$30,376	$39,443	$33,628	$46,379
	MY25 – high	$27,749	$29,708	$28,815	$34,220	$32,840	$42,413
Small SUV	MY20	$27,243	$30,787	$33,014	$48,266	$37,352	$61,033
	MY25 – low	$30,576	$33,938	$33,490	$43,488	$37,442	$53,216
	MY25 – high	$30,175	$32,136	$31,586	$37,493	$36,247	$48,876
Medium SUV	MY20	$28,874	$32,430	$34,697	$51,304	$39,344	$66,084
	MY25 – low	$33,649	$36,977	$36,534	$47,331	$40,496	$58,412
	MY25 – high	$32,101	$34,040	$33,512	$40,030	$38,436	$52,876
Pickup	MY20	$32,406	$37,581	$41,721	$59,644	$48,457	$76,418
	MY25 – low	$37,513	$42,337	$42,923	$54,126	$48,788	$66,943
	MY25 – high	$35,173	$38,274	$38,367	$44,891	$45,833	$59,768

TABLE 3.2 Cost modeling for Autonomie MHDV for all size classes in MY2020 and MY2025 (blanks not modeled)

		ICE-CI	HEV	PHEV	FCEV	BEV
Tractor - Sleeper	MY20	$143,548	$155,852	$568,370	$359,511	$949,389
	MY25 – low	$146,084	$155,573	$435,322	$288,939	$693,354
	MY25 – high	$149,736	$159,667	$288,494	$233,172	$416,399
Tractor - Day cab	MY20	$122,338	$133,243	$351,950	$312,713	$536,185
	MY25 – low	$123,704	$132,297	$276,542	$248,147	$398,444
	MY25 – high	$129,307	$134,462	$194,493	$198,898	$248,186
Class 8 Vocational	MY20	$96,772	$110,520	$262,745	$204,890	$391,536
	MY25 – low	$98,113	$108,340	$209,357	$167,628	$294,293
	MY25 – high	$102,315	$108,669	$155,044	$139,466	$193,812
Class 6 - Pickup/Delivery	MY20	$73,439	$87,182	$169,263	$158,481	$231,840
	MY25 – low	$73,831	$84,003	$137,699	$127,973	$177,683
	MY25 – high	$77,373	$84,360	$108,916	$104,860	$121,426
Class 4 - Pickup/Delivery	MY20	$59,051	$69,630	$115,458	$124,717	$158,909
	MY25 – low	$59,599	$66,967	$94,653	$98,614	$120,865
	MY25 – high	$63,814	$68,748	$76,734	$79,914	$83,382
Transit Bus	MY20	$120,303	$134,798	$233,663	$209,542	$324,794
Class 8 Refuse	MY20	$102,949	$112,333			$329,349

In our analysis, we use the high-technology, MY2025 vehicle as our baseline vehicle, specifically the small SUV for LDV. For sensitivity analyses on vehicle manufacturing costs, we used the two sets of results from Autonomie simulations, the low and high technology price simulations, as upper and lower bounds on manufacturing price. For the retail price markup factor, we assumed a range from 1.2 to 2.0, based on estimates from literature (NRC 2013; Kelly 2020). Additionally, Autonomie models vehicles with a baseline trim and a performance-level trim with greater acceleration. In lieu of more detailed modeling of trim levels, we use the performance vehicles as a stand-in for luxury vehicles in the sensitivity analysis.

3.2.1.1. Other Vehicle Cost Literature

In the literature on ownership costs of LDVs, few studies estimate vehicle manufacturing costs using a bottom-up approach in which vehicle costs are estimated by adding up estimated direct costs of components and the estimated indirect manufacturing costs. Owing to a lack of publicly available manufacturing cost data, and to uncertainty about costs of new technologies such as batteries, electric motors, hydrogen storage tanks, and fuel cells, many studies that attempt such an approach rely on assumptions or approximate cost models to estimate the component manufacturing costs and the indirect costs. Hamza et al. (2020), MIT Energy Initiative (2019), Morrison et al. (2018), Elgowainy et al. (2018), Rousseau et al. (2015), Burke et al. (2015), NRC (2013), and Delucchi and Lipman (2001) all estimated vehicle costs using estimates of costs of vehicle components. Often cost models and projections are available for individual components, including PEV battery packs (e.g., Nelson et al. 2019) and fuel cells and hydrogen tanks for FCEVs (James 2020; Kleen and Padgett 2021). Other LDV TCO studies have used more aggregate or top-down estimates derived from values reported in earlier literature or based on MSRPs of conventional or hybrid electric vehicles and modifying these to account for differences in prices of vehicles with other powertrains (e.g., Al-Alawi and Bradley 2013).

Additionally, uncertainties in the assumptions about vehicle manufacturing costs, fuel economy, and other factors make it difficult to draw definitive or robust conclusions about the relative costs of ownership of vehicles with different powertrains. Wu et al. (2015) used Monte Carlo analysis to estimate distributions of ownership costs of ICEV, HEV, PHEV, and BEV with assumed distributions of vehicle prices, electric drive component costs, and fuel prices in Germany. They reported fairly wide distributions of ownership costs estimated for the year 2025, with significant sensitivity to assumed driving distance, vehicle purchase price, and vehicle size class.

The National Academy of Sciences (NAS) recently published a comprehensive, 400-page techno-economic evaluation of technologies to reduce the fuel use and GHG emissions of MDTs and HDTs (NAS 2020). The NAS considered powertrain modifications, alternative fuels, and battery-electric vehicles. They provided a comprehensive review of estimates of: 1) the technical characteristics and manufacturing cost of batteries; 2) the climate, air-quality, and energy-security benefits of different fuel and technology options; and 3) the indirect-cost component of the total retail price (e.g., corporate costs, sales costs, engineering costs, and engineering and advertising). The authors of the NAS 2020 study did not develop new estimates of vehicle manufacturing costs, but reviewed literature documenting such estimates, including direct manufacturing costs, indirect costs, retail price equivalents, indirect cost multipliers, economies of scale, learning effects, and stranded capital. They did update manufacturing costs of some technologies (waste heat recovery and electrified powertrain components). They found that with expected reductions in cost and improvements in reliability of lithium-ion batteries, hybrid powertrains would be economically attractive in medium-duty vehicles in some applications, especially in applications with stop-and-go driving. They mentioned that although costs of electric machines and battery systems continue to decline, the requirements for commercial vehicles are more stringent than those of passenger vehicles, therefore costs of electrified powertrains would be higher, and adoption of electric powertrains in commercial vehicles would probably be limited over the next ten years.

3.2.1.2. Battery Pack Costs and Considerations

As seen in Figures 3.1 to 3.3, PEVs are forecasted to have a higher retail cost than other types of vehicles, due to having expensive batteries. The U.S. DOE Vehicle Technologies Office (VTO) has targets for reducing the manufacturing costs of lithium-ion batteries at large scale to less than \$100/kWh and decreasing charging time to 15 minutes or less, with an ultimate goal of \$80/kWh (Boyd 2020).

Many estimates of battery pack costs are available from cost modeling and industry announcements and the range of battery pack costs is fairly wide, both for forecasts and for batteries already on the market. Sakti et al. (2017) reported estimates of BEV battery pack costs in 2020 ranging from less than \$200/kWh to over \$400/kWh (nameplate capacity), but some of these estimates were published in 2010. Future battery pack costs are more uncertain. Hsieh et al. (2019) modeled Li-ion battery pack costs in 2030 under a range of assumptions about chemistry, design, raw materials costs, and other factors and estimated BEV pack costs ranging from \$93 to \$140/kWh. They compared their model with others, which under the same assumptions gave battery pack costs in 2030 ranging from \$77 to \$150/kWh. A more optimistic estimate of \$62/kWh by 2030 was made by Goldie-Scot (2019).

In our base case we assumed that battery packs in PEVs would last the lifetime of the vehicle, i.e., no battery repair or replacement cost was assumed. This is reasonable to assume for LDV PEVs, since although some degradation in usable battery pack energy capacity occurs with use, few PEVs have required battery pack replacement. In addition, battery technology continues to improve, with new chemistries and battery management systems promising to reduce capacity degradation (Harlow et al. 2019; Boyd 2020). Lifetimes of battery packs in medium- and heavy-duty PEVs are less well-established. Currently, electric transit buses may have a battery replacement at mid-life, though recent warranty plans, cycle-life analysis, and preliminary field reports suggest that for many original equipment manufacturers (OEMs) the battery will last the 12-year life of the buses (Johnson et al. 2020). Therefore, we assume battery packs in MHDVs will last as long as the vehicles.

In the sensitivity analysis, we assumed a lower bound on battery pack salvage value of zero (Dai et al. 2019; Gaines 2019; Harper et al. 2019). For an upper bound on the salvage value of battery packs, we used a model developed by the National Renewable Energy Laboratory (NREL) which provides battery salvage value as a percentage of initial purchase price, accounting for the forecasted future new battery price, forecasted battery health, relative cost of refurbishment, and a used product discount (Neubauer and Pesaran 2010). The salvage value of a BEV battery pack was estimated as:

$$V_{Salvage} = (1 - K_r - K_u)(1 - K_h)(C_{new})(F_{RPE}) \qquad \text{Eq 3.1}$$

where

V_{Salvage} = the salvage value of the battery pack
K_r = refurbishment cost factor = 15%
K_u = used product discount factor = 15%
K_h = battery health factor = 0% in year 0; increases by 3%/yr
C_{new} = cost per usable kWh of usable battery pack capacity for a new battery (in the year the pack is salvaged)
F_{RPE} = ratio of retail price to manufacturing cost = 1.5 (retail price equivalent)

We assumed a value of $185/kWh for C_{new} in 2020, which we took as the current manufacturing price of BEV lithium-ion battery pack. This price is consistent with manufacturing costs estimated using Argonne BatPaC model for typical battery pack designs and current production volumes (Nelson et al. 2019). For MY2025, we used C_{new} from Autonomie modeling, starting at $150/kWh in 2025 (Islam et al. 2020). We assumed that C_{new} decreases annually consistent with battery price reductions projected by Bloomberg New Energy Finance (Holland 2019), following a power function trend over the 15-year analysis window.

3.2.2. Vehicle Fuel Economy

In this section, we discuss fuel economy data for both LDVs and MHDVs, which most directly impacts total fuel costs. As it is a characteristic of the vehicle, it can have an impact on retail price, among many other factors. Fuel economy is an important consideration in a TCO analysis as it can vary significantly between powertrain types, size classes, market segments, and vocations for MHDVs. Since fuel is the second-largest cost component in our TCO for most LDVs and MHDVs, this variation is clearly important to consider. We first discuss the fuel consumption data collection and then present fuel economy results for LDVs followed by MHDVs.

3.2.2.1. Vehicle Fuel Consumption Data Collection

For comparison, real-world and simulated fuel use data were collected for different fuel types from multiple other sources. We collected data for ICE (both SI and CI), HEV, PHEV, BEV, and FCEV across multiple light-duty size classes. These data total 1,047 records for LDV energy use and 1,684 records for MHDV energy use. Each record is distinguishable by vehicle type (e.g., powertrain, class, and use type), driving conditions (e.g., charge-sustaining, CS, and charge-depleting, CD), and data source (i.e., different papers and reports). For energy use and idling fuel rate of medium- and heavy-duty vehicles (MHDVs), there is no single recent, representative, and comprehensive data source that contains the energy use data for most of the MHDV types. To validate the Autonomie modeling results, the team collected related data from journal papers, conference papers, and government and lab reports (e.g., Reinhart 2015; Davis and Boundy 2020). Also, compared to LDVs, vehicle type classification is more complex with MHDVs.

For most MHDV, the incumbent powertrain is some form of an internal combustion engine, typically a CI fueled by diesel, but occasionally an SI fueled by gasoline, natural gas, or propane instead. For improved fuel economy, conventional ICE engines are becoming more hybridized, either with integrated starter generators (ISG) or as mild to full HEV. Table 3.3 shows the extent to which each of these powertrains has been studied across MHDV vocations. A summary of generalized vocation and body types is listed in Table 3.3, using identifications in the Vehicle Inventory Use Survey (VIUS) (U.S. Census 2004) and other literature (CARB 2015a; b; c; d; e; Barnitt et al. 2008; Burke and Fulton 2020; Gao et al. 2018; Gao et al. 2017; Jaller et al. 2018; Lammert et al. 2012; Reinhart 2015; Sripad and Viswanathan 2019; Zhao et al. 2013). For each of these vehicle powertrains, fuel economy measurements or simulations for different size classes and vehicle use cases were collected from the literature, and compared with Autonomie as data validation. Even within a single label, fuel economy and body style can vary enormously.

TABLE 3.3 Collected energy use data for MHDVs by powertrain technology and vehicle descriptor

Powertrain	**Fuel**	**Generalized Vehicle Descriptor**
BEV	Electric	Bucket truck, Construction, Delivery (class 3-7), Drayage, Long-haul, Refuse, School bus, Service utility, Short-haul, Transit bus, Utility, Van (class 2-3), Vocational (class 8), Walk-in (class 4)
FCEV	Hydrogen	Construction, Delivery (class 4-6), Long-haul, Short-haul, Transit bus, Vocational (class 8)
HEV	Diesel	Construction, Delivery (class 4-6), Long-haul, Refuse, School bus, Service utility, Short-haul, Transit bus, Utility, Van (class 2-3), Vocational (class 8), Walk-in
ICE	Biodiesel	Transit bus
ICE	Diesel	Bucket truck, Construction, Delivery (class 3-7), Drayage, Long-haul, Pickup (class 2-3), Platform, Refuse, School bus, Service utility, Short-haul, Tanker, Tow truck, Transit bus, Utility, Van (class 2-3), Vocational (class 7-8), Walk-in (class 4)
ICE	Gasoline	Delivery (class 6), Pickup (class 2-3), Short-haul, Tow truck
ICE	Natural gas	Long-haul, Short-haul
ISG	Diesel	Construction, Delivery (class 4-6), Long-haul, Refuse, School bus, Service utility, Short-haul, Transit bus, Utility, Van (class 2-3), Vocational (class 8), Walk-in
PHEV	Diesel + Electric	Bucket truck, Construction, Delivery (class 4-7), Long-haul, Refuse, School bus, Service utility, Short-haul, Transit bus, Utility, Van (class 2-3), Vocational (class 8), Walk-in

3.2.2.2. LDV Fuel Economy

As with vehicle prices, Autonomie results of light-duty fuel economy were provided for two sets of projections: low and high technology progress, representing pessimistic and optimistic estimates of future vehicle attributes including fuel economy, for five vehicle classes (Islam et al. 2020). For illustration, Autonomie simulation fuel consumption results for the small

SUV and the pickup truck are shown in Figure 3.4 for each powertrain (ICE-SI, ICE-CI, HEV, PHEV, FCEV, BEV). The vehicles plotted are the MY2020 and MY2025 vehicles. The y-axis represents the fuel consumption rate for each of the six powertrains in gasoline-gallon equivalent per mile (gge/mi), averaged on for real-world driving (combining highway and urban drive cycles). Results shown in both figures indicate that future fuel economies are higher in DOE's high technology scenario than in the low technology scenario, and in both scenarios, all fuel economies are projected to improve over time. ICE vehicles consume the most fuel, followed by hybridized vehicles, and finally all-electric vehicles. For PHEV (with 50-mile electric range), the total fuel consumption is a combination of CD and CS modes, with the utility factor of electric driving percentage determined based on SAE standard J2841 (SAE 2010). The BEV shown is the 300-mile range BEV. While it is not shown here, electric vehicles with smaller batteries (lower range on a single charge) generally have higher fuel economies (lower electricity consumption) owing to the weight penalty of larger battery packs. Table 3.4 compiles MY2020 and MY2025 fuel economies from the Autonomie model for five size classes into a single table.

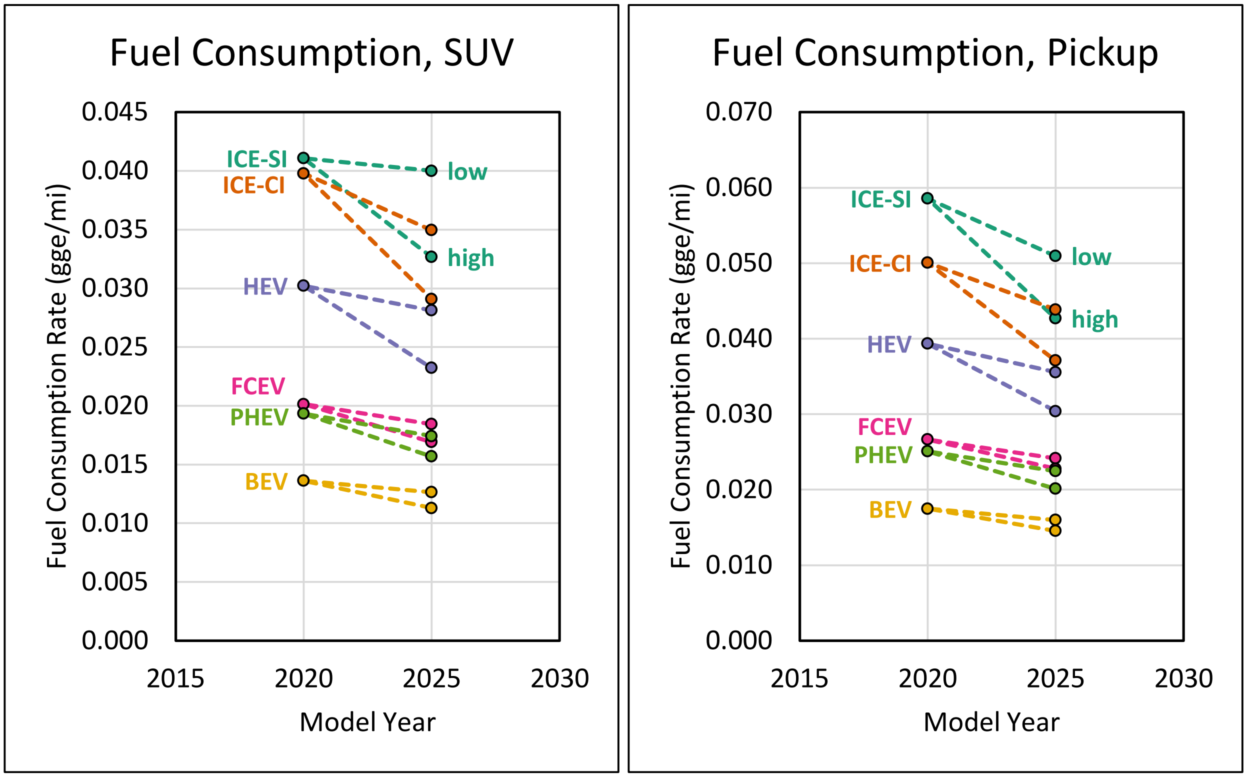


FIGURE 3.4 Fuel consumption rates for small SUV and pickup truck as modeled by Autonomie for MY2020 and MY2025

TABLE 3.4 Fuel economy (miles per gge) for Autonomie LDV for all size classes in MY2020 and MY2025

		ICE-SI	ICE-CI	HEV	PHEV	FCEV	BEV
Compact sedan	MY20	27.63	29.56	39.33	62.96	62.99	91.90
	MY25 – low	29.50	33.48	40.84	69.99	67.97	98.07
	MY25 – high	35.16	40.36	50.98	78.32	74.45	110.05
Midsize sedan	MY20	24.29	26.80	35.92	58.97	56.73	85.04
	MY25 – low	26.66	30.84	40.00	65.68	62.49	92.50
	MY25 – high	32.10	37.41	45.44	74.06	69.17	105.09
Small SUV	MY20	24.34	25.13	33.08	51.70	49.66	73.40
	MY25 – low	24.99	28.61	35.55	57.41	54.23	79.13
	MY25 – high	30.60	34.36	43.05	63.73	59.13	88.48
Medium SUV	MY20	20.74	23.84	30.80	47.76	45.92	67.01
	MY25 – low	24.40	27.60	31.74	53.52	50.99	73.30
	MY25 – high	29.18	32.94	40.26	59.07	54.73	80.90
Pickup	MY20	17.07	19.97	25.41	39.87	37.51	57.21
	MY25 – low	19.62	22.80	28.12	44.54	41.41	62.60
	MY25 – high	23.42	26.94	32.90	49.65	43.90	68.75

The team analyzed fuel economies of recent model year vehicles of selected LDV size classes to assess the difference in the fuel economy between luxury and non-luxury LDVs. We calculated sales weighted harmonic average fuel economies from fuel economy reported in the EPA/DOE Fuel Economy Guide (DOE and EPA 2020b) for luxury and non-luxury vehicles as defined in Wards Vehicle Specifications (Wards Intelligence 2020). The “luxury” designation may be based only on MSRP or on other vehicle features, but documentation from Wards does not explain how the luxury designation is applied. These average fuel economies are compared in Figure 3.5, which shows that in all cases for which data were available and analyzed, the non-luxury vehicles have higher fuel economy. Fuel economy is presented here for all powertrains in units of miles per gasoline-gallon equivalent (mpgge).

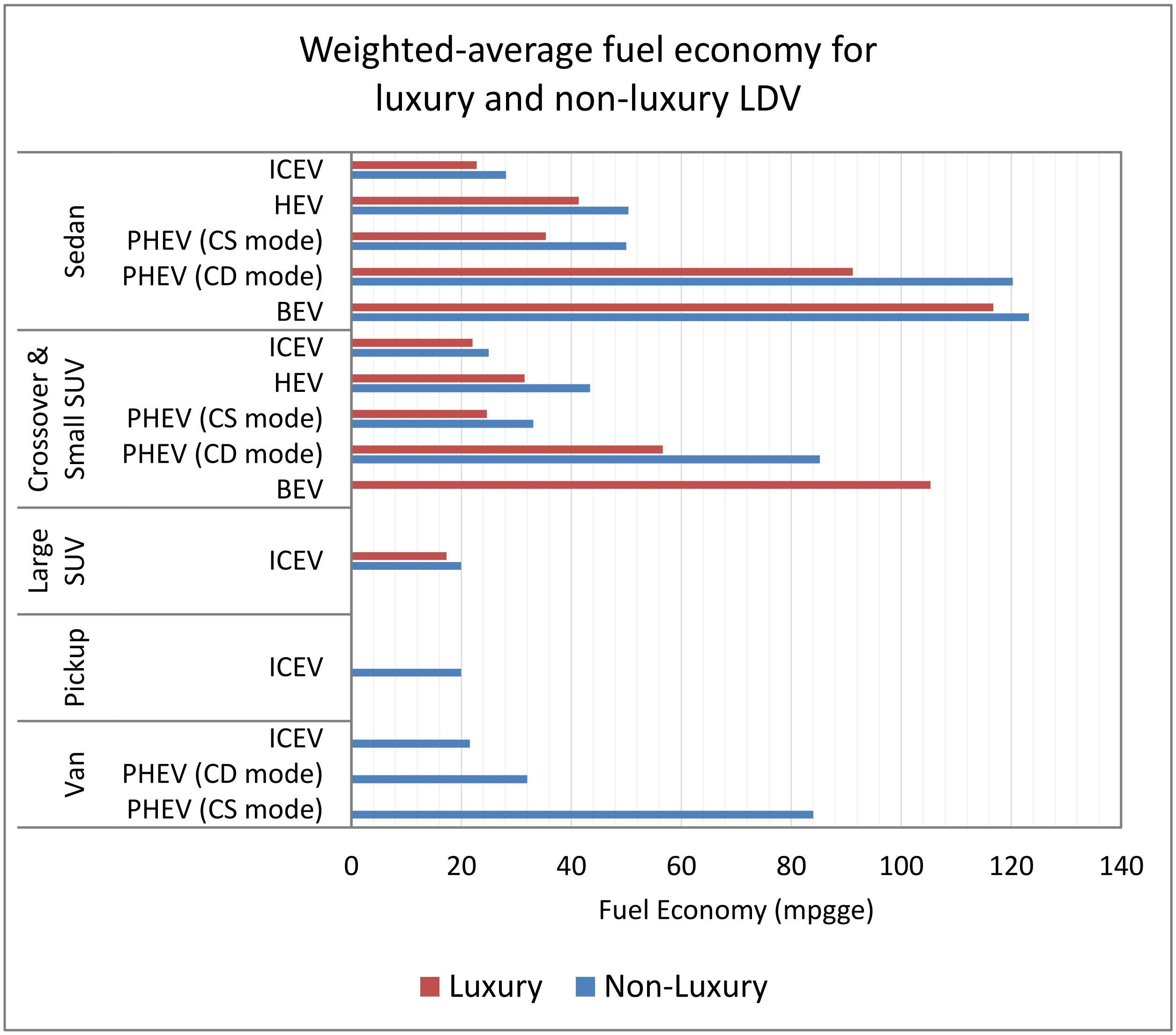


FIGURE 3.5 Comparisons of weighted average fuel economies of luxury and non-luxury LDVs

In addition to the difference in fuel economy between luxury and non-luxury vehicles, automakers recommend or require using premium gasoline in most luxury gasoline vehicles, which is more expensive than regular gasoline prices. Automakers also often recommend or require premium for new, smaller, higher efficiency (high compression) engines in ordinary vehicles due to issues with premature ignition (knocking). In the sensitivity analyses, we quantify the differences between luxury and non-luxury vehicles, and the impact on TCO of using premium instead of regular gasoline. See Section 0 for an in-depth examination of the relationship between regular and premium gasoline prices and the effect that has on fuel costs of luxury versus non-luxury vehicles.

3.2.2.3. MHDV Fuel Economy

Autonomie simulation results served as the primary source for consistent MHDV fuel consumption estimates. These simulations used regulatory drive cycles and weighting factors from the Phase 2 MDHD fuel efficiency standards (EPA and NHTSA 2016). We obtained fuel economy results for MHDVs for low and high technology progress in years 2020-2050 (Vijayagopal et al. 2019). In addition, we collected some fuel economy values for selected MHDVs from literature sources, including fuel consumption during idling and power-take-off (PTO). Certain commercial vehicles, e.g., utility trucks, can consume a significant amount of energy during idling and PTO use. We provide an in-depth discussion on how idling may affect overall fuel use for commercial vehicles in Section 3.7.3.2. We also use limited case studies to show the important of payload variation, though the analysis presented here uses average payloads.

Fuel economy data of various MHDV types are used. For illustration, Figure 3.6 shows Autonomie simulation fuel consumption results for the class 4 delivery truck and the class 8 day-cab tractor trailer. Here, the y-axis represents the fuel consumption rate in diesel-gallon equivalent per mile (dge/mi). For the medium-duty delivery truck, the fuel economy follows the same trend as the LDV in Figure 3.4, with ICE consuming the most fuel, with hybridized vehicles performing better, and BEVs consuming the least energy. However, for the day-cab truck, most powertrains have very similar total fuel consumption. This is because the driving cycle is primarily at highway speed, where hybridized powertrains offer the least benefit over conventional ICE, while also carrying an extra weight burden. Table 3.5 summarizes MY2020 and MY2025 fuel economy for all seven size classes considered.

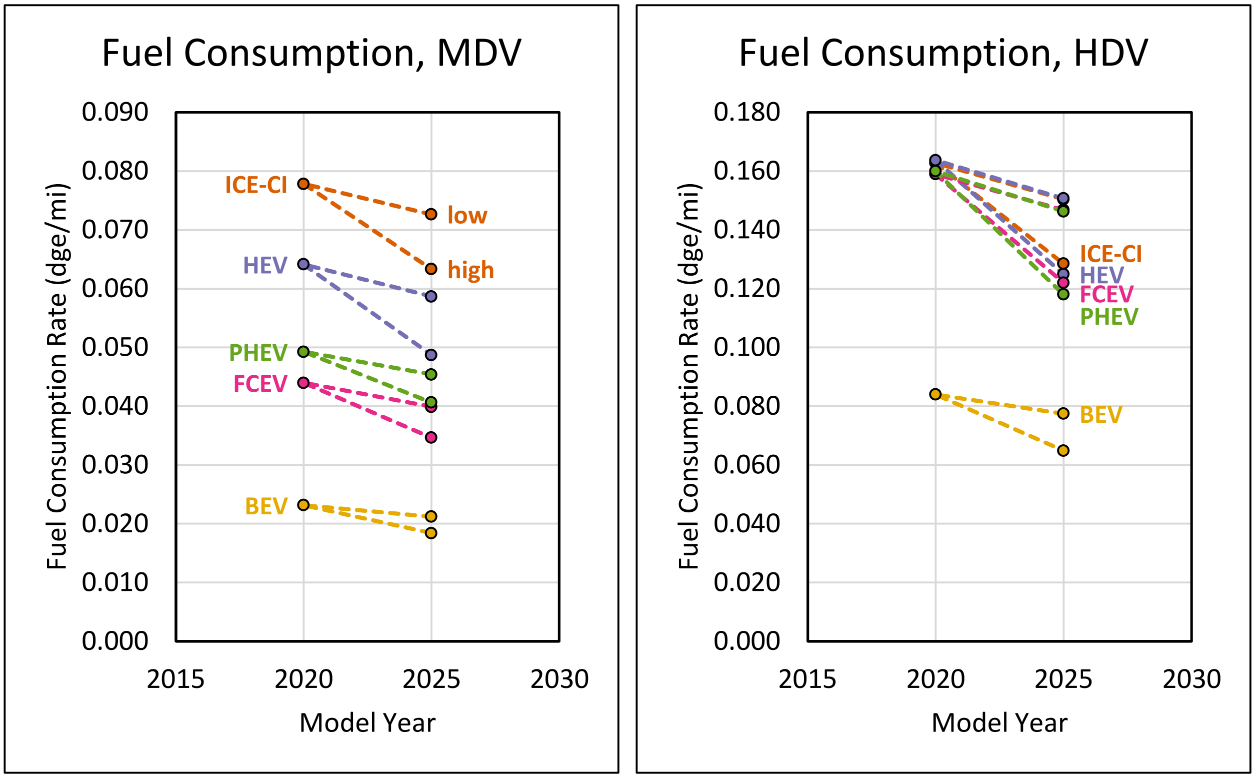


FIGURE 3.6 Fuel consumption rates for class 4 delivery truck (MDV) and class 8 day-cab tractor trailer truck (HDV) as modeled by Autonomie for MY2020 and MY2025

TABLE 3.5 Fuel economy (miles per dge) for Autonomie MHDV for all size classes in MY2020 and MY2025 (blanks not modeled)

		ICE-CI	HEV	PHEV	FCEV	BEV
Tractor - Sleeper	MY20	6.66	6.56	6.43	6.70	11.59
	MY25 – low	7.17	7.07	7.00	7.18	12.60
	MY25 – high	8.27	8.28	8.49	8.34	14.67
Tractor - Day cab	MY20	6.14	6.11	6.25	6.29	11.90
	MY25 – low	6.65	6.64	6.83	6.81	12.91
	MY25 – high	7.78	8.01	8.47	8.19	15.41
Class 8 Vocational	MY20	7.01	7.98	9.51	9.31	17.46
	MY25 – low	7.49	8.65	10.47	10.10	18.92
	MY25 – high	8.56	9.78	12.23	11.48	21.40
Class 6 - Pickup/Delivery	MY20	10.18	11.28	14.66	14.37	27.41
	MY25 – low	10.93	12.36	16.18	15.80	29.72
	MY25 – high	13.20	15.72	19.44	18.30	34.06
Class 4 - Pickup/Delivery	MY20	12.85	15.59	20.30	22.73	43.18
	MY25 – low	13.76	17.04	22.02	25.07	47.18
	MY25 – high	15.79	20.52	24.60	28.87	54.36
Transit Bus	MY20	7.08	7.86	11.08	9.88	18.79
Class 8 Refuse	MY20	5.39	6.13			18.04

Another important consideration for the fuel consumption by commercial vehicles is payload, especially for freight vehicles. For example, a tractor trailer operating at maximum gross vehicle weight rating can weigh more than twice as much as a tractor pulling an empty trailer. Duty cycles can also vary considerably both across and within applications, with varying proportions of highway speeds and lower speed transient cycles with more frequent braking and acceleration events. Duty cycles specific to each application are important considerations in determining alternative powertrain applicability, design, and TCO. Figure 3.7 shows the variation in fuel economy of a Kenworth class 8 tractor trailer under different driving cycles and payloads (Reinhart 2015). Five driving cycles and three different payload levels were considered. The figure shows significant variation in fuel economy, ranging from 3.78 miles per gallon (MPG) for the CARB driving cycle with full payload to 9.26 MPG for 55 MPH driving cycle with empty payload. For all driving cycles, the payload assumption is an important factor that affects the fuel economies. Generally, higher payloads result in lower fuel economy in terms of miles per gallon, but higher freight efficiency in terms of ton-mile per gallon, which is reflected by Figure 3.8. This figure shows the variation in freight efficiency in ton mile per gallon for the same driving cycles and payload levels as shown in Figure 3.7. 50% payload is 23,020 pounds and 100% is 46,040 pounds in cargo weight.

Due to the high variation in payload and the difficulty in modeling the payload of a general vehicle of certain characteristics, we do not include adjustments in fuel economy due to payload in our calculations. The effect of payload on fuel economy is important future work.

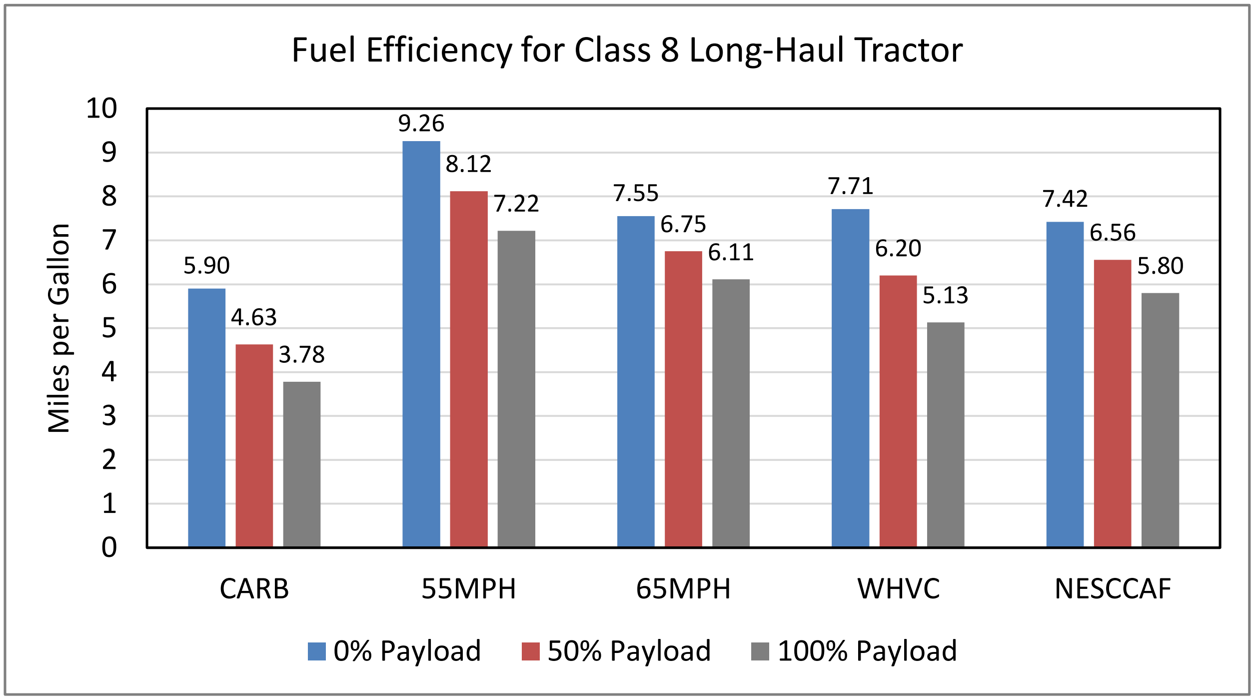


FIGURE 3.7 Mile per gallon variation in truck fuel economies with different driving cycles and payload levels for Kenworth long haul tractors (data from Reinhart 2015)

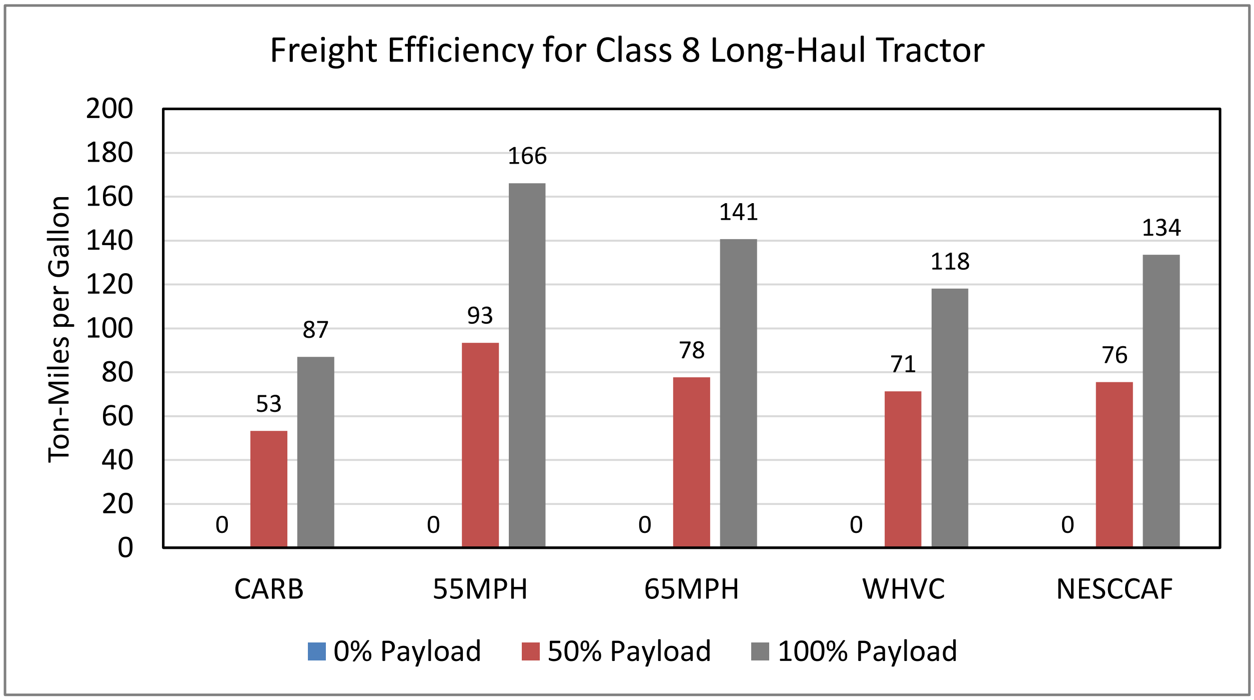


FIGURE 3.8 Ton-mile per gallon variation in truck fuel economies with different driving cycles and payload levels for Kenworth long haul tractors (data from Reinhart 2015)

3.2.3. Validation of Retail Price and Fuel Economy

In this section, we compare Autonomie simulation fuel economy and retail price results with real-world values from FuelEconomy.gov for selected powertrain types and size classes (DOE and EPA 2020a). We use simulated values in order to examine certain vehicle and powertrain types that may not exist in the real-world, such as AFV pickup trucks, among others. They are also advantageous in that they allow us to examine future MY vehicles, and to make comparisons across powertrains with comparable characteristics of the vehicles. However, simulated vehicles can differ from real-world ones for a variety of reasons, and particularly with fuel economy and retail price. Table 3.6 compares MY2020 Autonomie simulation retail price results with real-world data. The real-world data was sales-weighted data, acquired from Wards Auto, with the fuel economy from the FuelEconomy.gov database, and the retail price equal to the base trim MSRP for that vehicle (Wards Intelligence 2020; DOE and EPA 2020a). Each cell in Table 3.6 indicates the percentage difference between the Autonomie values and the real-world values (i.e., a positive value indicates that the Autonomie price is higher; a blank cell indicates that there is no real-world vehicle of that type). While not included in this table, Autonomie also models a BEV400, which was not commercially available in 2019. Noting differences in retail price is key, as MSRP affects nearly every other cost component in the TCO, explicitly for the vehicle cost, but also for financing, insurance, repairs, and taxes and fees, as described in the sections to follow. Lower retail prices for certain powertrain types may significantly reduce the TCO for these vehicles.

Using a sales-weighted average, the Autonomie simulation results nearly perfectly estimate retail prices for ICE-SI vehicles, though it varies from one size class to another. For HEVs, the Autonomie simulation results overestimate retail prices by about 9% on average. This is a key difference; although HEVs already have the lowest TCO over a 15-year window, a downward adjustment in the retail price of our modeled HEVs would further decrease the TCO of vehicles with a hybridized powertrain.

For PHEVs, Autonomie slightly underestimates the retail price compared to the real-world vehicles, though it severely overestimates the price of longer-range PHEVs. As a stand-in for PHEV20, real-world PHEV with between 15 and 25 miles of all-electric range were used; for PHEV50, any real-world PHEV with over 30 miles of all-electric range was considered. This eliminated many, but not all, of the high-power luxury short-range PHEV available for sale today. Once again, an overestimation of retail prices for these longer-range PHEVs is key; as the TCO of the ICE-SI and PHEV50 are so similar, even a small decrease in the retail price of the PHEVs could easily affect the rank order of these two powertrain types. For both BEV200s and BEV300s, and severely for all BEVs in terms of sales-weighted average, Autonomie overestimates retail prices. One possible explanation for this discrepancy is the manufacturing to retail price equivalent markup factor (RPE). For this analysis, we use an RPE of 1.5 for all powertrain types; however, it is thought that a single value may fail to capture the complexity in original equipment manufacturer (OEM) markups for emerging technologies (Kelly 2020). Specifically, it is thought that AFVs may be sold at lower profit margins; using a lower RPE factor for HEVs and BEVs might explain some of the discrepancy between the real-world and simulated values.

Regardless of RPE, the vehicle costs used in our base case analysis severely overestimate the cost of BEVs in comparison to real-world data. Once again, this can have a large impact on TCO, as nearly all of the component costs scale with retail price. Although our current results indicate that BEVs have the highest lifetime TCO, a downward adjustment on the retail price of BEVs similar to that suggested by our real-world comparison could make BEV TCO as low or lower than that of the other powertrain types. In general, lower retail prices for all of these alternative fuel vehicles may make them more competitive or even cheaper than conventional counterparts, in terms of lifetime TCO, than the current results indicate. Although there are limited data for FCEVs and diesel vehicles, Autonomie tends to underestimate the retail price of these powertrain types across all size classes.

TABLE 3.6 Autonomie simulation/Real-world retail price comparison, percentage difference of Autonomie modeling from real-world data

Cost difference (%)	Gas	Diesel	Hybrid	FCEV	BEV200	BEV300	PHEV20	PHEV50	SWA
Sedan - small	-10.0%	-23.5%	5.6%	-49.9%	-18.2%		-54.2%	16.8%	-10.2%
Sedan - medium	-10.5%	-45.7%	9.2%	-31.5%	36.3%	60.2%	2.8%	43.8%	-1.7%
SUV - small	15.0%		25.3%	-35.9%	33.3%	64.1%	11.3%		15.5%
SUV - medium	-3.6%	-25.2%	7.1%		-24.9%	-12.1%	-1.1%		-3.6%
Pickup - all	14.4%	-18.2%	38.5%						7.3%
SWA	0.4%	-18.4%	9.1%	-45.3%	9.6%	44.6%	-16.3%	35.3%	0.4%
					All BEV: 37.3%		All PHEV: -3.3%		

Note: SWA = Sales-weighted Average; Powertrain types with a number indicate the all-electric range in miles

In Table 3.7, we compare Autonomie-simulated fuel economies with real-world values. Though fuel economy has a much smaller impact on TCO than retail price as it only affects the fuel cost, underestimations in terms of fuel economy can result in overestimations of TCO. Across all powertrain types except PHEV, the Autonomie simulations underestimate the fuel economies relative to real-world values. The fuel economy for PHEVs is highly sensitive to the definition of "short-range PHEV" and the utility factor; a difference in definitions between the two sources leads to this discrepancy. This underestimation in fuel economy is greatest for BEVs and followed by HEVs. Data for FCEVs and diesel vehicles show that Autonomie simulations similarly underestimate fuel economy, though, once again, there is a limited number of models for these fuel types. On average, across all vehicles, the Autonomie modeling has a size-class weighted fuel economy difference of 16% relative to the real-world sales in 2019.

TABLE 3.7 Autonomie simulation/Real-world fuel economy comparison, percentage difference of Autonomie modeling from real-world data

MPG difference (%)	Gas	Diesel	Hybrid	FCEV	BEV200	BEV300	PHEV20	PHEV50	SWA
Sedan - small	-12.1%	-21.2%	-25.4%	-13.6%	-16.9%		105.0%	2.4%	-12.1%
Sedan - medium	-19.6%	-22.0%	-24.7%	-27.4%	-18.1%	-34.0%	-3.6%	-5.0%	-20.2%
SUV - small	-7.2%		-30.6%	-12.9%	-35.6%	-38.8%	43.0%		-7.6%
SUV - medium	-18.4%	-14.0%	-16.4%		-9.9%	-34.9%	66.1%		-18.3%
Pickup - all	-15.6%	-18.0%	27.9%						-15.9%
SWA	-15.8%	-17.9%	-21.9%		-23.9%	-34.2%	32.1%	-2.8%	-16.0%
					All BEV: -32.2%		All PHEV: 21.9%		

Note: SWA = Sales-weighted Average; Powertrain types with a number indicate the all-electric range in miles

Real-world comparison of fuel economy for medium- and heavy-duty vehicles across powertrains is much more limited as there is extreme data scarcity for alternative fuel vehicles in the MHDV sector, since only diesel and compressed natural gas vehicles (CNGV) have seen appreciable historical sales. Furthermore, the available real-world data for both retail price and fuel economy of MDHVs is much more limited than LDVs. We compared Autonomie results with existing real-world retail price data from Commercial Truck Trader and Truck Paper (CTT 2019; Truck Paper 2019). While there is uncertainty and variation based on the vocation and other factors, we find that for the pickup and delivery and vocational trucks, sleeper and day cabs, the difference between the Autonomie and real-world retail prices for diesel trucks is less than 10%. We are aware that the Autonomie retail prices for the class 8 bus and refuse truck are lower than other sources. Real-world bus prices tend to be much higher than the Autonomie results, but there is significant variation in bus prices due to configuration options, sources of contract, federal grants, and certain types of restrictions.

We compared Autonomie fuel economy results with existing real-world analysis as well as the model year 2021 estimates from the EPA Regulatory Impact Analysis (RIA) for the Phase 2 MHDV fuel efficiency standards (EPA and NHTSA 2016). We find that the simulated results for class 8 sleeper and day cab trucks are within 2% of the real-world analysis (Stephens et al. 2020) and only slightly worse for the RIA comparison: within about 5%. While the other MHDVs are generally modeled as more fuel efficient than the fuel economy regulations, a direct comparison based on both the weight class and the vocation is sometimes unavailable. For the MHDV vocations other than sleepers and day cabs, the Autonomie simulations results are generally within 15% of the existing real-world analysis.

Though there are discrepancies between the Autonomie simulation results and real-world values in terms of both retail price and fuel economy, there are certain distinct reasons for using the simulated values. For example, modeling vehicles that do not yet exist on the market is one advantage of using simulated values. Furthermore, simulations represent distinct configurations and duty cycles rather than real-world, highly variable operations that depend on payload, geography, driving style, and day-to-day operational demands. This enables fair one-to-one comparisons across powertrain types and model years and, as such, avoids issues arising from use of real-world average fuel economies. The focus of this study is not to create new vehicle cost or fuel economy estimates; therefore, we use the Autonomie modeling results as they are available for a wide variety of powertrain types, size classes and vocations, and model years. However, we do find it valuable to compare the results with real-world data to note several key differences that should be taken into account when considering the TCO results in this report.

3.2.4. Vehicle Financing

In this analysis, vehicle financing charges are payments of interest on a loan taken out to purchase the vehicle (and payments for processing the loan, but these are assumed to be incorporated into the interest rate for analytical simplicity). For a given vehicle, calculations are made for the cost of interest on a typical loan with a fixed monthly payment, as shown in the following equation:

$$Fixed\ Payment = Vehicle\ Cost\ \times \frac{Rate \times (1 + Rate)^n}{(1 + Rate)^n - 1} \qquad \text{Eq 3.2}$$

The financing cost is directly proportional to the vehicle retail price. For monthly payments, the rate in the above equation is the monthly interest rate, approximately one-twelfth of the APR. This is calculated using standard loan parameters, assuming a 12% down payment, a 63-month loan term, and a 4% APR (in constant-dollars). These parameters are described in greater detail in Section 2.3.1. As the loan reaches maturity, a growing fraction of the monthly payment is applied to the principal, as opposed to the interest.

This analysis does not explicitly account for leased vehicles. In 2019, 30% of new vehicle purchases were leased in the United States (Zabritski 2020). Lease shares vary widely geographically, with approximately 3% of new vehicles leased in Arkansas to over two-thirds of vehicles in Michigan. In this analysis, we assume that all vehicles are purchased outright (with or without financing).

In the sensitivity analysis, we account for interest rates which are 0% and 8%, representing sales incentives from the dealership and loan terms for less creditworthy consumers, respectively.

3.2.5. Vehicle Cost / Depreciation

In the following section, we introduce vehicle depreciation and then describe the methodology for determining the resale value of a certain used LDV. Next, we provide some important results, including the vehicle cost input for the TCO calculations and key depreciation insights across powertrains and mass-market/luxury. We then present two sensitivity cases, including a discussion on battery salvage value, followed by MHDV vehicle cost data and results.

If depreciation is assumed to incur every year, but we only want to discount actual cash flows, then the net vehicle ownership cost for a vehicle purchased prior to year 1 and sold in year m is:

$$Net\ Vehicle\ Cost = \sum_{1}^{m} Vehicle\ Cost_n = \sum_{1}^{m} (RV_{n-1} - RV_n)\ = (C - RV_m) \qquad \text{Eq 3.3}$$

In this telescoping sum, C represents the initial vehicle cost, RV_n represents the residual value at the end of year n. Therefore, the goal is then to estimate a resale value based on the characteristics of the vehicle of interest. For LDVs, we provide resale values for each year based on the MSRP, powertrain, market segment (mass-market/luxury), and size class of the vehicle. For MHDV, we provide resale values for each year based on the MSRP, weight class/body type, and mileage of the vehicle.

Depreciation is one of the largest factors in a calculation of the TCO of a vehicle, especially in the first few years of the vehicle's life (Hamza et al. 2020; AAA 2019). However, the vehicle is an asset which retains resale value through its life. Since most new car buyers do not own their vehicle for the entirety of its lifetime, residual value is an important consideration in the TCO calculation for a new car. For those that lease a vehicle, for whom resale value may not seem to be as important as the vehicle need not be resold, the depreciation is factored into the monthly/annual vehicle leasing costs.

In general, many factors affect the residual value of used vehicles. The National Automobile Dealers Association (NADA) User Guide, Autoblog, Consumer Reports, Kelley Blue Book (KBB), and Edmunds all provide estimations of used car resale values based on vehicle conditions. The major factors these providers utilize when determining price include vehicle make, model and model year, mileage, location, overall condition, and some other vehicle characteristics such as specific trim lines or additional equipment. Variation is especially evident in the case of PEVs, whose battery performance and range, as well as accessibility to charging, may have a large effect on residual value. Additional factors such as market fluctuations, economic impacts, and various incentives at the federal, state, and local levels also affect depreciation; many of these exogenous factors are not directly captured in our analysis.

Despite the scarcity of data, several past studies have explored the resale value of PEVs. In 2016, Zhou et al. (2016) analyzed residual value across different powertrains using adjusted (i.e., accounting for federal PEV incentives) retention rate. They found that PEV retention rates were comparable to HEVs and ICEVs in the early years but somewhat lower at three years and beyond. In a follow-up study, Guo and Zhou (2019) found that the long-range, high-performance Tesla Model S holds value better than any other vehicle type evaluated. HEVs and PHEVs were comparable to each other and held slightly less value than conventional models, but significantly more than short-range BEVs. In their TCO calculation, Hamza et al. (2020) similarly found that PHEVs and ICEVs hold value relatively the same, while BEVs experience 11% lower 5-year retention. This could be due to many factors, including actual or a perceived fear of battery degradation or range/charging availability anxiety, as battery range is the most important vehicle aspect for consumers when considering purchasing a BEV (Schoettle and Sivak 2018), and to decreasing prices of new BEVs, which lead to lower prices for used PEVs (Holweg and Kattuman 2006).

To determine the residual value of LDVs, we assume that when an owner decides to sell their vehicle, they choose the greatest of three options:

1) Sell the vehicle on the used market
2) Scrap the vehicle for \$500, or analytically equivalently, take an IRS deductible charitable donation of \$500 for donating the vehicle
3) For PHEVs and BEVs, salvage the battery to be repurposed for further use

We describe the methodology for determining the resale value of the used vehicle below. While the IRS deduction is not quite equivalent to cash value, we assume that consumers value the deductible at \$500 regardless of the age, mileage, or any other characteristic of the vehicle (IRS 2015). For the battery salvage value, we use a baseline case of \$0 for the primary analysis.

A PEV owner can salvage the battery by selling it for second-life applications or recycling; unfortunately, both second-life applications and recycling are not profitable at present and will remain so in the near future (Dai et al. 2019; Gaines 2019; Harper et al. 2019). We examine a non-zero battery salvage value in the sensitivity analysis.

3.2.5.1. LDV Depreciation

We access data on the value of used light-duty vehicles from Edmunds.com (Edmunds TMV 2020). Edmunds provides "True Market Value" (TMV) of used vehicles based on real transactions. These estimates are updated monthly and reflect market conditions. Edmunds also projects annual depreciation for the first five years of a new vehicle's life as a part of their True Cost to Own® data (Edmunds TCO 2020). Edmunds True Cost to Own® provides future projections and is not based on actual transactions; for this reason and to eliminate the projection bias by Edmunds, we selected the first method (TMV).

We selected Edmunds over other data sources because many of the other third-party sources such as KBB, Autoblog and Consumer Reports only provide TCO-formulated depreciation costs, which are based on projected costs rather than actual transaction prices. Furthermore, while we are aware of other sources that provide self-reported transaction data, such as truecar.com, it is challenging to validate the self-reported values with the true transaction prices. Finally, while there are sources such as KBB, Cars.com, Craigslist and Facebook Marketplace that provide vehicle listing prices, it is difficult to ascertain the relationship between listing price and transaction price. Our research purpose is to quantify the general vehicle depreciation trends by vehicle class, segment, and powertrain type, not by make and model. As such, we selected one data source, Edmunds, as (1) its TMV data are based on real transactions, and (2) to be consistent with the data source used in other sections (e.g. insurance, maintenance and repair). Future research is needed to compare the market values estimates from different resources.

The data presented here represent TMV from July 2020 for MYs 2013–2019. As opposed to tracking TMV data for one MY over several years, this method provides a snapshot of TMV estimates at the time of collection. For example, TMVs at year one are estimates of MY2019 in 2020 and TMVs at year three are estimates of MY2017 in 2020. All TMV values we collected were for private party transactions for used vehicles in clean condition with 12,000 annual VMT, in between the average annual VMT for cars and light trucks reported by the Transportation Energy Data Book (Davis and Boundy 2020). We performed a sensitivity analysis of annual VMT and observed little effect on TMV for adjustments under several thousand annual VMT.

We selected 23 makes and 98 models (Table 3.8) for 51 zip codes: one in each of the 50 U.S. states and Washington D.C. While Edmunds provides TMV data for all available trim lines, we selected the most popular 2019 trim line and then used the same trim for each previous MY. These models were selected to cover different powertrain technologies, size classes, market segments, and various popular manufacturer brands and originating countries. We began by selecting the best-selling non-conventional vehicles; our analysis included 33 best-selling PEV models, 22 best-selling HEV models, and the 3 FCEV models in the U.S., accounting for 97%

and 96% of total 2019 PEV and HEV sales (ANL 2021b). To compare depreciation rates for alternative fuel vehicles with ICEVs, we picked conventional ICEV versions of the PEV, HEV, and FCEV models (e.g., Kia Soul, Kia Soul EV). When a direct conventional counterpart was unavailable, we picked a comparable model that fell into the same EPA size class and MSRP range (e.g., Nissan Leaf, Nissan Altima). In total, our analysis included 40 ICEV models.

We obtained MSRP and size class data from the fueleconomy.gov website (DOE and EPA 2020a) and PEV federal incentive data from the IRS website (IRS 2020). For models for which federal incentives were being phased out during 2019 (GM, Tesla), we computed a 2019 sales-weighted average incentive (ANL 2021b). We aggregated depreciation by market segment (luxury/mass-market) as defined by Wards (Wards Intelligence 2020).

TABLE 3.8 Makes and models selected for depreciation analysis

Make	ICEV	BEV	PHEV	HEV	FCEV
Acura	MDX, ILX, RLX			MDX, RLX Sport Hybrid	
Audi	A4, Q7	E-tron		A8	
BMW	X6, 5 Series, 7 Series	i3	5 Series Plug-in, 7 Series Plug-in, i8		
Cadillac	XTS				
Chevrolet	Cruze, Malibu, Spark	Bolt EV	Volt	Malibu Hybrid	
Chrysler	Pacifica			Pacifica Hybrid	
FIAT	500	500e			
Ford	Fusion, Escape		Fusion Energi	Fusion Hybrid, C-Max Hybrid	
Honda	Civic, Accord	Clarity	Clarity	Accord Hybrid, Insight	Clarity
Hyundai	Sonata, Kona	Ioniq Electric, Kona Electric	Sonata Plug-in, Ioniq Plug-in	Sonata Hybrid, Ioniq Hybrid	Nexo
Kia	Optima, Soul	Soul EV, Niro EV	Optima Plug-in, Niro Plug-in	Optima Hybrid, Niro	
Land Rover	Range Rover, Range Rover Sport				
Lexus	ES350			ES300h, RX450h, NX300h	
Lincoln	MKZ			MKZ Hybrid	
Mercedes-Benz	GLE-Class, G-Class	B-Class Electric Drive	GLC-Class		
Mitsubishi	Outlander		Outlander Plug-in		
Nissan	Sentra, Altima	Leaf			
Porsche	Panamera, Cayenne		Panamera Plug-in, Cayenne Plug-in		
Subaru	Crosstrek		Crosstrek		

TABLE 3.8 (Cont.)

Make	ICEV	BEV	PHEV	HEV	FCEV
Tesla		Model S, Model X, Model 3			
Toyota	Camry, RAV4, Highlander, Avalon		Prius Prime	Camry Hybrid, RAV4 Hybrid, Highlander Hybrid, Avalon Hybrid, Prius, Prius c	Mirai
Volkswagen	Golf GTI	E-golf			
Volvo	XC90		XC90 Plug-in		

To control for the effect of the federal tax incentive for PHEVs and BEVs, we define an adjusted retention rate, ARR_i, such that

$$ARR_i = \frac{P_0 - I - \Delta_i}{P_0 - I}, i = 1,2,3, \ldots \qquad \text{Eq 3.4}$$

where

ARR_i = the adjusted retention rate at year i,

P_0 = the original MSRP,

Δ_i = the accumulated depreciation through year i, and

I = the federal income tax credit applicable to a specific model.

For each vehicle's MSRP, we used the 2019 MSRP of the most similar make and model to minimize concerns about inflation across the analysis window. We also ran a sensitivity analysis where P_0 was equal to the MSRP in the year the car was sold as new (i.e. MSRP of MY2017 for Δ_3, etc.) and found no significant effect on ARR_i. Ideally, we would include state and dealer incentives in addition to the federal one; however, it is very difficult to track these incentives as they change over time and may not be applied to each vehicle.

Using the ARR allows us to normalize across MSRPs and powertrain types that qualify for different federal tax credits. As discussed by Zhou et al. (2016), adjusted retention rate is a more objective metric for comparing depreciation of BEVs, PHEVs, and conventional vehicles; since the Edmunds TMV data is based on real-world value, they are relative to this adjusted initial cost. As such, we use ARR. In this case, the cumulative depreciation through year *i* is given by

$$P_0 - I - TMV_i = (P_0 - I)(1 - ARR_i), i = 1,2,3, \ldots \qquad \text{Eq 3.5}$$

where TMV_i = the resale value in year *i*. In order to calculate a value for ARR_i for each year *i* of the lifetime of a vehicle, accounting for effects of powertrain, market segment, and size class, we disaggregate the data by powertrain and market segment (luxury/mass-market); later, we performed an adjustment for the size class.

Figure 3.9 shows the average ARR of different powertrain types for each MY in luxury and mass markets. In general, luxury vehicles tend to depreciate more slowly than mass-market vehicles. We also see that BEVs and PHEVs depreciate more quickly than their HEV and ICEV counterparts do. We aggregated vehicle size class into the two regulatory size classes, light truck (Small SUV, Standard SUV, Minivan) and car (all other LDV) to examine depreciation by powertrain type. Further disaggregation (by vehicle type) is not considered in order to maintain sufficiently large samples for analysis by powertrain. The ARRs plotted in Figure 3.10 show the average ARR for different powertrains for cars (shown as solid lines) and for light trucks (shown as dashed lines). Figure 3.10 shows that light trucks have higher adjusted retention rates than cars across all powertrains. The difference between light trucks and cars is higher for alternative fuel vehicles.

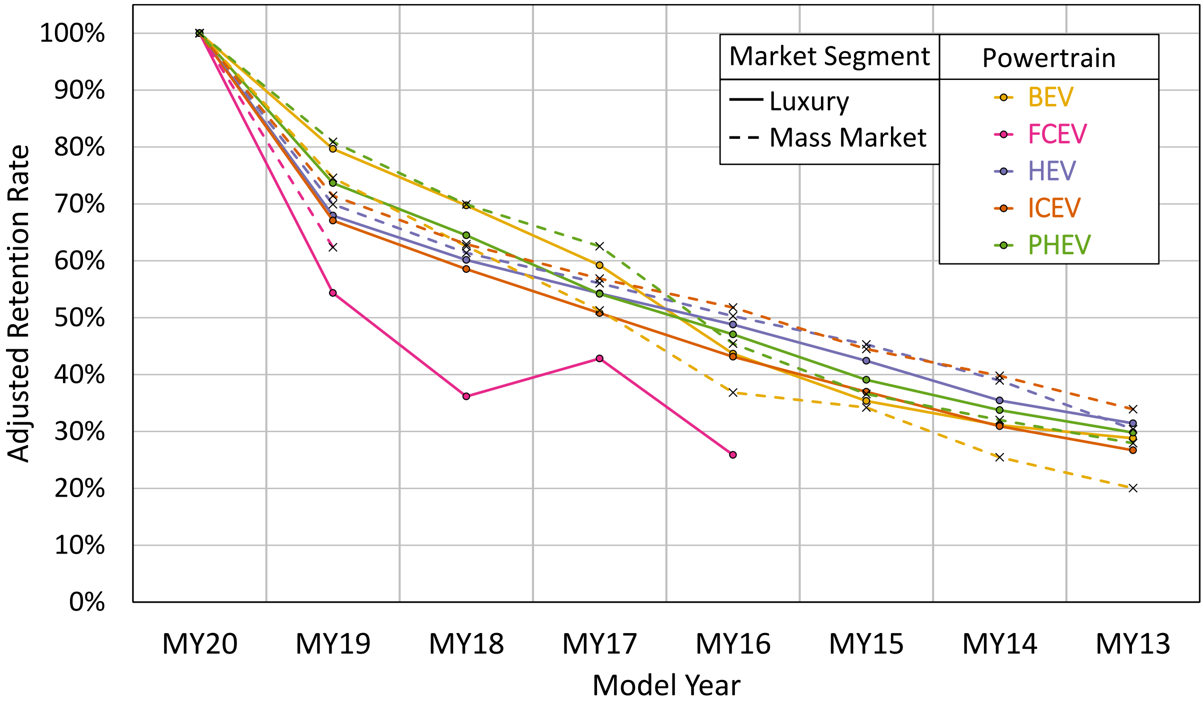


FIGURE 3.9 Average annual ARR by powertrain and market segment. Solid lines represent luxury vehicles while dashed lines represent mass market vehicles.

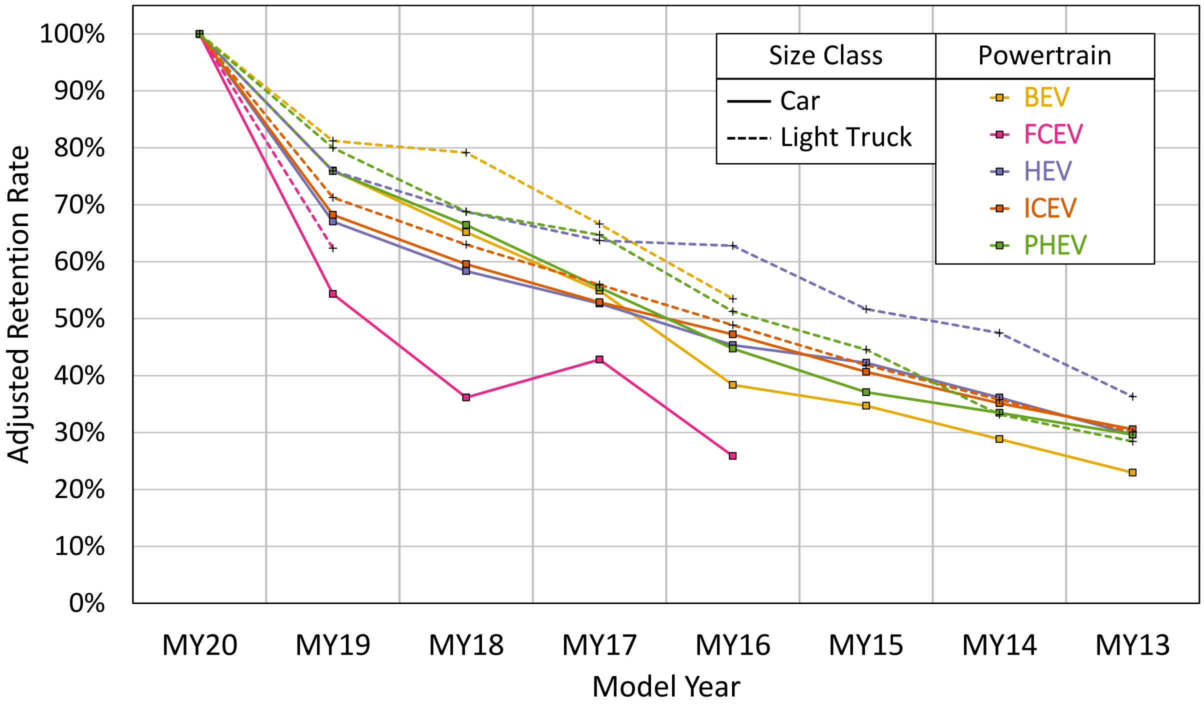


FIGURE 3.10 Average annual ARR by powertrain and regulatory size class. Solid lines represent cars while dashed lines represent light trucks.

In order to forecast depreciation for the lifetime of any generalized vehicle, we fit an exponential model of the form for the adjusted retention rate $ARR_{i,l,p}$ as a function of age (i), powertrain type (p), and luxury classification (l)

$$ARR_{i,l,p} = b_{l,p} \times exp(k_{l,p} \cdot i), \qquad \text{Eq 3.6}$$

where $\exp(k_{l,p})$ is the percentage value retention from the previous year for a vehicle of luxury classification l and powertrain p, and

$b_{l,p}$ is a scaling factor representing the loss in residual value immediately upon initial sale,

assuming a constant annual depreciation rate (percentage of previous year resale value) for vehicles in each powertrain/market segment subset. As $\exp(k_{l,p})$ is the percentage value retention from the previous year, the annual depreciation rate (percentage decrease in resale value for each one-year increment in age) is calculated by $[1 - \exp(k_{l,p})]$. While there are several possible methods to fit an exponential model of the TMV data, we found little variation among the methods we explored; all fell within or near the 68% prediction interval examined in the sensitivity analysis (i.e. within approximately one standard deviation) for the method we chose. We fit the function only starting after the first year (years 1-7) and did not use the initial sales price as a data point because the depreciation from year 0 to year 1 is not representative of the depreciation over the rest of the vehicle's life (Krome 2018; Lewerer 2018), and so we introduce the factor $b_{l,p}$ to account for this first-year depreciation. For each powertrain/market segment subset, we estimated $ARR_{i,l,p}$ for each year by extrapolating the exponential fit from year 1 to the entire analysis horizon. For FCEV, we do not make a distinction for luxury/mass-market due to data scarcity. Table 3.9 summarizes the annual depreciation rates (percentage decrease relative to previous year resale value) and the additional first-year depreciation for each powertrain and luxury segment, as derived from the exponential model fitting. Note that the values for $b_{l,p}$ are on top of the annual depreciation; at the end of the first year, a vehicle has depreciated by the product of $b_{l,p}$ and $exp(k_{l,p})$.

TABLE 3.9 Annual depreciation rates and first-year value adjustment by powertrain and market segment

Annual Depreciation Rates, 1-exp($k_{l,p}$)					
	BEV	**FCEV**	**HEV**	**ICEV**	**PHEV**
Mass-market	19.2%	19.5%	12.1%	11.3%	16.6%
Luxury	17.4%		12.0%	14.5%	14.3%
Additional First-Year Value Adjustment, $b_{l,p}$					
	BEV	**FCEV**	**HEV**	**ICEV**	**PHEV**
Mass-market	92.2%	71.4%	80.0%	80.3%	98.6%
Luxury	97.9%		77.8%	79.5%	85.9%

While Figures 3.9 and 3.10 show real-world data based on specific models, our TCO calculations require a more generalized comparison between cars and light-trucks that is independent of specific model years. We calculated the average difference between the ARRs of the two size classes (cars and light trucks) within each powertrain type (but not segmenting by luxury/mass-market due to small sample sizes), and adjusted the ARRs for each powertrain type and market segment as a proportion of the average ARR for each year, where

$$ARR_{i,p,k} = ARR_{i,p} \times \left(1 \pm S_p / 2\right), \qquad \text{Eq 3.7}$$

where i is the age of the vehicle, p labels each powertrain, k represents the size class, and S_p is the adjustment for the size for each powertrain. The values of these proportional differences for cars and light trucks are shown in Table 3.10. For all powertrain types, we make an upward adjustment for light trucks and a downward adjustment for cars.

TABLE 3.10 Proportional differences (of average ARR) between size classes (Car and Light trucks)

Powertrain	BEV	FCEV	HEV	ICEV	PHEV
Difference	21.6%	14.1%	22.6%	3.2%	7.6%

We show a sample result for a mass-market ICEV in Figure 3.11. Individual data points represent the residual value of actual vehicles as a function of vehicle age. The dashed line represents ARR for ICE vehicles, while the solid lines represent the ARR for cars and light trucks. An inset is included in Figure 3.11 to show the differences in ARR more clearly. Note how light trucks exhibit marginally higher ARRs than cars throughout the analysis window, though they both approach zero over time. Also note the variation in ARR of individual vehicles decreases from initial purchase through the end of the data window (years 6-7).

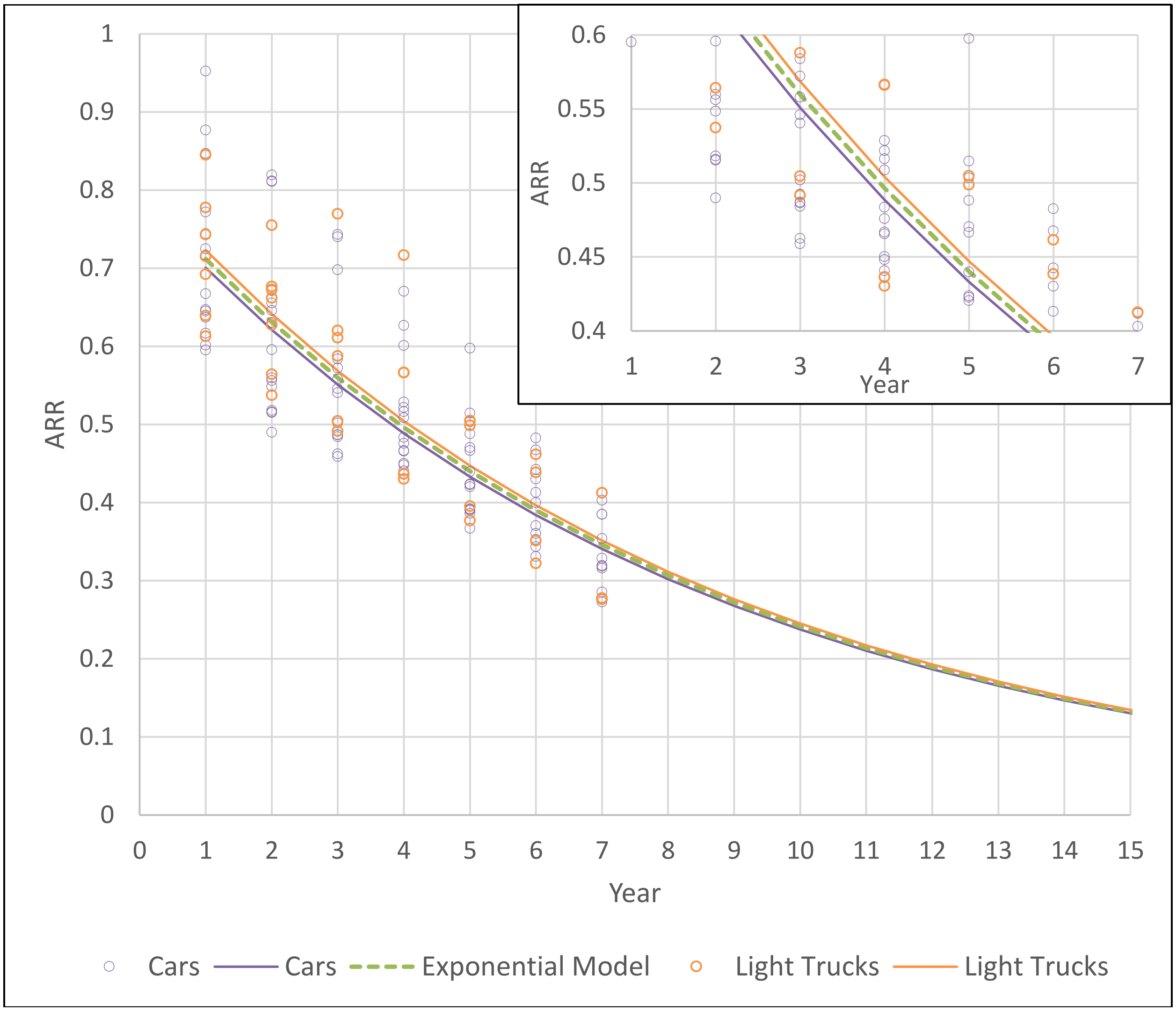


FIGURE 3.11 Size-class adjusted ARR for mass-market ICEV used as TCO input

Comparing depreciation across powertrains, we find some interesting differences. As shown in Figure 3.9, both BEVs and PHEVs tend to have higher ARRs in early years before dropping off between MY17 and MY16. A recent study conducted by Guo and Zhou (2019) using TMV data on MY13 - MY16 found that powertrain accounted for over 10% of the variance in 3-year ARR while we found that it explains less than 5%, indicating that depreciation differences between powertrains are diminishing. We also found that BEVs and PHEVs both have *higher* 3-year ARRs than their HEV and ICEV counterparts do, albeit only marginally higher in the case of BEVs. This is a key difference from Guo and Zhou (2019), who found that BEVs and PHEVs had lower 3-year ARRs than HEVs and ICEVs, substantially lower in the case of BEVs.

This key finding indicates that *both BEVs and PHEVs increasingly maintain higher residual value*; in fact, we found that BEVs and PHEVs have higher 3-year ARRs than ICEVs and HEVs. This is consistent with recent industry reports of improving resale values of used PEVs (e.g., Halvorson 2019). This suggests that alternative powertrain technology has reached the point where it can compete with conventional models, after accounting for federal incentives; possibly indicating growing consumer confidence in the capability of BEVs and PHEVs. This could be due to improving BEV technology in recent MYs, including increased electric range and charging capability. BEV sales-weighted average range increased from 228 miles in August 2017 to 304 miles in August 2020 (ANL 2021b). Moreover, sales-weighted average electricity consumption across the BEV market, a measure of how much electricity is needed to drive a given distance, decreased from 33 kWh/100 miles in August 2017 to 29 kWh/100 miles in August 2020 (ANL 2021b). Both of these trends indicate increasing electric range for BEVs, making them more viable alternatives to conventional powertrain vehicles.

In order to assess the uncertainty in depreciation during the first few years of a vehicle's life, we examined the variability in depreciation data within each powertrain/market segment subset. We performed linear regression on a semi-log plot to obtain a 68% prediction interval for the first 7 years after transforming back to the original variables. This provides an interval within which we expect new data points to fall with 68% confidence. We selected a 68% interval to be consistent with the plus/minus one standard deviation range, as described in Section 3.1. As an example, Figure 3.12 shows a prediction interval for mass-market BEVs. In sensitivity analyses involving deprecation at different confidence intervals, we find the counterintuitive result that increased deprecation early in the vehicle life has little impact on TCO and can even lead to decreased TCO over the lifetime of the vehicle. This is because a lower residual value decreases the cost of insurance earlier in the vehicle lifetime (as will be described in Section 0), but the ultimate sale price at the end of the analysis window (e.g., year 15) is very similar.

We also considered a non-zero battery salvage value for PHEVs and BEVs for a second sensitivity analysis. While second life applications and recycling of PEV batteries are not profitable at present, it is plausible that this could change in the future (Dai et al. 2019). We used a model developed by NREL, as described in Section 3.2.1.1, that provides battery salvage value as a percentage of age, battery size, and initial purchase price, accounting for the forecasted future new battery price, forecasted battery health, relative cost of refurbishment, the used product discount, and the retail price to manufacturing cost ratio of 1.5 (Neubauer and Pesaran 2010).

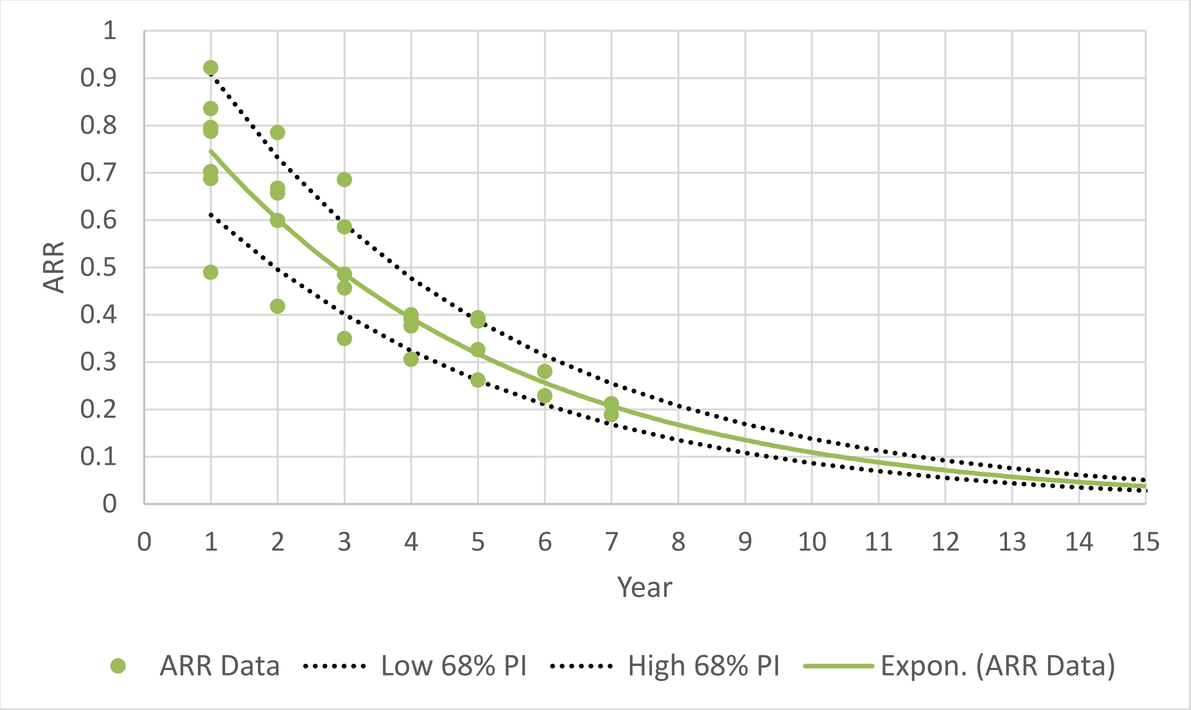


FIGURE 3.12 Sample prediction interval sensitivity analysis: Mass-market BEV

In calculating the value of the vehicle each year, we then used the greatest of the vehicle resale value, battery salvage value, and $500 vehicle scrappage value. Using an Autonomie result as an example, Figure 3.13 shows the maximum vehicle value of a mass-market BEV, unadjusted for size class, with an MSRP of $34,649 and a battery size of 61.3 kWh. To estimate initial battery price, we multiplied the battery size of the vehicle of interest by the current battery manufacturing cost of $185/kWh (Boyd 2020). The solid line indicates the maximum of the three curves. Note how the resale value is by far the greatest in early years but drops quickly due to the fast depreciation of the vehicle in comparison to the battery. Salvaging the battery becomes the most valuable option around year 9 and remains so until year 28 when it finally drops below the $500 vehicle scrappage value. While this is beyond the analysis timeframe in this report, we include this result to emphasize how late the battery salvage value finally falls below the vehicle scrappage value. Without accounting for battery salvage, scrappage becomes more cost effective than selling the vehicle around year 20.

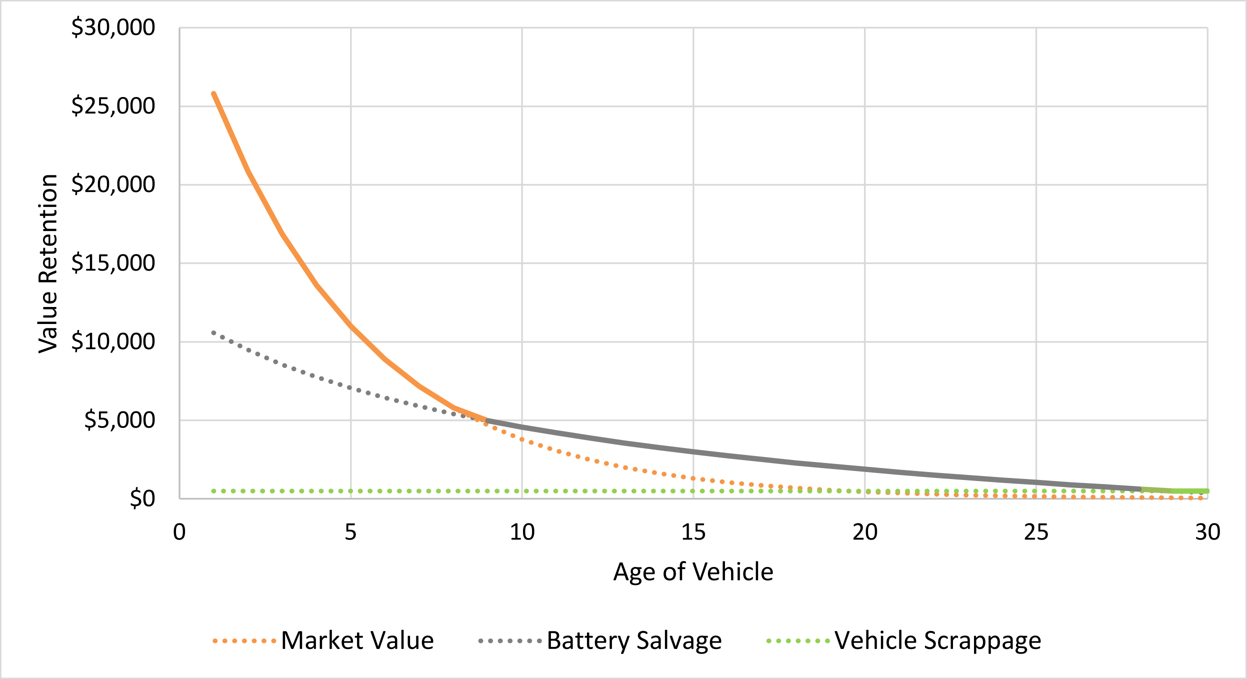


FIGURE 3.13 Sample selection of maximum vehicle value (solid line = maximum)

3.2.5.2. MHDV Vehicle Depreciation

While the available MHDV depreciation data are more limited than for LDVs, we analyzed listing price data from Commercial Truck Trader and TruckPaper.com (CTT 2019; Truck Paper 2019). Note that the data used in this section come from listing data, not actual transaction data nor estimated market values made by a third party. These data sources were advantageous because they provided data about other characteristics of the vehicle beyond the list price and are two of the only publicly available sources for such data. These data were collected in September 2019 and included vehicle age, mileage, weight class, and body style in addition to the list price. While we do not know the exact prices of each transaction, the listing price is a good estimator of the sale price. Unfortunately, there is extreme data scarcity for alternative powertrain vehicles in the medium-duty and heavy-duty sectors, since only compressed natural gas vehicles have seen appreciable historical sales. Therefore, we are unable to differentiate depreciation rates across powertrain types. However, we are able to subset the listing price data into five vehicle segments defined by weight class and body type: class 8 sleeper tractors, class 8 Day Cab, class 8 Box Truck, class 6 Box Truck, and class 4 Step Van (Davis and Boundy 2020).

For validation, we also accessed market value estimates from PriceDigests for two segments, class 8 sleeper and day cab tractors (Carr 2020). Overall, the two datasets agree quite closely, with Pearson correlation coefficients of 0.973 and 0.989 for sleeper cabs and day cabs, respectively. Figure 3.14 also shows the agreement between the two datasets (in this case, for sleepers), as well as how MHDVs depreciate with vehicle age.

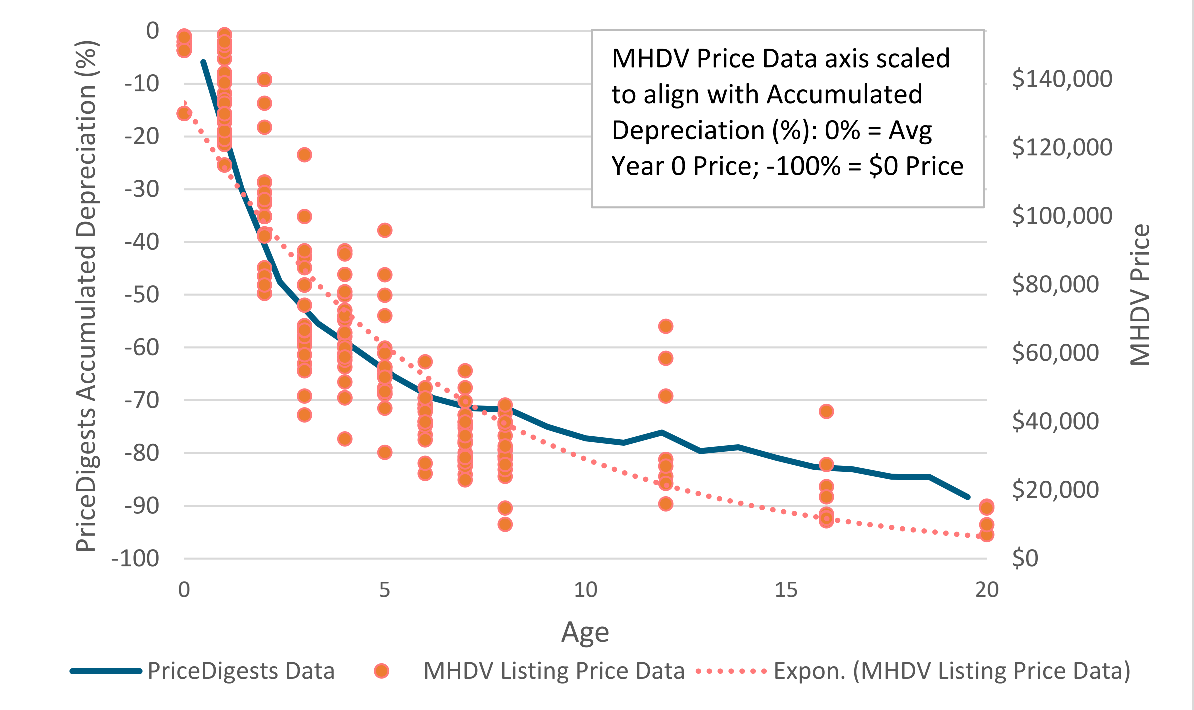


FIGURE 3.14 Comparison between price datasets, by age: class 8 sleeper cab tractors

To estimate the MHDV depreciation in the TCO calculation, we used a regression model of the listing price data for each segment to estimate the price of a vehicle based on its age and mileage. This functional form provides flexibility to account for the effect of both age and cumulative mileage under different VMT schedule assumptions. For each segment, we estimated a regression model for the residual value (*RV*) of the form

$$RV(a, m) = C \cdot \exp(A \cdot a + M \cdot m) \qquad \text{Eq 3.8}$$

where C is the regression-estimated retail price at age 0 with no mileage,
a is the age in years,
m is the mileage in thousands,
exp(A) is the percentage price retention from the previous year, and
exp(M) is the percentage price retention from the previous 1000 miles,

which assumes that the effects of both age and mileage are exponential. Figures 3.14 (above) and 3.15 (below) demonstrate the effect of age and mileage on price for class 8 Sleepers, indicating an exponential relationship for both; the other size classes show similar trends. In this case, C is a scaling factor to account for differences in initial retail price across segments and can be interpreted as the regression-estimated retail price for a vehicle in a given segment. In Figure 3.15 below, the dotted line shows an exponential fit for all model years simultaneously to guide the eye and show the exponential dependence.

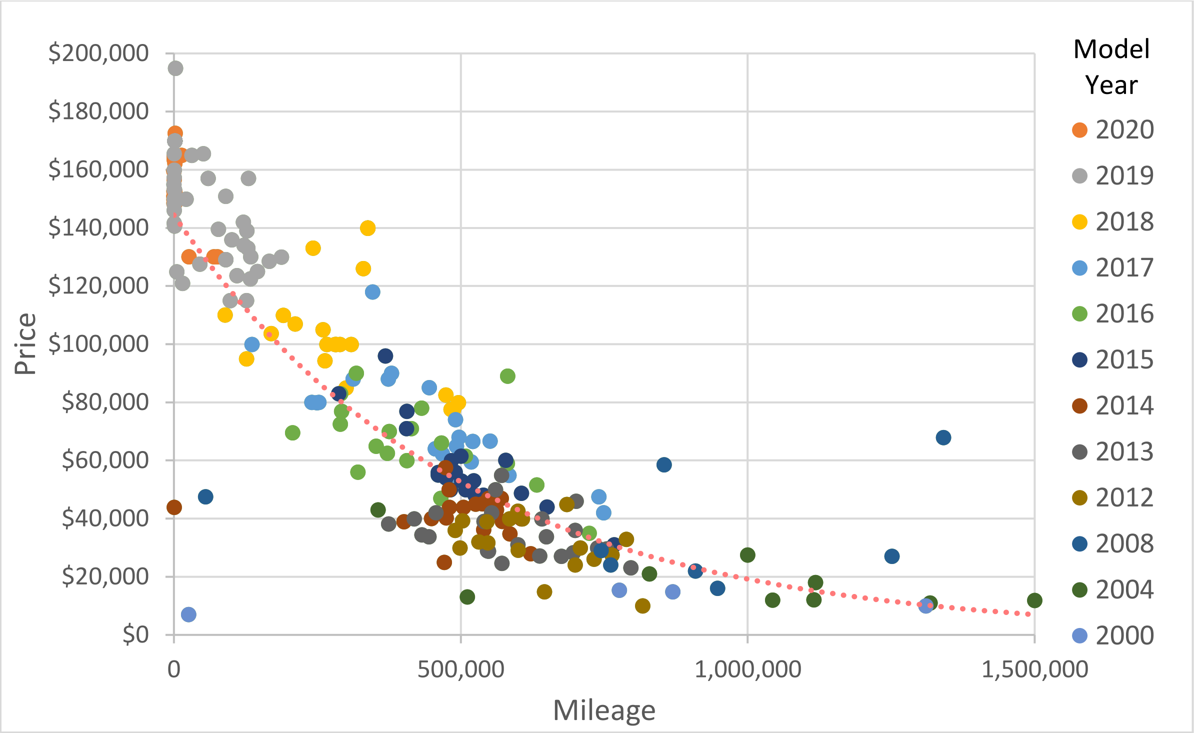


FIGURE 3.15 Sample effect of mileage on price: class 8 sleeper cab tractors

The parameter values for exp(*A*) and exp(*M*) for each segment along with their p-values are reported below in Table 3.11. For example, a sleeper depreciates 9.3% every year holding the mileage constant and depreciates 0.1% for every additional 1000 miles holding the age constant. If a sleeper drives 100,000 miles over the course of a year, it would retain $(90.7\%) \times (99.9\%)^{100} = 82.1\%$ of what it was worth at the beginning of the year.

TABLE 3.11 Parameter values for effect of age (*A*) and mileage (*M*) of MHDV, by size class

	Class 8 Sleeper	**Class 8 Day Cab**	**Class 8 Box**	**Class 6 Box**	**Class 4 Step**
exp(*A*)	0.9071***	0.9113***	0.9220***	0.9007***	0.9342***
exp(*M*)	0.9990***	0.9991***	0.9999*	0.9991***	0.9996**

Note: ***p < 0.0001, **p < 0.1, *p = 0.64

With the values from Table 3.11, the net vehicle ownership cost for a MHDV purchased prior to year 1 with 0 miles and sold in year *a* with *s* total miles is then

$$Depreciation = \sum_{1}^{a} Vehicle\ Cost_n = C(1 - \exp(A \cdot a + M \cdot s)) \qquad \text{Eq 3.9}$$

3.3. FUEL COSTS AND INFRASTRUCTURE

In this section, we examine energy prices to determine fuel costs for both LDVs and MHDVs. The total cost for fuel over the analysis window can be expressed in the form:

$$Fuel\ Cost = (fuel\ price) \times (fuel\ consumption\ rate) \times (annual\ VMT) \times (analysis\ window) \qquad \text{Eq 3.10}$$

Thus fuel cost is linked to the specific fuel, the vehicle fuel economy, and behavior by the vehicle owner. Differences in price across fuel types can have a significant effect on the TCO of various powertrain types as fuel is the second-largest cost component in the TCO for many LDVs and MHDVs. We collected energy price data and projections of future prices for gasoline, diesel, electricity, and hydrogen from the Energy Information Agency’s 2020 Annual Energy Outlook (AEO), recent reports on VTO and HFTO prospective program benefits analyses (EIA 2020; Islam et al. 2020; Vijayagopal et al. 2019; Stephens et al. 2020), and the DOE’s Alternative Fuel Data Center (AFDC) alternative fuel price reports (Bourbon 2020). We also collected historical prices of regular and premium gasoline from the EIA, and analyzed the difference between these over recent years to try to forecast premium gasoline prices in the future. Fuel prices are assumed to be those delivered to the vehicle; we do not add additional costs for fueling or charging infrastructure in our baseline case.

We created a database of energy price from compiling data from the sources described above, totaling 123 records, including estimates for 2020 and projections for future years. The 2025 energy price assumptions used as the first year in the baseline TCO calculations are aggregated in Table 3.12. In Table 3.12, we provide the cost-per-natural-unit for each type as well as in dollar per gasoline gallon equivalent (gge) and diesel gallon equivalent (dge) for easy comparison. We convert energy content between fuels using the lower heating values in the Transportation Energy Data Book (Davis and Boundy 2020).

TABLE 3.12 2025 energy prices by type in natural units, $/gge, and $/dge

Energy Type	**cost-per-natural-unit**	**$/gge**	**$/dge**
Gasoline (regular)	$2.63 / gallon gasoline	$2.63	$3.01
Gasoline (premium)	$2.99 / gallon gasoline	$2.99	$3.42
Diesel	$3.08 / gallon diesel	$2.69	$3.08
Hydrogen	$9.41 / kg H_2	$9.41	$10.77
Electricity (LDV)	$0.129 / kWh	$4.33	$4.96
Electricity (HDV)	$0.123 / kWh	$4.16	$4.76

Regular gasoline and diesel prices come from AEO 2020 reference case. Hydrogen prices come from HFTO targets, starting at a 2020 price of $13.82/kg of H_2 in 2020 and reaching $5.00/kg delivered by 2030, with a linear decrease in price until then. The electricity price for light-duty vehicles comes from the residential end-use electricity price from AEO 2020, while the electricity price MHDV comes from the average transportation end-use electricity price from AEO 2020. This represents the price paid by the consumer, and so implicitly includes charging infrastructure, including electric vehicle supply equipment (EVSE). A projection of future premium gasoline prices is not available from EIA. Therefore, we collected historical annual average regular and premium gasoline prices from 1994 to 2020 from EIA to develop a weighted linear regression models. The data weights were assigned to give greater weight to more recent years; a weight of 1 was assigned for the year 1994 and each year's weight increased linearly to 27 for the data point in year 2020. Fitting the data, we found the best fit by the equation:

$$Prem_i = 1.02 \times Reg_i + \$0.309 \qquad \text{Eq 3.11}$$

where $Prem_i$ is the price per gallon of premium gasoline and Reg_i is the price per gallon of regular gasoline.

Although future fuel prices can be highly volatile and may not affect consumer decisions, in calculating a lifetime TCO, it is important to consider the best estimate of the future cost to a consumer. As such, we use the projected fuel prices in each year to determine the fuel costs in that year. While there is little variation in future fuel prices for the petroleum-based fuels and electricity, research and development efforts by the DOE and other organizations project to decrease the price of hydrogen significantly over the next decade. As such, using projected fuel prices is especially important in the case of FCEVs, as DOE research aims to lower the price of hydrogen from about $14/kg to $5/kg or less (Ramsden and Joseck 2018; Marcinkoski et al. 2019).

In addition to our baseline analysis, we explore sensitivity cases for low and high values for fuel prices. For petroleum-based fuels, the low and high sensitivity cases come from the AEO 2020 low oil and high oil cases. The high-price case for hydrogen comes from the 'no program' case from a recent DOE office program benefits analysis (Stephens et al. 2020). For electricity there is great uncertainty in required infrastructure and charging capacity and rate demands, among other factors. For LDV electricity rates, we rely on recent analysis from Borlaug et al. (2020). Here the lower bound for residential electricity is $0.08/kWh, where vehicles are largely charged during off-peak hours, and the upper bound of $0.27/kWh represents charging predominantly at high-power public charging stations. For MHDV electricity, we use the EIA commercial rate as the lower bound for MHDV electricity (~$0.10/kWh), while we use $0.36/kWh for extremely fast charging from Burnham et al. (2017). This electricity may be sourced from private depots rather than public charging facilities, and so we also consider side cases with different costs of EVSE. For LDV, we consider a typical charging station installation of $800, while MHDV charging station installation can cost much more. Based on limited estimates from literature, we assume values of $4,000 for medium-duty applications, $50,000 for day cabs, and $120,000 for sleeper-cab tractors (Nicholas 2019; Borlaug et al. 2020; Nelder and Rogers 2019).

3.4. INSURANCE COST

Insurance is a large component of the total cost of ownership for both light-duty and medium-/heavy-duty vehicles (Hagman et al. 2016). Vehicle insurance costs depend on many factors including the type of coverage, the type of vehicle, the value of the vehicle, where the vehicle is operated, and characteristics of the driver. There are over 650 U.S. automotive insurance companies and they use a mix of more than 40,000 rating factors to generate insurance premiums (The Zebra 2020). In this analysis, we examine both average insurance rates for passenger light-duty vehicles, as well as data using a base profile (i.e. location and driver profile held constant) to explore the impact of vehicle cost, vehicle class, and powertrain type on rates. We examine average insurance rates for select commercial heavy-duty vehicles, as well as data using a base profile. Publicly-available HDV insurance data is very limited in comparison to LDV data.

3.4.1. Passenger Light-Duty Insurance

The three major types of coverage for private passenger vehicles are liability, collision, and comprehensive. Liability insurance covers bodily injuries and property damage to other people if the policyholder is responsible for an accident. Nearly every state requires a minimum level of liability coverage for owners of light-duty passenger vehicles, though that level of coverage can vary significantly. There are three major components of a liability policy, which are typically represented in this format "50/100/25". The first number ("50" in above example) represents the maximum the insurance company will pay for bodily injury per person injured in an accident, the second ("100") is the maximum amount for bodily injury per accident, and the third ("25") is the maximum amount for property damage, in thousands of dollars (e.g., $50,000/$100,000/$25,000). Increasing any one of these coverages will increase the cost of the policy (i.e. premium).

Collision insurance covers damage of the policyholder's vehicle if they are responsible for an accident, while comprehensive insurance covers theft and damage of the policyholder's vehicle in cases not involving an accident (e.g. fire, flood, hail). Comprehensive and collision (C&C) policies may have a deductible, which is the amount the policyholder will pay out-of-pocket on a damage claim. For example, if the policyholder has a $500 deductible and has a collision claim for $3,000, the insurance company would only cover $2,500. Decreasing the deductible will increase the cost of the policy. States do not require collision or comprehensive insurance, but if the car is financed (or leased), the lender typically will (Pogol 2020). Most often, these coverages are bundled together; in 2017, 74% of insured drivers purchased collision coverage, while 78% purchased comprehensive (III 2020). As a vehicle depreciates, the value of C&C insurance diminishes and a rule of thumb is to drop these coverages when the annual premium exceeds 10% of the maximum payout (i.e. value of vehicle minus deductible) (Pogol 2020).

Vehicle location has a significant effect on the cost of each coverage type, as state policy can limit what rating factors are eligible to be used, mandate discounts for certain safety features, and determine if and when rates can be raised (The Zebra 2020). In addition, insurance rates are affected by other local factors, such as the number of uninsured drivers, vehicle thefts, and severe weather events. Figure 3.16 shows the annual insurance premium by state for a MY 2015 Honda Accord EX for a 30-year old single male with a good driving history (The Zebra 2020). As seen in Figure 3.16, the cheapest insurance is typically in low density states that also have low numbers of uninsured drivers. In contrast, Michigan has had one of the highest insurance rates due to the requirement that drivers carry unlimited, lifetime medical coverage resulting from car accident injuries, and the resulting large number of uninsured drivers due to this rule. In 2020, Michigan lowered the personal injury protection requirements to help reduce these rates.

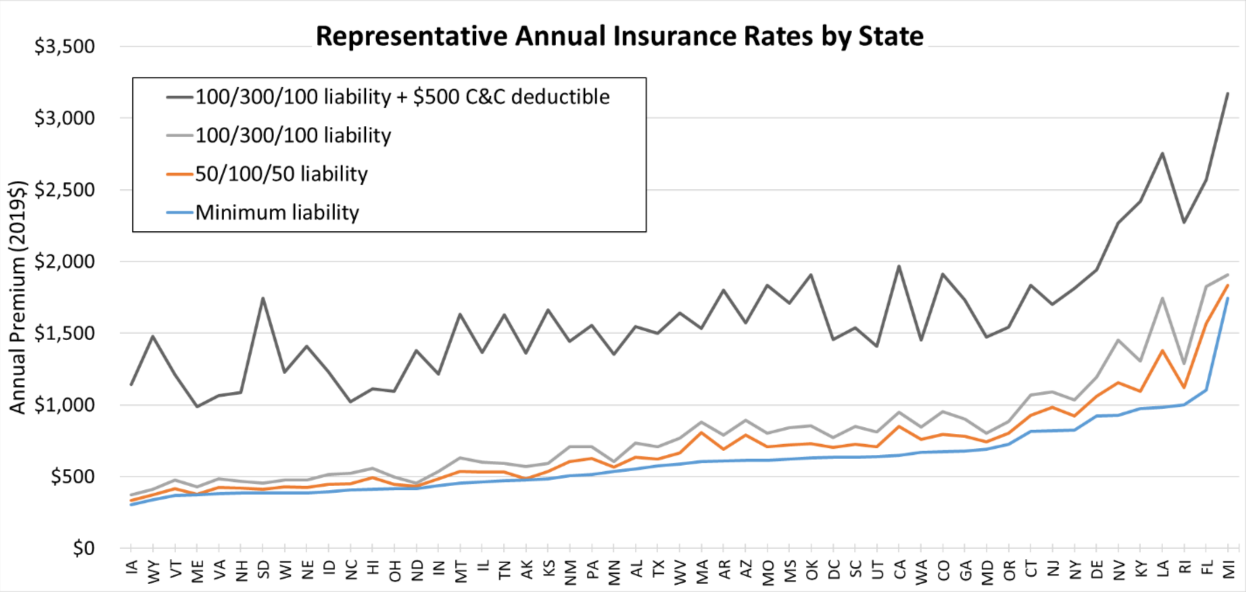


FIGURE 3.16 Annual insurance rates by state for MY2015 Honda Accord EX for a 30-year old single male with a good driving history (data from The Zebra 2020)

3.4.1.1. LDV Liability Insurance

As seen in data presented by the National Association of Insurance Commissioners (NAIC) in Figure 3.17, national average liability premiums for private passenger vehicles have stayed relatively constant in real dollars (2019 dollars) for the past two decades, about $600 per year (NAIC 2020). We similarly found that liability insurance premiums are relatively constant across light-duty vehicle classes and powertrains when analyzing quotes from Progressive (2020) for a variety of makes and models. However, this is an area that requires further study to understand how vehicle size and weight impacts claim cost and frequency, as one would expect larger vehicles to cause more bodily injury and property damage in an accident.

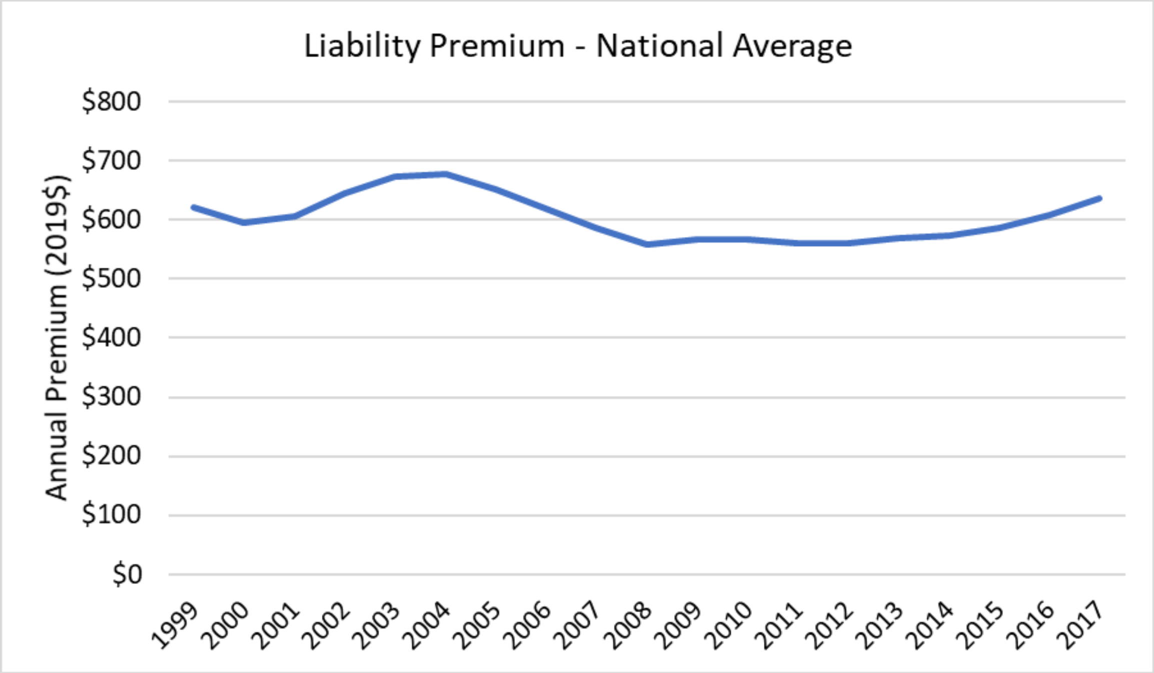


FIGURE 3.17 National average liability insurance premium for light-duty vehicles

3.4.1.2. LDV C&C Insurance: Base Profile and Key Factors

In our analysis, we examined the effect of vehicle type and powertrain on comprehensive and collision insurance rates by using the Edmunds True Cost to Own® dataset for new model year 2019 and 2020 vehicles (Edmunds TCO 2020). Edmunds provided national average insurance rate data by make and model for a base profile that had the following demographic characteristics: male, 45 years old, married, employed, excellent driving record, homeowner, and a good credit score (Levin 2020). Some of the factors included in the Edmunds base profile are prohibited from being used to price insurance in several states, most notably gender and credit score (The Zebra 2020). Nonetheless, the Edmunds base profile factors largely minimize insurance cost results and will not represent a true national average, which would require further analysis of how these factors impact rates and the demographics of registered drivers (e.g. what percent of the population has an "excellent" driving record) (The Zebra 2020). As discussed below, we adjusted the Edmunds insurance cost data for age, which is one of the largest factors in premiums, in order to find a representative national average.

The Edmunds base profile liability has a coverage of 50/100/25 with a $500 deductible for both comprehensive and collision coverages (Levin 2020). The insurance cost data was provided in aggregate (e.g. the total premium for all coverages per vehicle). Therefore, to analyze the cost of liability versus C&C, we estimated the national average 50/100/25 cost of liability coverage to be about $500 (2019$), and subtracted that value from the total Edmunds premium to estimate C&C premiums per vehicle (Progressive 2020). Our cost estimate of 50/100/25 liability coverage ($500) is less than the NAIC (2020) cost estimate of average liability coverage ($600). It is possible that the Progressive (2020) estimate is an underestimate, as other companies could have higher premiums for this profile across the country or that NAIC represents a higher average coverage level than 50/100/25. Reconciling the Progressive (2020) and NAIC (2020) results is difficult due to the lack of demographic and premium data for all insured drivers. Further study of these issues is needed to better understand national average liability, comprehensive, and collision premiums at a make and model level.

As mentioned above, the Edmunds insurance data are for a specific demographic profile and changing those factors will influence premiums. Two of the largest factors on premiums are age and driving history (The Zebra 2020). Table 3.13 shows the percentage of licensed drivers by age group (FHWA 2002) and The Zebra (2020) insurance premium scaling factors that use the age from Edmunds (45 years old) as a baseline. As seen in the table, the costs for both young and old age groups can be significantly higher than middle age groups. For example, a $1,000 annual premium for a 45-year-old would be $3,410 for a 19-year-old holding all other factors constant. The weighted average scaling factor of 1.19 is used in our analysis for C&C premiums. As we use the NAIC (2020) national average liability premium of $600 (2019$) in our analysis, which takes these factors such as age into account, we do not need to adjust that value.

Further research is needed on national average driving records, as this type of information does not seem to be publicly available. Tickets, accidents, and claims will all affect premiums, typically for three years. For example, violations for a seat belt, red light, speeding, and driving under the influence will increase insurance premiums by 6%, 23%, 25%, and 71%, respectively, while an at-fault accident will increase premiums by 41% (The Zebra 2020). Filing a medical claim can increase rates from 0% to more than 40% depending on the state (The Zebra 2020).

TABLE 3.13 Percentage of licensed drivers and insurance premiums by age

Age	% of Licensed Drivers	Insurance Premium Scaling Factor with 40-49 Baseline
19 and Under	5%	3.41
20-29	18%	1.35
30-39	21%	1.04
40-49	21%	1.00
50-59	16%	0.93
60-69	10%	0.94
70-79	7%	1.09
80 and Over	3%	1.28
Weighted Average	N/A	1.19

3.4.1.3. LDV C&C Insurance by Vehicle Type

Using our make and model classification for passenger cars, SUVs, and pickup trucks, we analyzed the relationship between national average comprehensive and collision new vehicle insurance premiums (with a $500 deductible) and MSRP by vehicle type, as seen in Figure 3.18.

This insurance data can be modeled with a linear function. The SUV equation in Figure 3.18 is based on SUV models for MSRPs less than $60,000. The SUV data points beyond that price become scattered due to the limited number of makes and models at those prices, which likely are impacted strongly by the OEM, rather than the vehicle type. From this data, we find that insurance rates are higher for passenger cars than for SUVs and pickups, when MSRP is held constant. SUVs and pickup trucks currently have much higher profit margins than cars, meaning they have lower manufacturing and component costs as a percentage of MSRP (Ulrich 2019). Therefore, it is likely this reduces repair costs (and resulting C&C premiums) as a percentage of MSRP for these vehicles. This is further discussed in Section 3.5. Another possible reason for lower comprehensive and collision insurance costs for pickup trucks and SUVs is their prevalence in lower-density areas where claim frequencies are lower (Vallet 2019). Vehicle weight and dimensions could be another factor why cars have different insurance rates than SUVs and pickups, and which should be analyzed further.

While the above equations are based on MSRP, as a vehicle depreciates insurance companies will reduce the maximum payout for C&C coverage based on the vehicle's value at the time of the claim, which will lead to a lower premium (Allstate 2018). There is little public information on the magnitude of C&C premium changes as different vehicle types age year-to-year and further analysis is needed. However, The Zebra (2020) presents data for a Honda Accord that suggests that premiums may directly be tied to depreciated value, with a large decrease in the first year and smaller changes in following years.

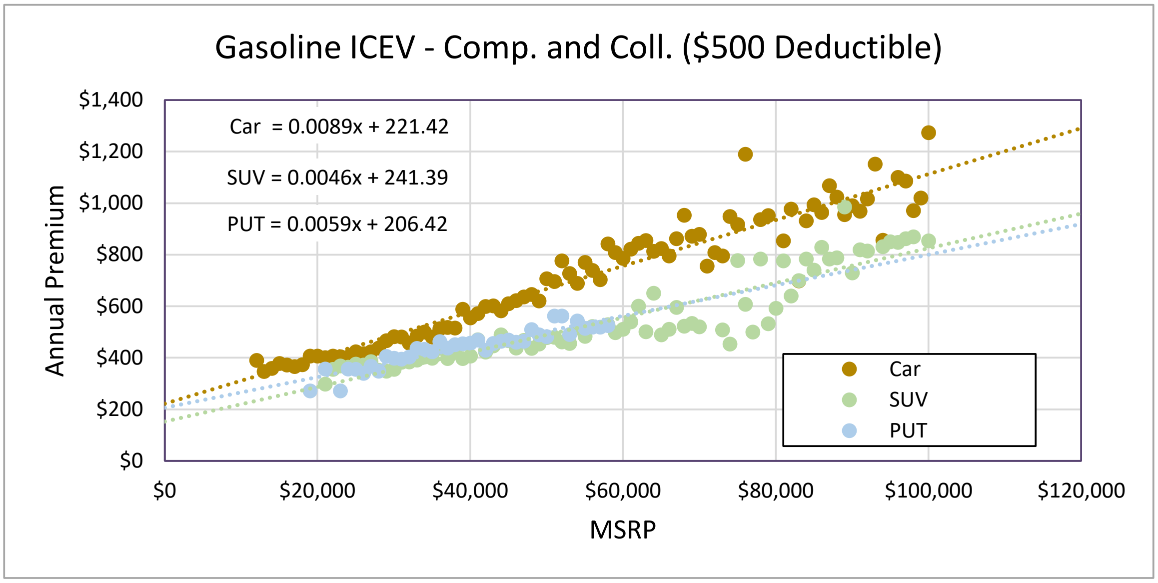


FIGURE 3.18 Annual premium for comprehensive and collision insurance for gasoline vehicles plotted against MSRP

3.4.1.4. LDV C&C Insurance by Powertrain Type

Next, we analyzed the relationship between comprehensive and collision insurance premiums and the MSRP by powertrain. As passenger cars have significantly more advanced powertrain models available in 2020 than SUVs and especially pickups, we show their results in Figure 3.19 for gasoline cars, HEVs, and BEVs (there was very limited PHEV data). As the number of makes and models are limited for powertrains other than gasoline, it is difficult to determine how much powertrain impacts C&C rates using this data. This is similar to the issue with gasoline SUVs described above in that the insurance rates are potentially impacted more by the OEM than the powertrain.

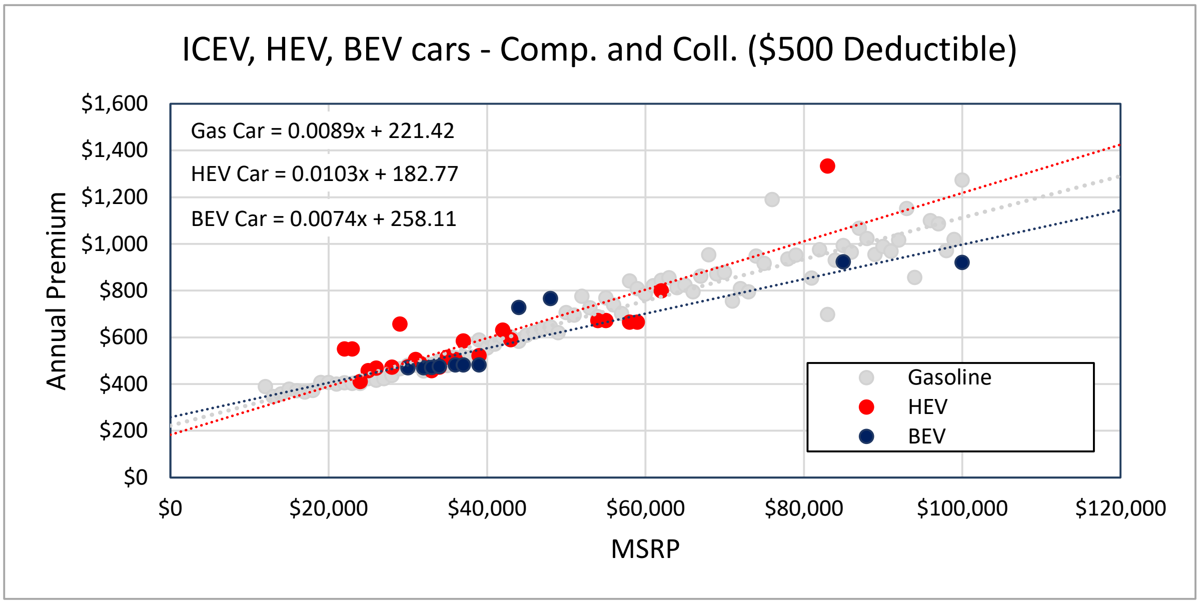


FIGURE 3.19 Annual premium for comprehensive and collision insurance for gasoline, HEV, and BEV cars plotted against MSRP

Therefore, to examine this issue further, we compared the insurance rates of HEVs, PHEVs, and BEVs to their ICEV counterparts with an equivalent make, model, and trim as listed in Table 3.14. This approach allows us to isolate the impact of changing the powertrain on insurance costs, removing the impact of specific OEMs and other outliers. The total annual insurance (liability, comprehensive, and collision) costs as a percentage of MSRP were 12% for HEVs, and the total insurance costs for their ICE counterparts were also 12%. Similarly, annual costs were 9% for PHEVs, and 12% for BEVs, while for their ICEV counterparts were 10% and 15%, respectively. These results suggest that total annual insurance rates as a percentage of MSRP for each of these powertrain types are at least equal and potentially lower than rates for comparable ICEVs.

When estimating just comprehensive and collision costs (assuming the liability costs are fixed at $500 per year for the Edmunds 50/100/25 coverage), their costs as percentage of MSRP were 5% for HEVs, 4% for PHEVs, and 6% for BEVs, while their ICEV counterpart were 5%, 4%, and 5%, respectively. These data suggest that C&C rates as a percentage of MSRP for these powertrain types are either equal to or slightly higher than those for ICEVs. While there might be differences by powertrain, these data (Table 3.14) suggest the differences are limited. Therefore, we do not make any insurance cost adjustments by powertrain for the TCO calculations in this study.

TABLE 3.14 Alternative Fuel Vehicle models and their ICEV counterparts

Powertrain	Make (AFV)	Model (AFV)	Make (ICEV counterpart)	Model (ICEV counterpart)
HEV	Acura	MDX	Acura	MDX
HEV	Acura	RLX	Acura	RLX
HEV	Buick	LaCrosse	Buick	LaCrosse
HEV	Chevrolet	Malibu Hybrid	Chevrolet	Malibu
HEV	Ford	Fusion Hybrid	Ford	Fusion
HEV	Honda	Accord	Honda	Accord
HEV	Hyundai	Sonata Hybrid	Hyundai	Sonata
HEV	Kia	Optima Hybrid	Kia	Optima
HEV	Lexus	ES 300h	Lexus	ES 350
HEV	Lexus	NX 300h	Lexus	NX 300
HEV	Lincoln	MKZ Hybrid	Lincoln	MKZ
HEV	Toyota	Avalon Hybrid	Toyota	Avalon
HEV	Toyota	Camry Hybrid	Toyota	Camry
HEV	Toyota	RAV4	Toyota	RAV4
PHEV	BMW	5-Series	BMW	5-Series
PHEV	Chrysler	Pacifica Hybrid	Chrysler	Pacifica
PHEV	Ford	Fusion Energi	Ford	Fusion
PHEV	Subaru	Crosstrek Hybrid	Subaru	Crosstrek
PHEV	Volvo	XC90 AWD PHEV	Volvo	XC90
BEV	BMW	i3	BMW	3 Series
BEV	Fiat	500e	Fiat	500
BEV	Kia	Soul Electric	Kia	Soul

3.4.1.5. LDV Insurance Cost Findings and Results

A summary of our results is listed in Table 3.15 for use as inputs to the TCO calculation. Liability premiums are estimated to be the $600 (2019$) for all vehicle types and powertrains using NAIC (2020) national average data. Comprehensive and collision premiums are estimated using the linear regression equations presented in Figure 3.18 for cars, SUVs, and pickups, respectively multiplied by the age adjustment factor of 1.19 derived from The Zebra (2020) and FHWA (2002) data. The equation is based on annual vehicle value, with the first year using MSRP and future years using resale value. The year-over-year change in premiums is known as the escalation rate; escalation rates listed in Table 3.15 are assumed to be zero since costs are presented in real 2019 dollars.

TABLE 3.15 Summary of insurance costs for LDVs

	Vehicle Type	ICEV	HEV	PHEV	EV
Annual liability premium (2019$)	All	$600	$600	$600	$600
Annual liability escalation rate % (2019$)	All	0%	0%	0%	0%
Annual comprehensive and collision premium with $500 deductible (2019$)	Car	= (vehicle value * 0.009 + $220) * 1.19			
Annual comprehensive and collision premium with $500 deductible (2019$)	SUV	= (vehicle value * 0.005 + $240) * 1.19			
Annual comprehensive and collision premium with $500 deductible (2019$)	Pickup	= (vehicle value * 0.006 + $210) * 1.19			
Annual comprehensive and collision premium escalation rate % (2019$)	All	0%	0%	0%	0%

3.4.2. Commercial Heavy-Duty and Light-Duty Insurance

Commercial vehicle insurance depends on similar factors as consumer insurance such as levels for liability, comprehensive, and collision insurance and vehicle location, while factors like cargo type for freight or number of passengers for buses will also play a major role. Commercial vehicles typically cost much more to insure than consumer vehicles due to the potential for larger liability claims and the higher cost of the vehicle for property damage. Using Progressive (2020) quotes for 50/100/25 liability and a $500 deductible for comprehensive and collision for a 40-year-old male, business owner in Illinois, the annual insurance premiums for a class 4 delivery, class 6 delivery, class 8 vocational (dump), and class 8 refuse truck were about $3,000, $5,000, $5,000, and $7,500, respectively.

The U.S. government requires for-hire freight and passenger carriers to have minimum liability insurance coverage, ranging from $750,000 for general freight to $5 million for hazardous freight and $1.5 million to $5 million for passenger carriers with below and above a seating capacity of 15, respectively (Hymel et al. 2012). In 2018, the average insurance premium cost (2019$) for commercial freight trucks surveyed by ATRI was $0.086 per mile or $7,500 per year (Murray and Glidewell 2019). While this gives a suitable average value for freight truck insurance costs, it does not account for variations in driving distance or vehicle value nor does it distinguish between liability and comprehensive and collision insurance. The cost of comprehensive and collision insurance for commercial freight trucks is typically between $2 to $3 per month per thousand dollars of vehicle value (Podris 2019). For an ATRI-average truck of 4.4 years of age and 92,000 miles per year, this is approximately $0.021 per mile for physical damage insurance. Subtracting the estimated comprehensive and collision premium from the ATRI average premium from Murray and Glidewell (2019), $0.086 per mile, provides an estimated liability insurance cost of $0.065 per mile for freight trucks, which is assumed to be independent of vehicle powertrain.

The estimated annual premium for commercial buses with more than 15 passengers is $35,000 and $9,000 for 15 or less (Huneck 2020; Bus Insurance HQ 2018). Typically, public fleets (and some large fleets) are self-insured, as they have the resources to cover losses and the administrative capability, and doing so can lead to cost savings by cutting out much of the profit that is embedded in commercial premiums (Casale 2008; Government Fleet 2011). However, no per-vehicle cost data or expected average savings was available. For public fleet vocational vehicles and buses, estimates should be similar to those from commercial providers with small discounts, as a conservative assumption. Self-insurance is an area that should be researched further.

Many LDV owners have started to use their vehicles for ridehailing services, such as Uber or Lyft. These Transportation Network Companies (TNC) link passengers to willing drivers for single rides, like taxicabs. While the personally-owned vehicle is in service, it is typically not covered by a personal auto policy (III 2017). TNCs only provide liability coverage while the app is on and the driver is waiting for a ride request, so a driver would not be covered for their own injuries and damage to their vehicle from an at-fault accident. TNCs do provide C&C coverage once a driver has received a ride request, but deductibles are high ranging from $1,000 for Uber and $2,500 for Lyft. To supplement this insurance, drivers can add rideshare insurance. Kiernan (2021) analyzed rideshare insurance cost estimates from five insurance companies, finding an average incremental cost of approximately $150 per year (Kiernan 2021).

3.5. MAINTENANCE AND REPAIR COSTS

Maintenance and repair (M&R) are large components of vehicle total cost of ownership (TCO) for both LDV and MHDV. The category can be separated into 1) maintenance, which is the regular service to prevent damage and prolong vehicle life and 2) repairs, which are done to fix malfunctioning parts that inhibit the use of the vehicle. Maintenance may be further classified into scheduled and unscheduled maintenance (Edmunds TCO 2020). Scheduled maintenance includes the preventative replacement of vehicle parts and other maintenance services at regular intervals as described in a vehicle's owner's manual. Examples of scheduled maintenance include oil changes, tire rotation, spark plug replacement, and brake fluid replacement; however, the services listed depend on the automaker. Unscheduled maintenance includes the cost of services for inspection and replacement of vehicle parts that do not have set replacement intervals and are replaced based on inspection and diagnostic tests. Examples of unscheduled maintenance include tire replacement, starter battery replacement, and brake work. The differentiation between the items that are included in unscheduled maintenance versus repairs is likely arbitrary, but the items considered repairs seem to follow the systems that are covered in vehicle comprehensive (i.e., "bumper-to-bumper") warranties offered by automakers, which exclude common "wear" items like tires, brakes, and starter batteries (Muller 2017). Often, publicly available M&R cost estimates are aggregated, so it is not clear which services were considered either maintenance or repair. Therefore, caution is needed when comparing either maintenance or repair costs from different data sources. If specific data is lacking, it is best to consider total M&R costs to make sure these costs are being compared on a consistent basis.

In this section, we examine combined M&R costs from several sources for LDVs on both an annual basis and a per-mile basis. We then formulate a method for calculating total maintenance costs using typical OEM service schedules. Next, we use Edmunds repair cost data (Edmunds TCO 2020) to model repair costs by age, powertrain type, and size class. Finally, we explore M&R costs for a variety of MHDV vocations using several sources to create an M&R cost estimation. For LDV, we split maintenance and repair costs into separate line items in our analysis, but for MHDV we combine these due to lack of more detailed information.

3.5.1. Annual M&R Costs, LDV

The U.S. Bureau of Labor Statistics' (BLS) Consumer Expenditure Surveys (CE) data in Figure 3.20 show that household M&R costs per vehicle decreased from just under $600 (2019$) during the mid-1980s through the early 1990s to less than $500 (2019$) for much of the 2000s. While this data is aggregated and does not provide information on specific powertrains or model years, it does provide evidence that vehicle dependability has increased (J.D. Power 2020), especially as we see the average vehicle age has steadily increased and annual vehicle miles traveled (VMT) per vehicle has not changed significantly from the early 1990s, when M&R costs were near their peak (Davis and McFarlin 1996; FHWA 2002; BTS 2020a; BTS 2020b; BTS 2020c; Pfirrmann-Powell 2014). Figure 3.21 shows the reported CE survey data for 2014-2018 by service. In 2018, tire replacement, tire repair, and oil changes accounted for more than 40% of M&R expenditures (BLS 2020).

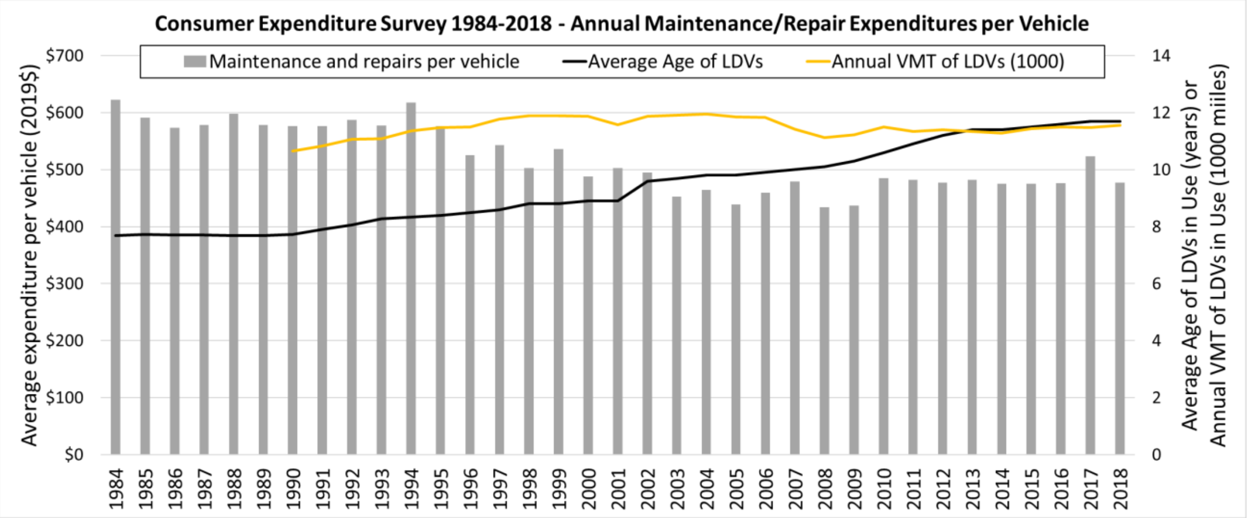


FIGURE 3.20 Consumer Expenditure Surveys 1984–2018 – Annual maintenance and repair expenditures per vehicle (data from BLS 2020)

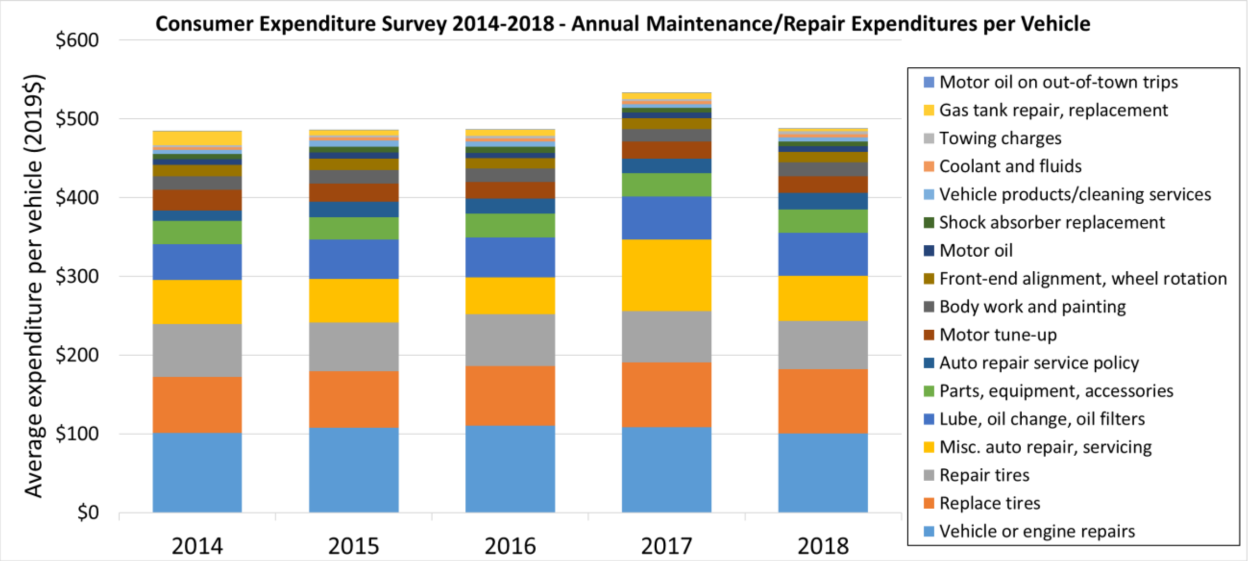


FIGURE 3.21 Consumer Expenditure Surveys 2014–2018 – Detailed annual maintenance and repair expenditures per vehicle (data from BLS 2020)

There is limited publicly available data on M&R costs by vehicle age; for example, the CE survey collects this data but does not provide it in its summary results nor in its Public Use Microdata. However, BLS did publish an analysis that provided M&R expenditures in 2012 by vehicle age categories (Pfirrmann-Powell 2014). As seen in Figure 3.22, the analysis found that M&R expenditures increased significantly from vehicles less than 5 years old to vehicles between 6 to 15 years old. Vehicle expenditures then decrease for 16 to 25 years old. M&R expenditures increased for the greater than 26 years old group, which was reported to be heavily influenced by antique/classic vehicles and their large expenditures on parts and accessories.

Maintenance and repair expenditures are influenced by annual vehicle usage, as more driving will require more scheduled maintenance and increase the likelihood of repair in that year. However, VMT data is not reported in the CE survey results, so they do not reflect M&R expenditures on a per-mile basis. However, if we assume oil change frequency and cost per oil change are equivalent among age groups, the reported annual oil change expenditures can provide a rough estimate of VMT. In Figure 3.22, the red "X" for each category represents the total M&R expenditures for each age group at a constant annual VMT if oil expenditures were scaled to match those of the 1-5 year age group. The total scaled expenditures increase by about $150 for each 5-year age group through age 25. The scaled "antique/classic" group expenditures are more than $300 higher than the 21-to-25 year old group. These data show that total annual M&R expenditures tend to decrease after vehicles reach 10 years old only because they are driven less, and M&R expenditures per mile increase significantly as a vehicle ages.

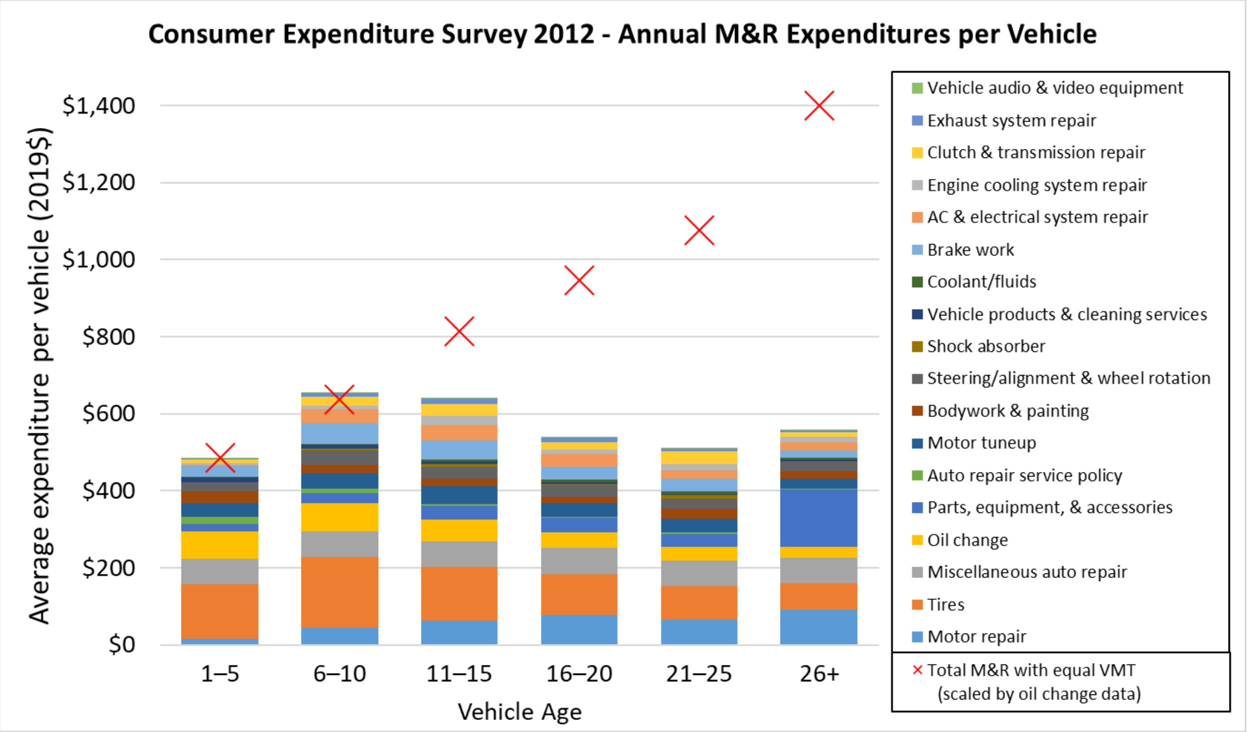


FIGURE 3.22 Consumer Expenditure Survey 2012 – Detailed annual maintenance and repair expenditures per vehicle by age (data from Pfirrmann-Powell 2014)

Annual M&R costs by vehicle age presented in Figure 3.23 were collected from Martin (2016a), who used data from the YourMechanic consumer automotive repair database, and Burnham (2020), who used information from the Utilimarc fleet benchmarking database of municipal and utility vehicles. Costs by Martin (2016a) are similar to CE survey expenditures for vehicles less than five years old. However, even when using our scaled CE survey estimates that assume equal VMT per age group, the Martin (2016a) data are significantly higher for vehicles that are 6 to 10 years old ($1,080 vs. vs. $650 CE vs. $640 CE scaled) and 11 to 15 years old ($1,780 vs. $640 CE vs. $810 CE scaled). The reasons for the discrepancy are unclear, but it is likely that the Martin (2016a) data does not have a representative sample, as it is skewed by vehicles that undergo expensive repairs and does not account for vehicles that do not visit a mechanic. In addition, annual VMT data was not provided so it is unclear whether there is a skew due to high mileage vehicles.

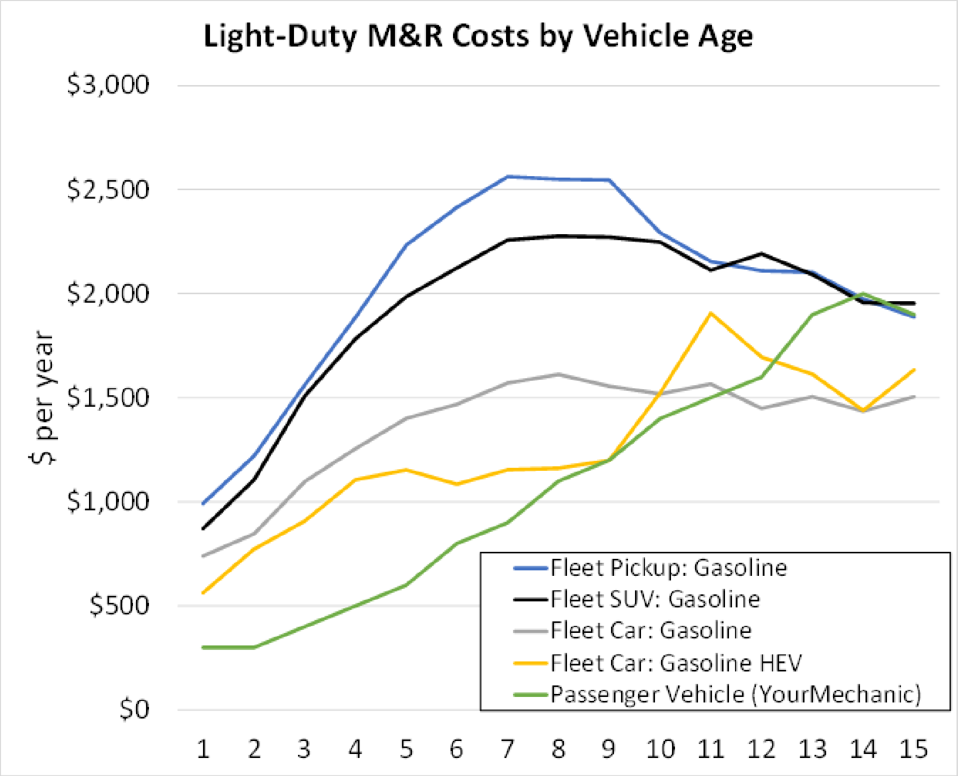


FIGURE 3.23 Annual maintenance and repair costs by age (data from Burnham 2020; Martin 2016a)

The Utilimarc dataset covers calendar years 2008 to 2017 and included information for gasoline passenger cars (94,000 units), gasoline HEV passenger cars (19,000 units), gasoline SUVs (85,000 units), and gasoline pickup trucks (270,000 units). One unit represents one vehicle in one calendar year. Fleet M&R cost data for light-duty vehicles from Utilimarc (Burnham 2020) were significantly higher than Martin (2016a). As the Utilimarc data is aggregated, it is not clear why the fleet costs are so much higher. However, it is likely that both the fleet management (e.g. technicians more frequently inspecting vehicles, costly overhead due to maintaining heavy-duty vehicles) and driving conditions (e.g. more idling and aggressive driving) of these vehicles are significantly different from consumer passenger vehicles.

Specifically, M&R costs for new fleet gasoline HEV cars, gasoline cars, gasoline SUVs, and gasoline pickups were $560, $740, $870, and $990, respectively. The new cars were driven on average 10,500 miles for the HEV and 11,500 miles for the ICEV, while the gasoline SUVs and pickups were driven each about 13,000 miles. As discussed later in this section, HEV M&R costs are significantly lower than their gasoline counterparts until a spike in year 10, which is just after the 8-year hybrid powertrain warranty ends (California has a 10-year warranty).

There is a lack of publicly available detailed light-duty M&R cost data to compare these results; however, a survey of more than 100,000 light-duty vehicles estimated the average M&R costs were $850 in 2019 (Antich 2020). It is not clear how the duty-cycles of these vehicles differ from those in the Utilimarc dataset, though it does include corporate LDVs, while

Utilimarc does not. Utilimarc suggested that potentially other data sources included vehicles that were not active and not in service for the entire year (Milner 2020). For Utilimarc, this is about 15% of vehicle data they receive from fleets (the Utilimarc dataset used in this analysis does not include those vehicles). The Antich (2020) data did not differentiate total M&R costs by age nor estimate the average age of the vehicles in their survey. However, they did provide repair costs by months in service and average 2019 repair costs are similar to their repair estimate for 3-year-old vehicles. If we assume that the $850 M&R cost is representative of 3-year-old vehicles, the cost data from Antich (2020) is lower than that from Utilimarc. The annual M&R costs of the New York City gasoline passenger car fleet in 2018, ranging from $920 to $1810 per year, were similar to Utilimarc values (Kerman 2019), suggesting there is likely significant variation between fleets.

3.5.2. Per-mile M&R costs, LDV

While the above annual data help bound our estimates, they are lacking context that could help us better understand what factors are driving M&R costs as a vehicle ages. An important factor that should be controlled for is annual VMT. The Utilimarc dataset provided annual mileage, so we can estimate fleet M&R costs per mile by age of the vehicle, as shown in Figure 3.24. The gasoline car, SUV, and pickup M&R costs increase annually in a roughly linear fashion from about $0.06-$0.08 per mile in year 1 to about $0.29 to $0.34 per mile in year 15 (Burnham 2020). Similar to the annual costs shown above, the per-mile HEV costs are lower than all of the gasoline LDVs until increasing significantly starting for 10-year-old vehicles. Over 150,000 total miles, each of the fleet vehicles had a weighted average per-mile cost of about $0.18 (Burnham 2020). While the gasoline cars had lower costs per mile than SUVs and pickups for each year, these vehicles have different mileage schedules. Specifically, gasoline cars were driven less miles per year than SUVs and pickups, with gasoline cars reaching 150,000 VMT in year 21, while SUVs and pickups reached the same threshold in year 14. Gasoline HEV data does not reach 150,000 VMT, but rather gets to 140,000 VMT in year 17.

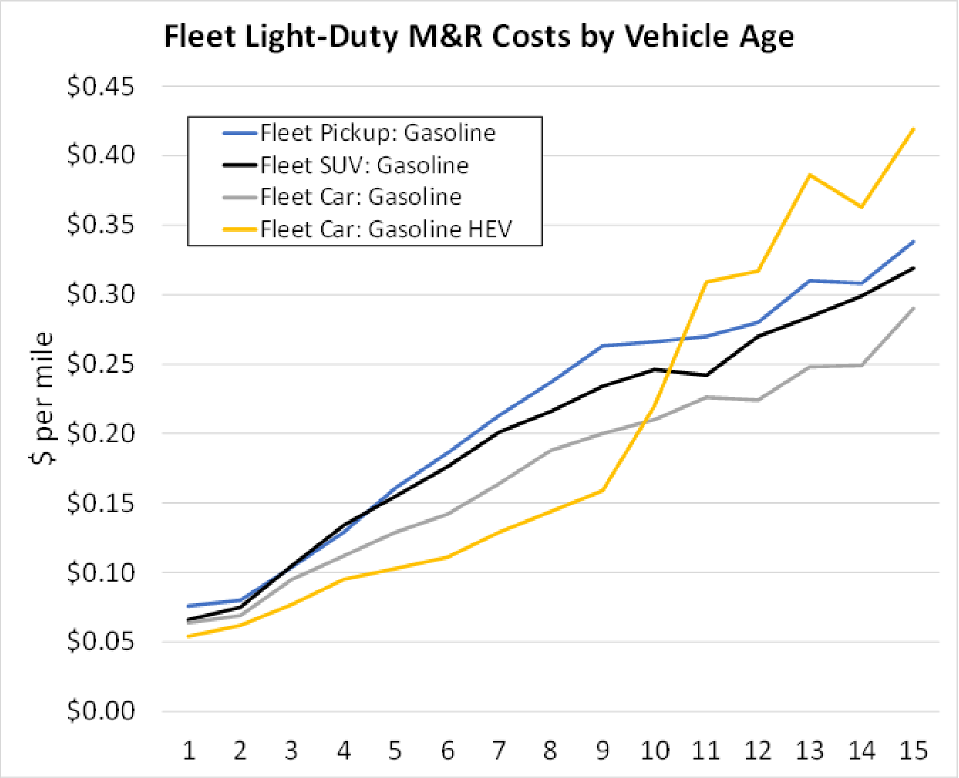


FIGURE 3.24 Per-mile maintenance and repair costs by age (data from Burnham 2020)

While data are not available for per-mile costs by age from the YourMechanic database, Martin (2016b) presented data by each 25,000 mileage interval from 0 to 200,000 miles, as seen in Figure 3.25. These costs increase linearly from 0 to 100,000 miles, and then, perhaps counterintuitively, this trend flattens significantly for 100,000 to 200,000 miles with the expectation being that the increase would continue to grow larger for older vehicles. However, as a vehicle reaches a high mileage, it is more likely to be scrapped than undergo a costly repair than if the vehicle was at a low mileage (e.g. owner is concerned that high-mileage vehicle will have another costly repair shortly). The YourMechanic average M&R cost for 0 to 200,000 miles is about $0.144 per mile (Martin 2016b). The YourMechanic results for 0 to 150,000 mile interval ($0.127) are about 30% lower than the above Utilimarc cost-per-mile data (Martin 2016b; Burnham 2020). The YourMechanic results very likely show survival bias, as the higher mileage vehicles that have more M&R issues that are being scrapped will not show up in this dataset. More research is needed to understand how consumer M&R costs change by age and mileage.

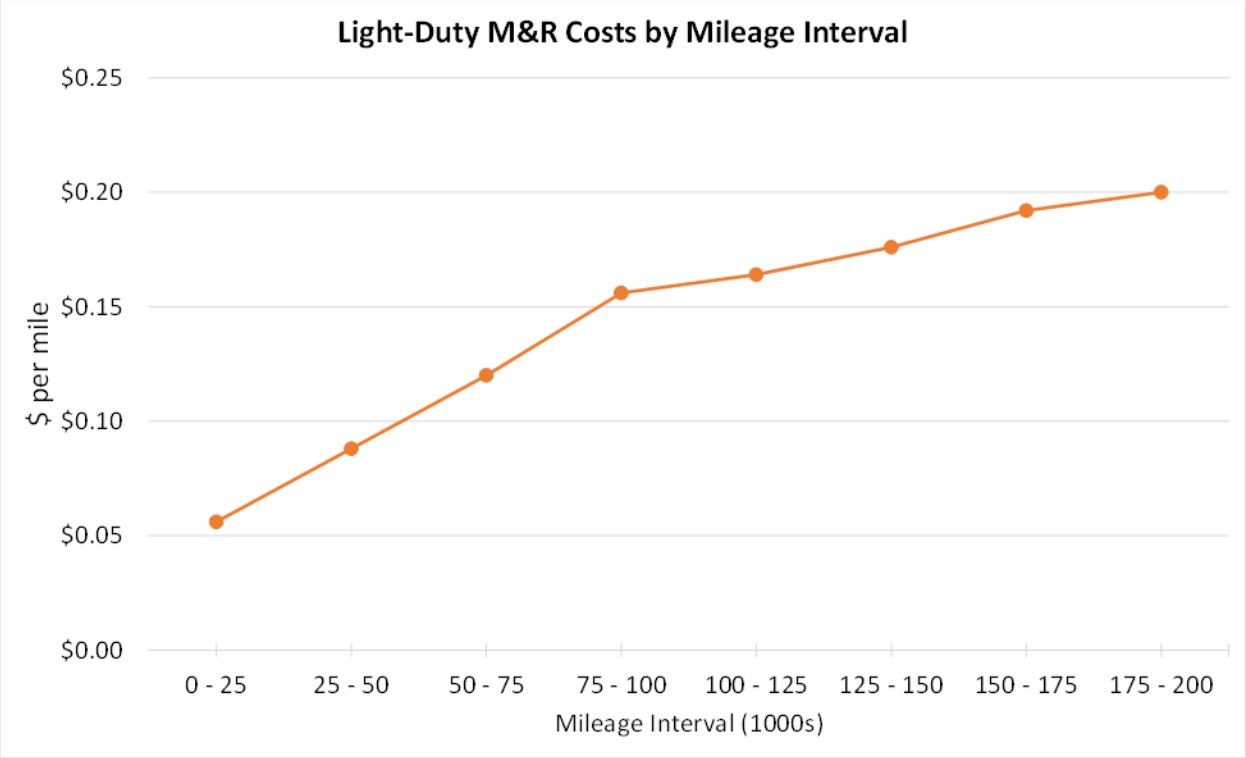


FIGURE 3.25 Per-mile maintenance and repair costs by mileage interval (data from Martin 2016b)

As shown in Figure 3.26, Martin (2016b) also presented models with the top ten highest and lowest M&R costs per 150,000 miles, which helps us bound costs even though the study does not state the range of model years examined. The average of the lowest M&R costs was $0.066 per mile, while the average of the highest was $0.150 per mile. If we assume the data for the large number of models between the top ten highest and lowest is not significantly skewed, the average M&R cost per mile would be about $0.108 per mile. This is similar to the results for their 0 to 150,000 mileage interval data shown in Figure 3.25.

The data from Martin (2016b) also shows that M&R costs vary by both make and model. Toyota had five of the ten lowest M&R costs by vehicle model, including three cars, an SUV, and a pickup. The only advanced powertrain vehicle presented by Martin (2016b) is the Toyota Prius, which had the lowest M&R costs of all models analyzed, at about $0.045 per mile. The Prius costs were 21% lower than the next vehicle, the Nissan Versa ($0.057), 35% lower than the Toyota Corolla ($0.069, also in the 10 lowest), and 69% lower than the Ford Focus ($0.144, in the 10 highest). As the Prius was one of the first HEVs introduced in 2000, its inclusion in this dataset of vehicles with 150,000 miles makes sense, though it is unclear how many other HEVs are in this 2016 dataset. PHEVs and BEVs were introduced in December 2010, so this dataset likely did not include any that had reached 150,000 miles. Further data collection is needed to analyze these advanced powertrain vehicles as they reach higher mileages. The other factor that should be taken into account is that when a new model is introduced, especially one with a new powertrain, it will typically undergo changes each model year, tending to improve reliability.

Therefore, focusing on just the earliest model years of a specific vehicle will likely overestimate the M&R costs of newer model years (Linkov 2019).

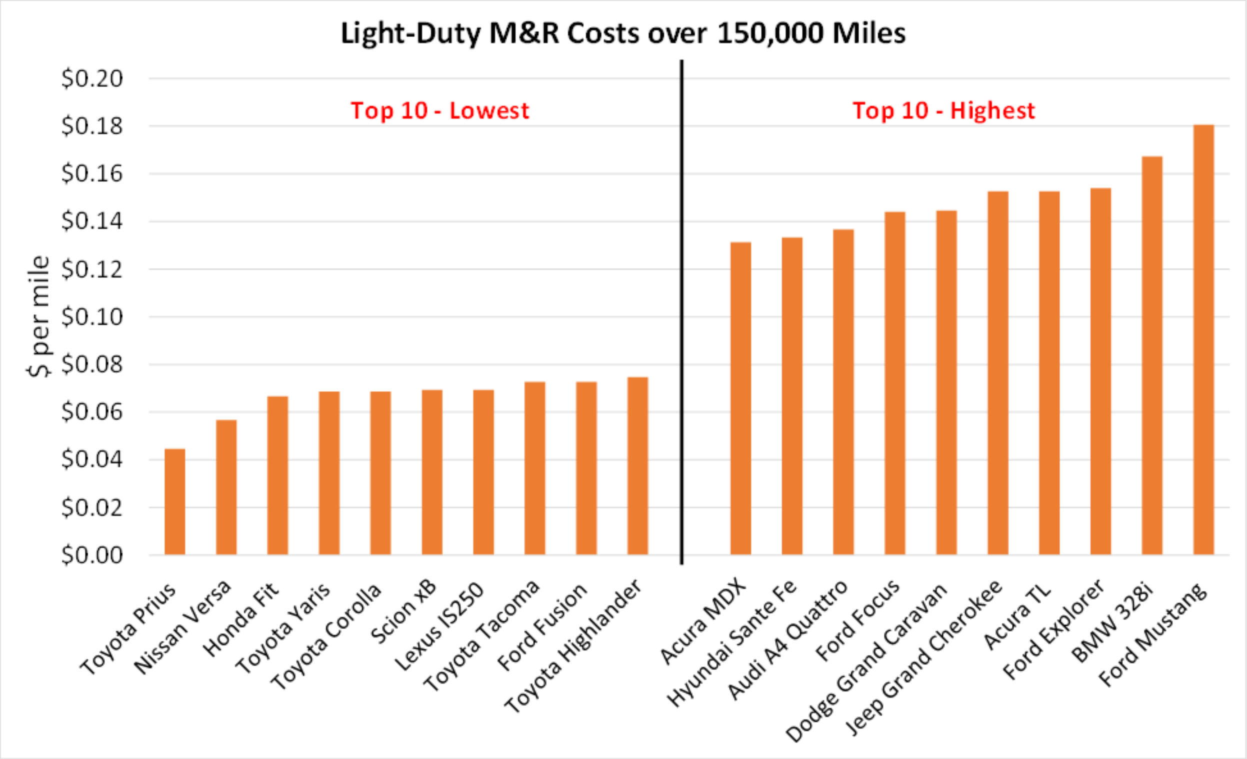


FIGURE 3.26 Per-mile maintenance and repair costs by make and model over first 150,000 miles (data from Martin 2016b)

Consumer Reports (CR) conducts an annual survey on car reliability, asking its members for maintenance and repair costs, annual mileage, and odometer readings for their vehicle over the previous 12 months (Consumer Reports 2019). The 2019 CR survey covered 420,000 vehicles for model years 2000 to 2020 and a subset of those (removing incomplete and outlier responses) were used by Harto (2020a) to examine the M&R costs for ICEVs, PHEVs, and BEVs. The study included survey data for vehicles with an annual VMT between 2,000 and 60,000 miles and annual M&R costs less than $20,000. With such a high VMT cut-off, the results most likely include ride-hail drivers. Similar to Martin (2016b), the CR study provided M&R costs per mile for three cumulative mileage intervals: 0 to 50,000; 50,000 to 100,000; and 100,000 to 200,000. It was noted that there was a small sample size for PHEVs (200 vehicles) and BEVs (55 vehicles) for the 100,000 to 200,000 mileage interval. To account for differences in OEM M&R costs, the estimates for ICEVs were averaged for each automaker and were weighted by the latest 5-year average market share. Harto (2020a) stated the sample size was not large enough to do the same for PHEVs and BEVs. This further points to the need to analyze data of advanced powertrain vehicles as they reach higher mileage operation.

The CR results for each powertrain and mileage interval are shown in Figure 3.27; in addition, the Martin (2016b) YourMechanic results (shown in Figure 3.25), averaged to match the CR intervals, are shown for comparison. The CR study shows that both PHEVs and BEVs had significantly lower M&R costs than ICEVs. The percent reduction in M&R cost per mile relative to ICEVs for PHEVs for 0 to 100,000 miles and 100,000 to 200,000 miles was 37% and 58%; for BEVs, the percent reduction was 55% and 46%, respectively (Harto 2020a). The CR lifetime average M&R cost per mile for ICEVs, PHEVs, and BEVs were $0.061, $0.030, and $0.031, respectively, which is about a 50% reduction for both advanced powertrains (Harto 2020a). Harto (2020b) suggested that as more data is collected, BEVs driven over 100,000 miles will likely have lower M&R costs than was reported in the CR study. This is due to the fact that the high-mileage BEVs in the current survey results predominantly included early versions of the Nissan Leaf and Tesla Model S. As mentioned previously, OEMs typically improve model reliability as new versions are released; this should especially be the case for newly introduced powertrains. In addition, the Tesla Model S is a luxury vehicle so its M&R costs are likely to be higher than mass-market BEVs (Harto 2020b).

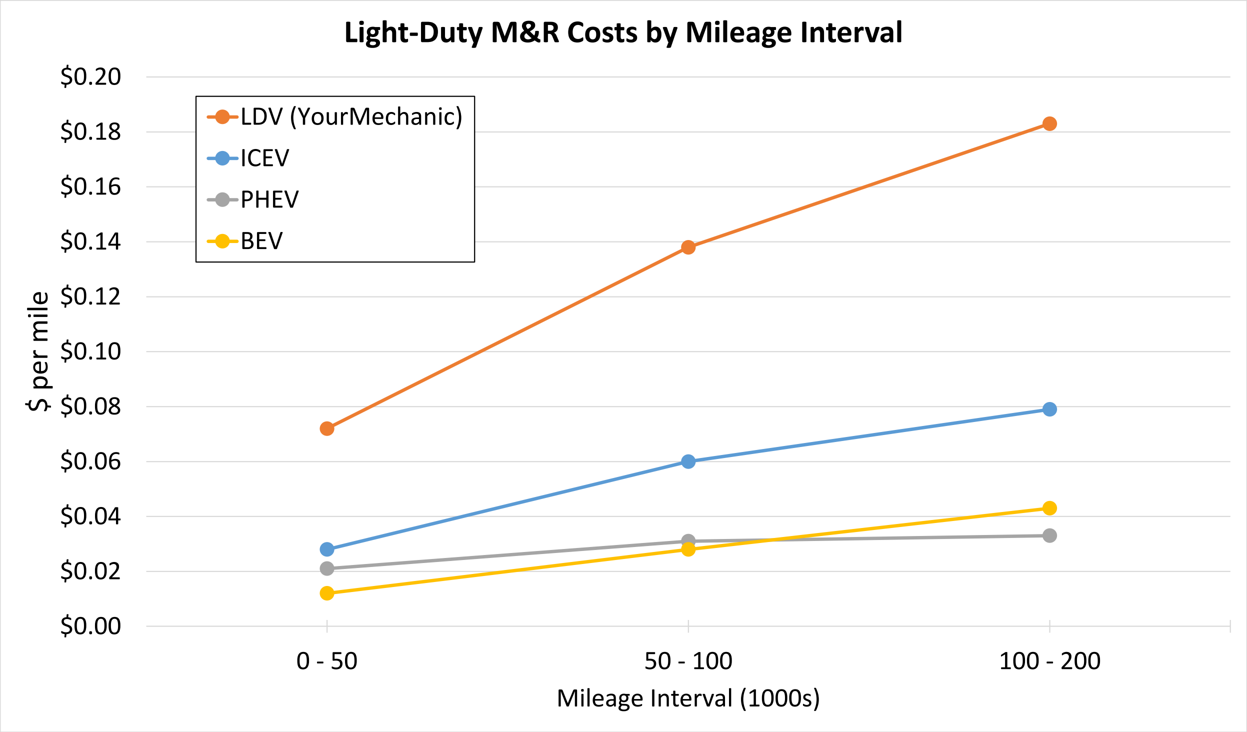


FIGURE 3.27 Per-mile maintenance and repair costs by mileage interval and powertrain (data from Harto 2020a; Martin 2016b)

The CR lifetime average ICEV M&R cost per mile is 58% lower than the YourMechanic data for all light-duty vehicles (which was predominantly ICEVs) for the same mileage interval (Martin 2016b). One obvious reason why CR data are lower than YourMechanic (and in all likelihood the national average), is that CR members are certainly more cost conscious than the average consumer. CR members may have lower M&R costs than average by performing some of their own maintenance (e.g. oil changes), purchasing longer-lasting parts (e.g. tires with high tread wear grades), and utilizing low cost mechanics (Harto 2020b). However, the difference between these and the Utilimarc per-mile data sources, as well as the annual data sources described above suggest further research is needed to better understand M&R costs by vehicle type and powertrain. We use the CR per-mile M&R costs as a sensitivity case for our maintenance and repair cost components for LDVs.

3.5.3. Maintenance Costs by Service Schedule, LDV

There is a lack of publicly available real-world data on solely maintenance expenditures, as the costs in this section from YourMechanic, Utilimarc, and Consumer Reports datasets include repairs. While we considered using maintenance costs from the Edmunds True Cost to Own® dataset, it is potentially missing maintenance costs from services that occur late in vehicle life as it only covers 10 years of ownership. However, as scheduled maintenance is supposed to be completed according to set intervals prescribed by OEMs, we developed a generic maintenance service schedule for each powertrain type using owner's manuals from various makes and models including the Toyota Yaris, Camry, Camry HEV, Prius, and Prius Prime; Chevrolet Cruze, Volt, and Bolt; Nissan Sentra, Kicks, and Leaf; Kia Optima, Optima HEV, and Optima PHEV; Kia Soul and Soul EV; Tesla Model 3 and Model S, Ford Focus; Lincoln MKZ; BMW i3; VW Golf and e-Golf; and Fiat 500 and 500e. This analysis assumes drivers follow the recommended service intervals, which in practice not everyone does (Harto 2020b). Datasets that include vehicles that have not followed preventative maintenance schedules may have lower reported costs than estimates from our approach, but likely at the expense of either future repair costs or the early scrappage of the vehicle. Analysis of how consumers maintain their vehicles in comparison to OEM recommendations is needed.

Since maintenance also includes wear items that do not have an explicit replacement interval in the owner's manuals (i.e. unscheduled maintenance), we estimated their average lifetimes based on guidance from several experts (Vyas 2012; Thomas and Boundy 2019; Cheung 2020) as well as automotive websites (RepairPal 2020; YourMechanic 2020). There is significant uncertainty in service intervals for wear items, since in many cases, a service will not be necessary for a significant portion of vehicles, while in other cases the part may fail early either due to factors such as improper preventative maintenance, harsh operating conditions, and/or differences in OEM part design life and quality. Further analysis of service intervals is required, especially for large cost items discussed below.

After developing the maintenance service schedule, we collected national average costs for each of the preventative and unscheduled services, which were used to calculate costs per mile for each powertrain (Thomas and Boundy 2019; Cheung 2020; RepairPal 2020; YourMechanic 2020). Service cost varies by several factors, including the type of mechanic (dealership vs. chain vs. independent), part quality (OEM vs. aftermarket), and make and model cost characteristics (domestic vs. import and mass market vs. luxury). We do not assume drivers perform any of their maintenance services, as there is not data available on how often drivers do so. "Do it yourself" maintenance will reduce costs, though depending on the service will require investment in both tools and skill development. For our goal of comparing powertrains, standardizing assumptions enables us to compare key services, though further analysis is needed to make these estimates more accurate.

As our data are based primarily on gasoline passenger cars and their advanced powertrain counterparts, we also wanted to examine the potential maintenance cost differences between vehicle types (e.g. car vs. SUV vs. pickup), gasoline and diesel powertrains, and BEV and FCEV powertrains. Vehicle type may influence maintenance costs as some part sizes and fluid capacities can be larger for bigger vehicles (e.g. larger tires needed for a pickup). However, when examining the Edmunds dataset, no significant difference was found over 10 years of ownership. Total maintenance and repair costs of medium-duty diesel vehicles were about 34% higher than of their gasoline counterparts, based on the Utilimarc dataset (Burnham 2020). While it is not clear whether the cost difference is due to maintenance or repairs, it seems most likely repairs are the issue since the most obvious maintenance difference between the vehicles is that diesels do not have spark plugs, which is a relatively small cost. The Edmunds dataset has a very limited number of diesel vehicles and there is no clear trend. In this analysis, we assume that the maintenance cost is the same for gasoline and diesel. As there are no FCEVs in the Edmunds dataset, and with the expectation that BEVs and FCEVs should have similar maintenance schedules, we assume their maintenance costs are the same. Each of these data gaps should, however, be examined further in the future as more data become available.

Table 3.16 summarizes the service schedules and costs for each major powertrain type. Many services have different schedules for the different powertrains (14 of the 24 in Table 3.16), as advanced powertrains can either extend service intervals (e.g. spark plugs for HEVs and PHEVs) or eliminate the service (e.g. oil changes for BEVs). The results show that the reduction in maintenance cost per mile for HEVs, PHEVs, and BEVs as compared to ICEVs were 7%, 11%, and 41%, respectively. Figure 3.28 presents the same data as Table 3.16. In Figure 3.28, red items represent powertrain maintenance, purple items represent filter replacement, green items represent fluid changes, orange items represent brake maintenance, gray items represent suspension maintenance, yellow items represent tire maintenance, and blue items represent general service items. Items marked with asterisks have service intervals that vary across powertrains. Hybridized powertrains have cost reductions relative to the conventional ICEV for the brakes and powertrains. BEVs have reduced costs for powertrain, filters, fluids, and brake maintenance.

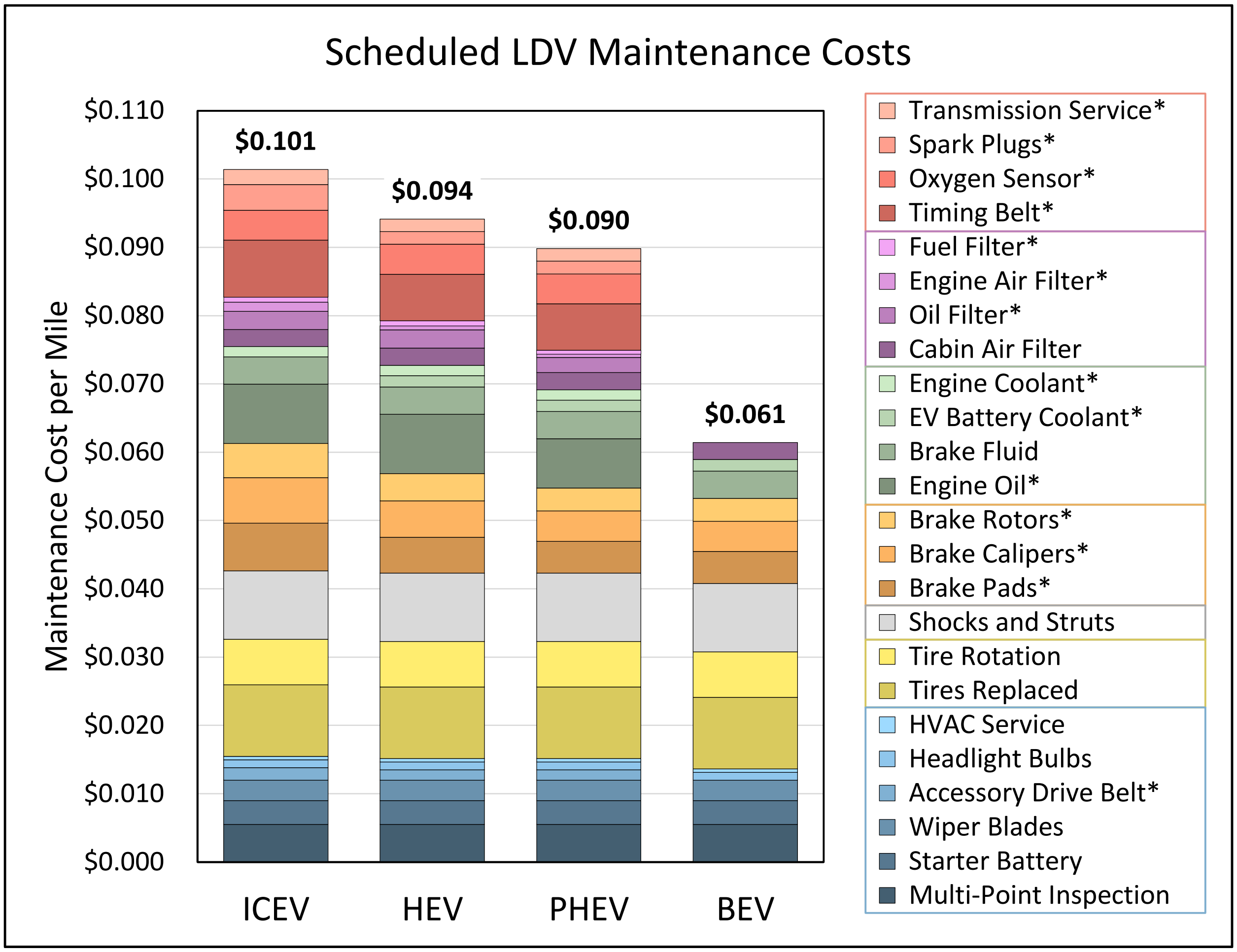


FIGURE 3.28 Scheduled maintenance costs for ICEV, HEV, PHEV, and BEV

These results show that tire replacement and rotation are large maintenance costs on a per-mile basis, ranging from 17% of total maintenance costs for ICEVs to 29% for BEVs. We assume that tire life and replacement costs are the same for all powertrains. However, advanced powertrain vehicles often are equipped with specially designed tires that provide low rolling resistance (LRR) to improve fuel efficiency. A National Research Council study by the Transportation Research Board (TRB) found that an LRR tire may exhibit a reduced tread life if it is designed with less tread thickness, volume, or mass than a conventional tire (NRC 2006). However, the TRB study suggested that the use of tread-based technologies can improve rolling resistance without significantly affecting wear, though many of the technologies were still under development. A follow-up study by the National Highway Traffic Safety Administration (NHTSA), conducted in-use testing (7,200 miles), which did not show a clear relationship towards tread wear rate and rolling resistance levels, while, when subjected to aggressive indoor testing, the tires did show more wear as rolling resistance decreased (Evans et al. 2009). There is limited quantitative analysis of the most recent models of LRR tires, but Bartlett (2019) suggests that many models can provide a long tread life. In addition to LRR tires, further analysis is needed to understand the effects of instant torque and of the additional weight of electric drive vehicles on tread life. Goodyear stated that traditional tires can wear up to 30% faster on EVs; it is one of the tire companies with tires specifically designed for these issues (Goodyear 2018; Adams 2018). If BEV tire life is reduced by 30%, then BEV maintenance cost per mile would increase by about 7%, from $0.060 to $0.064 per mile.

The replacement of brake fluids, pads, rotors, and calipers are another major maintenance cost on a per-mile basis, ranging from 18% for PHEVs to 26% for BEVs. We assume that brake pad, rotor, and caliper replacement intervals can be extended from ICEVs by 33% for HEVs and by 50% for PHEVs and BEVs due to less friction wear that results from the use of regenerative braking (Vyas 2012). We assume that PHEVs and BEVs have more regenerative braking capabilities than HEVs and, therefore, that their service intervals can be extended longer than HEVs due to their larger battery capacity and electric motor (Varocky 2011; Vyas 2012). However, it has been assumed that both HEVs and PEVs may not need any brake work during a 150,000 mile vehicle life (Davis et al. 2013), while another analysis suggested that BEV brake pad life could be around 134,000 miles (Logtenberg et al. 2018). Further study of brake life for advanced powertrain vehicles should be conducted as there is a dearth of real-world data available. If HEV, PHEV, and BEV brake pad and rotor service intervals were increased to 150,000 miles, their total maintenance cost per mile would decrease about 4%, 3%, and 4%, respectively. In a best case scenario, in which no brake pad, rotor, or caliper work is ever needed for these advanced powertrain vehicles, maintenance costs for HEV, PHEV, and BEV would be 22%, 24%, and 53% lower than a comparable ICEV, respectively.

Within this analysis, we use the generalized maintenance schedules in Table 3.16 for each powertrain. We further smooth these schedules by averaging costs over five years (two years prior and two years later), in order to account for both variations in driving behavior and deviations from a strict maintenance schedule.

TABLE 3.16 Maintenance service schedule by powertrain (Vyas 2012; Thomas and Boundy 2019; Cheung 2020; RepairPal 2020; YourMechanic 2020)

	Service Interval (mi)				Service Cost ($)	Cost per Mile ($)				Cost per Mile (%)			
Service	**ICEV**	**HEV**	**PHEV**	**BEV**	**All**	**ICEV**	**HEV**	**PHEV**	**BEV**	**ICEV**	**HEV**	**PHEV**	**BEV**
Engine Oil*	7,500	7,500	9,000		$65	$0.009	$0.009	$0.007	$0.000	9%	9%	8%	0%
Oil Filter*	7,500	7,500	9,000		$20	$0.003	$0.003	$0.002	$0.000	3%	3%	2%	0%
Tire Rotation	7,500	7,500	7,500	7,500	$50	$0.007	$0.007	$0.007	$0.007	7%	7%	7%	11%
Wiper Blades	15,000	15,000	15,000	15,000	$45	$0.003	$0.003	$0.003	$0.003	3%	3%	3%	5%
Cabin Air Filter	20,000	20,000	20,000	20,000	$50	$0.003	$0.003	$0.003	$0.003	2%	3%	3%	4%
Multi-Point Inspection	20,000	20,000	20,000	20,000	$110	$0.006	$0.006	$0.006	$0.004	5%	6%	6%	7%
Engine Air Filter*	30,000	66,667	83,333		$40	$0.001	$0.001	$0.000	$0.000	1%	1%	1%	0%
Brake Fluid	37,500	37,500	37,500	37,500	$150	$0.004	$0.004	$0.004	$0.004	4%	4%	4%	7%
Tires Replaced	50,000	50,000	50,000	50,000	$525	$0.011	$0.011	$0.011	$0.011	10%	11%	12%	18%
Brake Pads*	50,000	66,667	75,000	75,000	$350	$0.007	$0.005	$0.005	$0.005	7%	6%	5%	8%
Starter Battery	50,000	50,000	50,000	50,000	$175	$0.004	$0.004	$0.004	$0.004	3%	4%	4%	6%
Spark Plugs*	60,000	120,000	120,000		$225	$0.004	$0.002	$0.002	$0.000	4%	2%	2%	0%
Oxygen Sensor*	80,000	80,000	80,000		$350	$0.004	$0.004	$0.004	$0.000	4%	5%	5%	0%
Headlight Bulbs	80,000	80,000	80,000	80,000	$90	$0.001	$0.001	$0.001	$0.001	1%	1%	1%	2%
Transmission Service*	90,000	110,000	110,000		$200	$0.002	$0.002	$0.002	$0.000	2%	2%	2%	0%
Timing Belt*	90,000	110,000	110,000		$750	$0.008	$0.007	$0.007	$0.000	8%	7%	8%	0%
Accessory Drive Belt*	90,000	110,000	110,000		$165	$0.002	$0.002	$0.002	$0.000	2%	2%	2%	0%
HVAC Service	100,000	100,000	100,000	100,000	$50	$0.001	$0.001	$0.001	$0.001	0%	1%	1%	1%
Brake Rotors*	100,000	125,000	150,000	150,000	$500	$0.005	$0.004	$0.003	$0.003	5%	4%	4%	6%
Shocks and Struts	100,000	100,000	100,000	100,000	$1,000	$0.010	$0.010	$0.010	$0.010	10%	11%	11%	17%
Engine Coolant*	125,000	125,000	125,000		$190	$0.002	$0.002	$0.002	$0.000	1%	2%	2%	0%
EV Battery Coolant*		125,000	125,000	125,000	$210	$0.000	$0.002	$0.002	$0.002	0%	2%	2%	3%
Fuel Filter*	150,000	150,000	200,000		$110	$0.001	$0.001	$0.001	$0.000	1%	1%	1%	0%
Brake Calipers*	150,000	187,500	225,000	225,000	$1,000	$0.007	$0.005	$0.004	$0.004	7%	6%	5%	7%
Total Cost per Mile						$0.101	$0.094	$0.090	$0.060	**100%**	**100%**	**100%**	**100%**

* Service intervals that vary by powertrain

3.5.4. Repair Costs, LDV

There is a lack of publicly available real-world repair costs for vehicle types, powertrains, makes, or models, as the total M&R cost data in this section from YourMechanic, Utilimarc, and Consumer Reports include maintenance costs. The best dataset available was the Edmunds True Cost to Own® dataset, which estimates the costs of repairs not covered by the OEM's warranties using the cost of a zero deductible extended warranty (i.e. service contract) for each make and model, minus their estimate of the warranty provider's overhead and profit (Edmunds TCO 2020). The challenge of this approach is that many of the factors that impact the estimated repair cost are not transparent from the Edmunds dataset, including the exact extended warranty coverage level and Edmunds overhead and profit estimate (Cheung 2020).

The two types of extended warranty coverages are inclusionary, which enumerate what services are covered, and exclusionary, which state what services are not covered. Similar to an OEM warranty, even a "bumper-to-bumper" extended warranty will not cover most wear items (Vincent 2018; Endurance 2015). However, in our analysis we were mindful that an extended warranty could potentially cover services that were included in our maintenance schedule in Section 3.5.3. Therefore, we examined a "bumper-to-bumper" extended warranty service contract with the highest level of coverage to make sure we were not double-counting costs (Endurance 2015). This approach also helped clarify that we should include several services (e.g. oxygen sensors, shocks, struts, belts) in our maintenance schedule as they were not included in extended warranties. Therefore, assuming Edmunds data is based on a similar level of coverage, our repair results can be added to our maintenance schedule to estimate total M&R costs.

The Edmunds dataset included the 5-year ownership projections of both used (going back to MY2014) and new vehicles. We used the 5-year repair projections of both MY2014 and MY2019 vehicles. This allows us to look at a 10-year ownership window, with the caveat that the estimates for years 1-5 and 6-10 are for different model years. While it varies by OEM, a new vehicle "factory" warranty typically covers "bumper-to-bumper" for 3 years/36,000 miles and the powertrain for 5 years/60,000 miles. As seen in Figure 3.29, estimated repair costs are zero for the first two years and near zero for the third year, as the "bumper-to-bumper" warranty expires due to Edmunds' assumed 15,000 annual VMT. In this figure, we see the transition from the model year 2019 to 2014, as year six does not follow the previous trend; the repair cost in that year is an artifact of using two different model years, and so this is presented as a dotted line. However, we do see in years 6-10 that repair costs increase at roughly the same rate across the vehicle types.

Figure 3.29 shows that pickup trucks have lower average repair costs as a percentage of MSRP than cars, a 35% reduction for years 1-5 and 30% reduction for years 6-10, relative to cars. SUVs also had lower costs than cars, a 17% reduction for years 1-5 and 9% reduction for years 6-10, relative to cars. As mentioned previously in Section 3.4.1.3 a potential reason for this difference in repairs is because pickups and SUVs currently have higher profit margins than cars and thus lower component costs as a percentage of MSRP (Ulrich 2019). This would then likely reduce repair costs for these vehicles, since part costs as a percentage of MSRP are lower. Another potential reason could be the difference between repair frequency and/or cost between various OEMs and their model availability for each vehicle type (J.D. Power 2020). For example, many of the largest OEMs have focused production on SUVs and pickups, and those OEMs tend to have low repair costs for all vehicle types they produce (including cars). The OEMs that only produce cars (or cars and SUVs) tend to have higher repair costs. While the Edmunds TCO (2020) dataset does not exactly match the JD Power (2020) dependability rankings, it shows that of the 32 OEMs, 6 of the 12 OEMs with the lowest repair costs produced all three vehicle types, while the other 20 OEMs either produced only cars and/or SUVs. For some of the OEMs that only produce cars (or cars and SUVS), these higher repair costs might be at least partially attributable to the lack of mechanics and more difficulty sourcing parts for lower volume imported vehicles.

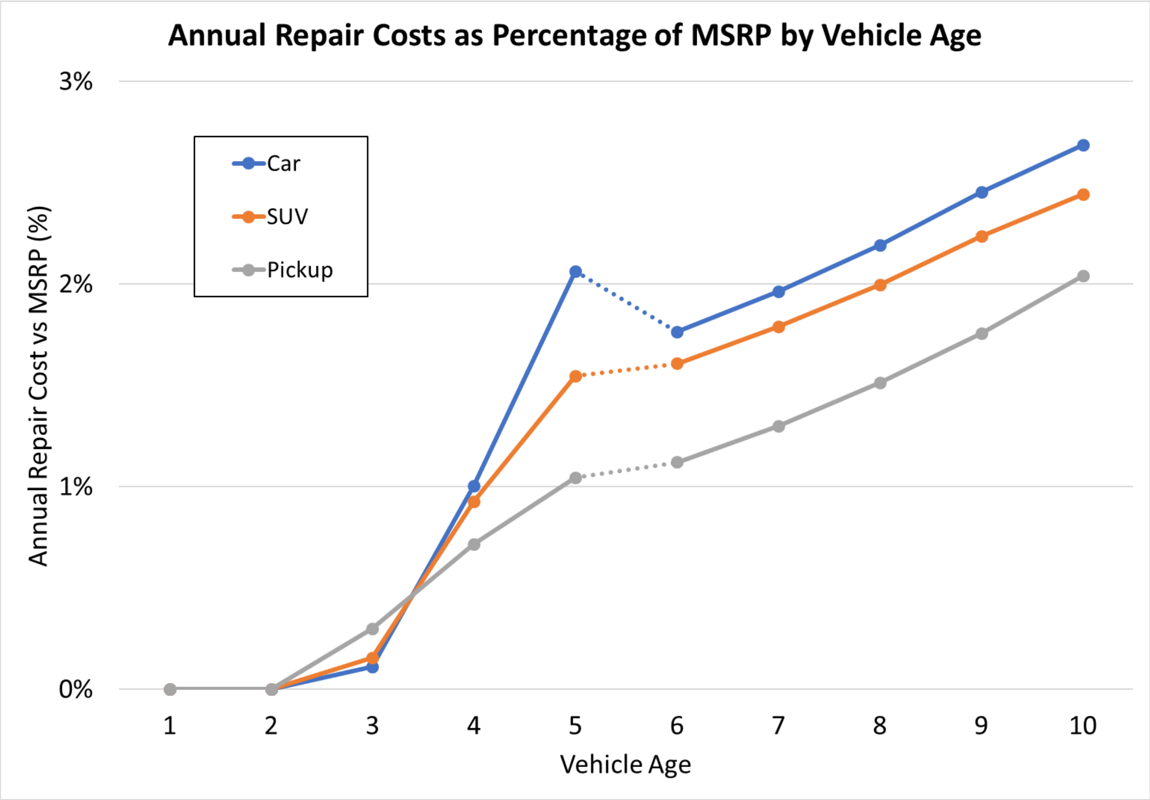


FIGURE 3.29 Annual repair costs as a percentage of MSRP by vehicle age (data from Edmunds TCO 2020)

We examined repair costs per mile as a function of MSRP for each vehicle age and type. Figures 3.30 and 3.31 show sample results for years 5 and 10 with the vehicle types aggregated to show the exponential form of the results. These empirical exponential fits have reasonably high R^2 values of 0.80 and 0.85. The model of repair costs developed from the Edmunds dataset for each year is of the form:

$$Repair_i = a_i e^{bx}, i = 1, \dots, 15 \qquad \text{Eq 3.12}$$

where

$Repair_i$ = the repair cost per mile in year i,

a_i = repair cost coefficient in year i,

b = exponential constant of 0.00002

x = the MSRP in the year the car was sold as new.

For simplicity, we use the gasoline car repair cost coefficients, a_i, as a baseline and provide scaling factors to account for differences between vehicle and powertrain type, as described below. In our analysis, the gasoline car repair cost coefficient, a_i, is 0 in years 1-2, 0.00333 in year 3, 0.010 in year 4, 0.0167 in year 5 and then increases by 0.00333 for each subsequent year (e.g. 0.020 in year 6). Further research is warranted to examine high mileage vehicles over 10 years old; however, the results from the CE survey (Figure 3.22) and Utilimarc (Figure 3.24) suggest that the growth rate is relatively constant (Pfirrmann-Powell 2014; Burnham 2020). For the other vehicle types, we apply a vehicle type multiplier using the percentage reductions for SUVs and pickups for years 6-10 as seen in Figure 3.29, 9% and 30%, respectively.

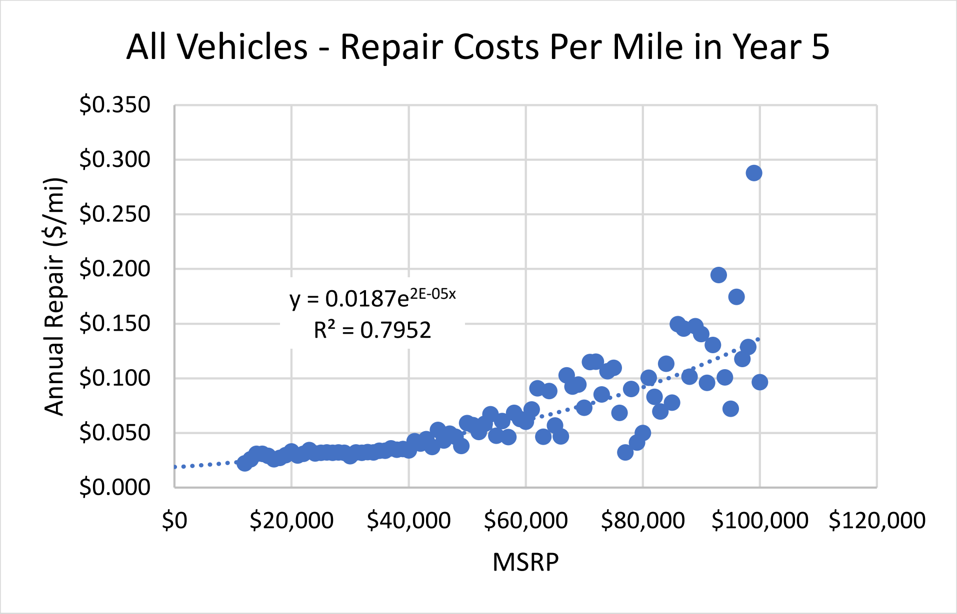


FIGURE 3.30 Average repair costs per mile for all vehicle types in year 5 plotted against MSRP

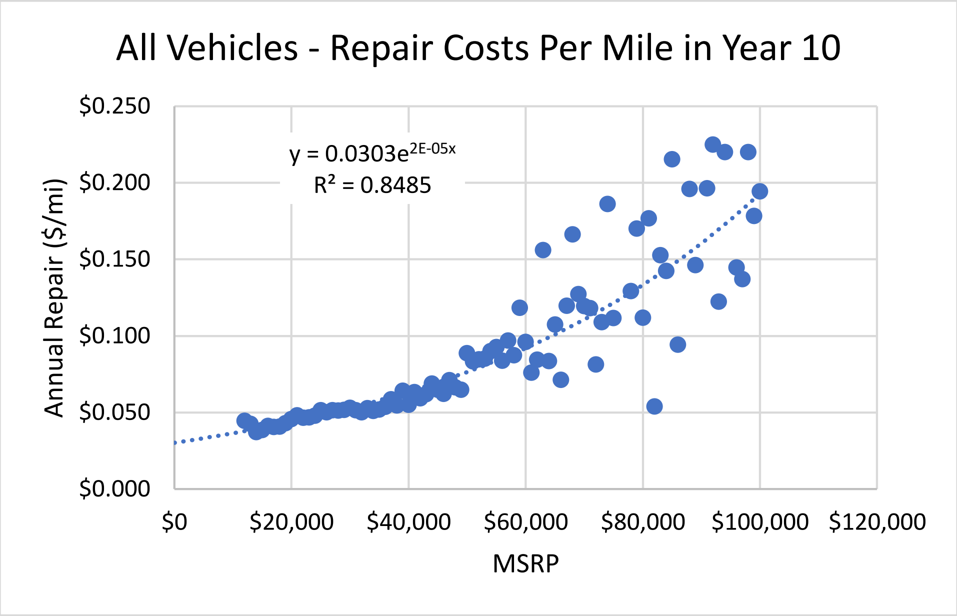


FIGURE 3.31 Average repair costs per mile for all vehicle types in year 10 plotted against MSRP

Next, we analyzed the relationship between repair costs and the MSRP by powertrain. As was discussed in the insurance analysis in Section 0, the Edmunds dataset has a limited number of makes and models for powertrains other than gasoline, so it is difficult to use that data to model and compare. Instead, we compared the repair costs of HEVs, PHEVs, and BEVs to their ICEV counterparts with an equivalent make, model, and trim; these are the same vehicles used in the insurance analysis listed in Table 3.14.

The total repair costs across all vehicle types for HEVs, PHEVs, and BEVs were 9%, 14%, and 33% lower than each ICEV counterpart on a percentage of MSRP-basis. We use these percent differences as the powertrain multipliers in Table 3.17. These percent differences are similar to the values generated for each powertrain from our maintenance service schedule in Section 3.5.3 (7%, 11%, and 41%, respectively). As discussed in Section 3.5.3, there is a lack of data on the repair costs of light-duty diesel vehicles and FCEVs. In this analysis, we assume that diesel costs are equal to gasoline and FCEVs equal BEVs, though suggest that this topic should be explored further. We assume that the fuel cell systems in FCEVs will last the lifetime of the vehicle, consistent with modeling and analysis by the HFTO (Joseck et al. 2018; James 2020; Kleen and Padgett 2021).

A summary of our scaling factors by vehicle and powertrain type is shown in Table 3.17 for use as inputs to the below repair cost per mile equation. The multipliers by vehicle (*v*) and powertrain (*p*) type are shaded in the table below. We also show the net multiplier (i.e. product of the two axes) in the non-shaded cells. For example, the repair cost per mile in a given year would be 39% lower for a BEV SUV than a gasoline car, if they had the same MSRP. The repair cost for a vehicle in year *i* is then given by Eq. 3.13:

$$Repair_i = v\,p\,a_i e^{bx}, i = 1, \dots, 15 \tag{Eq 3.13}$$

where

$Repair_i$ = the repair cost per mile in year i,
v = the appropriate vehicle type multiplier from Table 3.17,
p = the appropriate powertrain type multiplier from Table 3.17,
a_i = gasoline car repair cost coefficient in year i,
b = exponential constant of 0.00002,
x = the MSRP in the year the car was sold as new.

TABLE 3.17 Summary of repair cost multipliers by vehicle type and powertrain compared to gasoline car on MSRP-basis

	Powertrain	ICEV	HEV	PHEV	BEV	FCEV
Vehicle Type	Multipliers	1.00	0.91	0.86	0.67	0.67
Car	1.00	1.00	0.91	0.86	0.67	0.67
SUV	0.91	0.91	0.81	0.78	0.61	0.61
Pickup	0.70	0.70	0.62	0.60	0.47	0.47

3.5.5. Maintenance and Repair Costs, MHDV

For medium- and heavy-duty vehicles, we used the Utilimarc dataset to estimate MHDV M&R costs per mile by vehicle age as shown in Figure 3.32. The results can be grouped into categories: semi-tractors; medium-duty vans and pickups; transit buses; box, utility aerial, and dump trucks; and refuse trucks. The semi-tractor results were developed using both ATRI (Murray and Glidewell 2019) and the Utilimarc datasets, while all other values relied solely on Utilimarc.

The semi-tractors in municipal and utility service from Utilimarc had an average annual VMT that was much lower (25,000 when new) than those analyzed by ATRI and thus do not represent a commercial freight duty-cycle. The ATRI dataset only provides an average cost for all vehicles and the average age of those vehicles (4.4 years). Therefore, we scaled the Utilimarc semi-tractor cost curve to match ATRI costs for a 4-year-old vehicle, resulting in an M&R cost of $0.12 per mile in year 1 and $0.57 per mile in year 15. Further analysis is needed to understand commercial semi-tractor M&R costs as the vehicle ages since the truck will change vocations (e.g. moving from long haul to regional haul to drayage operations). A well-maintained semi-tractor engine may have a life of 1,000,000 miles, though a rebuild, which costs $20,000 to $30,000, can be expected by around 750,000 miles (Shadof 2017).

The medium-duty van and pickup M&R costs increase annually in a roughly linear fashion from about $0.07-$0.15 per mile in year 1 to about $0.55-$0.65 per mile in year 15. Transit bus life is typically 12 years and we see an increase from $0.20 per mile in year 1 to $1.70 in year 12. The box, utility, and dump trucks costs increase from $0.35-$0.50 per mile in year 1 to $1.55-$1.60 in year 15. The refuse truck costs have by far the largest costs for M&R,

due to their hydraulic compactor systems and difficult duty-cycles, increasing from about $1.30 per mile in year 1 to $5.00 in year 15.

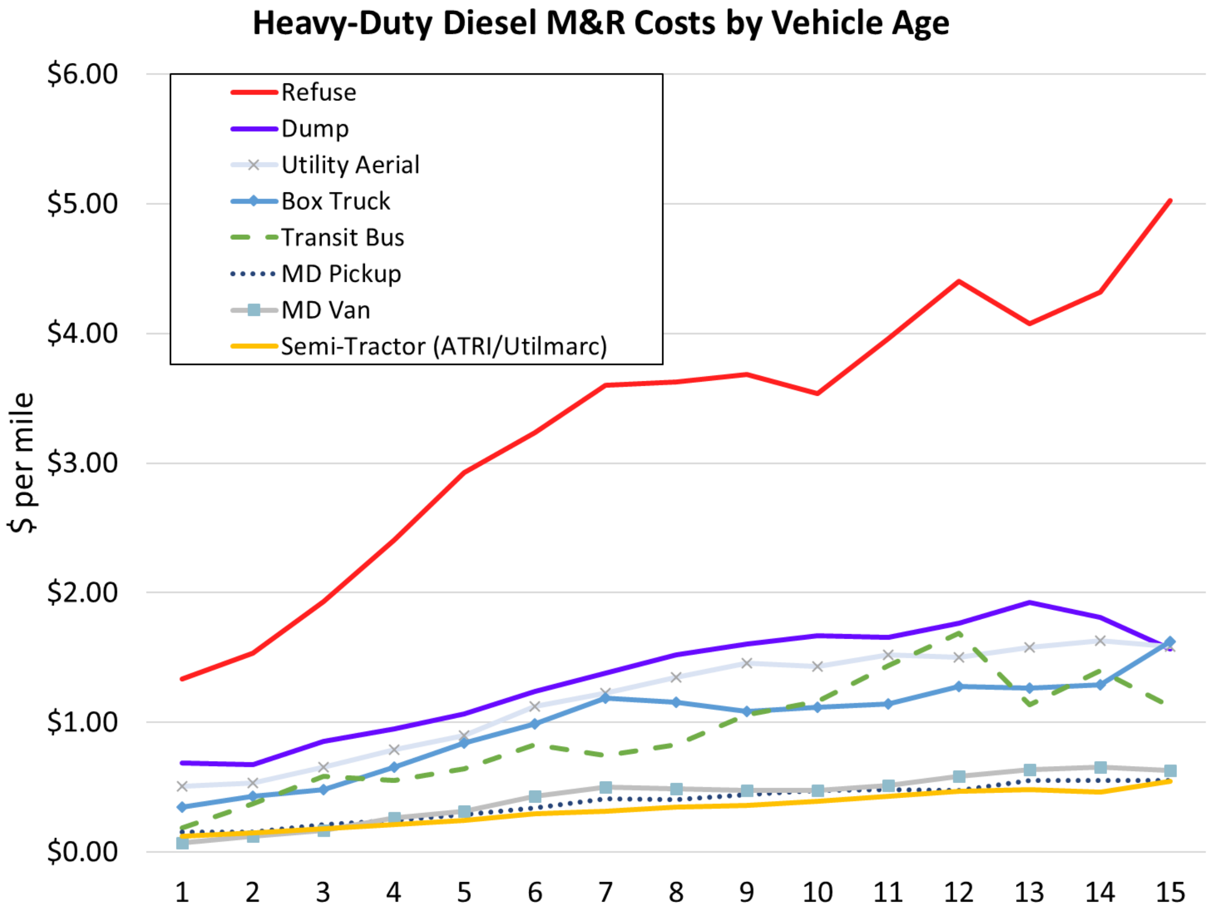


FIGURE 3.32 Diesel HDV per mile maintenance and repair costs by age (data from Burnham 2020)

As with LDVs, the use of alternative fuel and advanced powertrains can potentially influence M&R costs. Examinations of natural gas fuels have shown that these vehicles tend to have similar to slightly higher maintenance costs than their diesel counterparts (Ricardo 2012; Burnham 2020). However, even though the current generation of HD natural gas vehicles have been in fleets for more than a decade, there is limited publicly-available data. In response to this, the U.S. DOE recently awarded a project to investigate natural gas versus diesel M&R costs (Clean Cities 2019). For HEV and PEVs, these technologies are in the early stages of HDV deployment, with transit buses having the most experience. Urban transit bus duty-cycles can derive significant improvements in fuel economy from hybridization and electrification, but also enjoy the M&R benefits of regenerative braking and no exhaust aftertreatment in the case of BEVs and FCEVs. Eudy and Jeffers (2018) found that for over a one-year period ending March 2017, the average per-mile M&R costs were $0.26 for three battery electric buses, $0.32 for ten hybrid buses, and $0.46 for three diesel buses. Transit buses have many M&R issues and the cost differential was not fully due to the powertrains; for example, repairs to seats, doors, tires, and HVAC system were also included. The per-mile powertrain-only M&R costs were $0.05, $0.12, and $0.13 for the BEV, HEV, and diesel, respectively (Eudy and Jeffers 2018).

It is difficult to draw conclusions from individual transit bus fleet case studies, as M&R costs can vary widely for buses within an agency and between different agencies due to operating conditions like average speed, the size of the bus fleet, and experience of the maintenance staff (Clark et al. 2009). Therefore, it is useful to examine a wide range of studies to better understand this variance. Blynn (2018) surveyed the M&R cost savings claimed by battery electric bus manufacturers, projected savings by academic and government studies for CNGVs, HEVs, and BEVs, and estimated savings from empirical studies. Blynn (2018) developed values for three cases (low, mid, and high) for the relative M&R costs of the alternative fuel and advanced powertrains in comparison to diesel buses, as summarized in Table 3.18. The mid-case M&R reductions for CNGVs, HEVs, and BEVs were 0%, 13%, and 40% respectively. The results for HEVs and BEVs are very similar to both our LDV maintenance and LDV repairs estimates in Sections 3.5.3 and 3.5.4. Blynn (2018) did not provide estimates for HDV PHEVs or FCEVs; therefore, based on our light-duty analysis, we used the relative weighting of our LDV HEV, PHEV, and BEV M&R reductions versus gasoline to generate reductions of HDV PHEVs and assumed FCEVs have the same M&R reductions as BEVs. As mentioned in Section 3.2.1.1, we assume that PHEV and BEV battery packs in MHDV PHEVs and BEVs last the lifetime of the vehicle. As with LDV FCEVs we assume that the fuel cell systems in MHDV FCEVs will last the lifetime of the vehicle, consistent with analysis by the HFTO (Marcinkoski et al. 2019). These estimates can be applied as reasonable bounds for other HDV types as well, until further demonstration and analysis is conducted. As such, we use the mid-case results for all MHDV types as input for the TCO calculation. A summary of all of these results is found in Table 3.18.

TABLE 3.18 Summary of transit bus maintenance and repair cost multipliers (adapted from Blynn 2018)

Case	Powertrain				
	CNGV	HEV	PHEV	BEV	FCEV
Low	111%	96%	94%	79%	79%
Mid	100%	87%	84%	60%	60%
High	88%	73%	69%	41%	41%

3.6. TAXES AND FEES

Vehicle taxes and fees, including sales tax, license, registration, tolls, and parking, are an important component for comparing TCO across powertrains in both the LDV and MHDV sectors. In some cases, these fees can be dependent on the powertrain type (e.g. registration), while in others, the incremental price of advanced vehicles can play a role (e.g. sales tax). In this analysis, we focus on national average data, but also examine state and local data, as fees depend on enacted policies that vary by area.

3.6.1. Taxes and Fees, LDV

When purchasing a new vehicle, the owner will need to pay several different fees. In most states, a sales tax is placed on the purchase price of a vehicle. Local governments often add an additional tax on top of the state tax. Vehicle registration fees are paid to the state, which include the cost to register, title, and obtain license plates. In addition, dealerships charge a documentation fee for the administrative work to process paperwork involved in a vehicle sale, such as preparing the sales contract and filing for the title and registration. In some states, the documentation fee is capped by law, but in most, there is no limit (Gareffa 2019). Figure 3.33 shows state-based sales tax, registration fee, and documentation fees based on Gareffa (2019) and Avalara (2020) for a $38,000 LDV, which was the average new vehicle transaction price in 2020 (KBB 2020). The sales tax data in the figure represent the maximum rate accounting for both the state rate and the highest local rate in that state, which tend to be in place in a state's most populous areas. Delaware and Georgia do not have a vehicle sales tax, but have higher registration fees than most other states. The population-weighted national sales tax rate, initial vehicle registration fees, and documentation fee are 8.4%, $268, and $300, respectively.

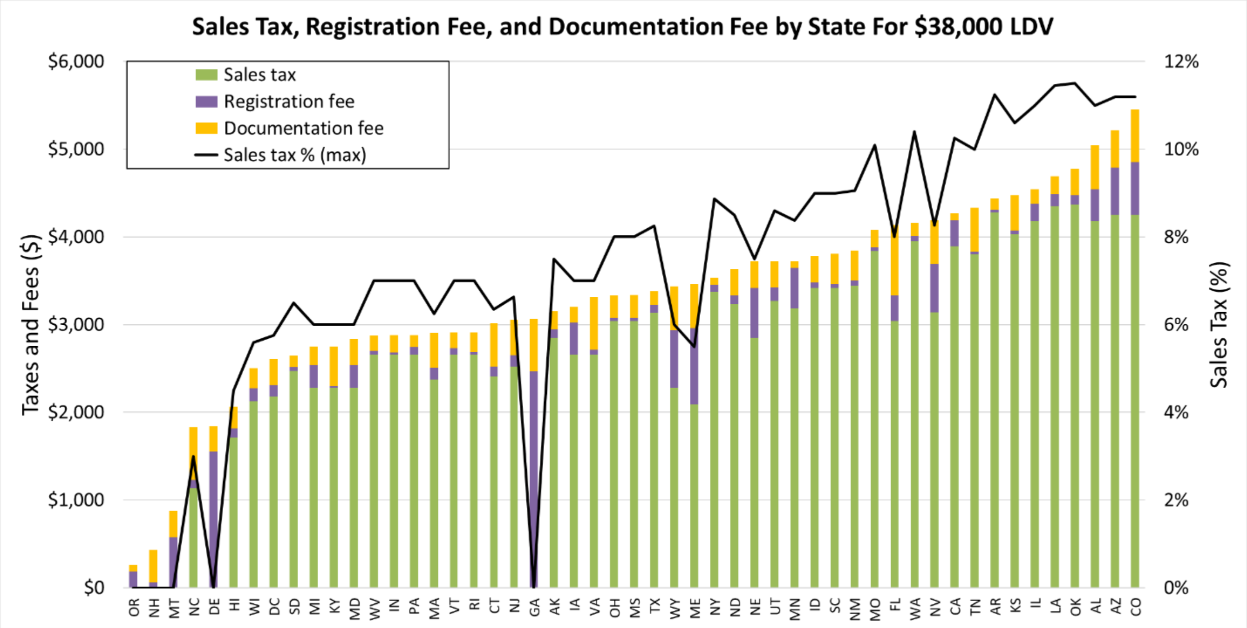


FIGURE 3.33 Sales tax, registration fee, and documentation fee by state (data from Gareffa 2019; Avalara 2020)

In addition to registering a vehicle at the time of purchase, each state has either annual or biennial vehicle registration fees. Depending on the state, registration can be a flat fee or is scaled by metrics such as vehicle weight and age. As seen in Figure 3.34, results from the Consumer Expenditure Surveys reported average annual state and local registration expenditures to be $68 in 2018.

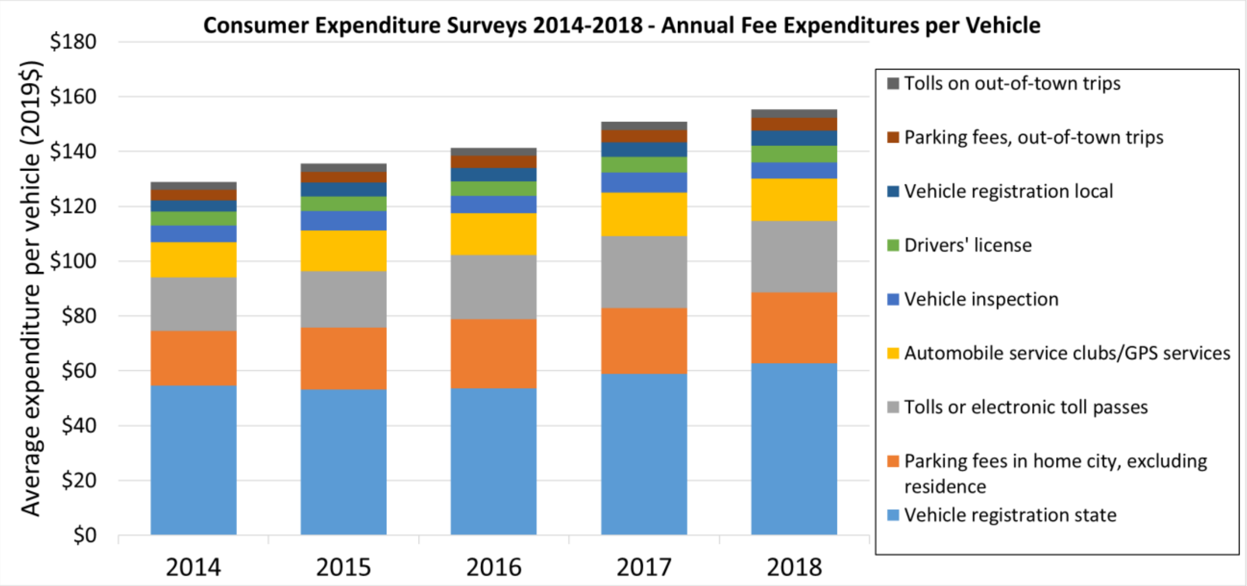


FIGURE 3.34 Consumer Expenditure Surveys 2014–2018 – Annual fee expenditures per vehicle (data from BLS 2020)

States are looking for additional transportation revenue streams as they are facing reduced revenues from motor fuel taxes, due to factors such as improved vehicle fuel efficiency and tax rates not being tied to inflation (Nigro and Rosenberg 2020). As of 2020, 28 states have additional registration fees (ranging from $15 to $269) for various advanced vehicles, most frequently for plug-in electric vehicles, due to these vehicles paying less or no fuel taxes (AFDC 2020). The population-weighted annual registration fees for HEVs, PHEVs, and EVs are $7, $36, and $73, respectively. Once again, registration fee data is quite limited for FCEVs. As such, we assume that registration costs for FCEVs are the same as for BEVs.

Additional fee expenditures reported by the CE survey include parking ($30), tolls ($29), automobile service clubs ($15), vehicle inspection ($6), and drivers' license ($6), accounting for $87 in 2018. Each of these fees will be applied to all powertrains, except for vehicle inspection (i.e. emissions testing), which will not be required for BEVs nor FCEVs. A summary of our assumptions for light-duty vehicle fees by powertrain is presented in Table 3.19.

TABLE 3.19 Summary of tax and fee assumptions (2019$)

	ICEV	HEV	PHEV	BEV	FCEV
Sales tax	8.4%	8.4%	8.4%	8.4%	8.4%
Initial vehicle registration	$268	$268	$268	$268	$268
Documentation fee	$300	$300	$300	$300	$300
Annual vehicle registration	$68	$68	$68	$68	$68
Annual AFV registration	$0	$7	$36	$73	$73
Other (parking, tolls, auto clubs, inspection, license)	$87	$87	$87	$81	$81

3.6.2. Taxes and Fees, MHDV

There is a 12% federal excise tax (FET) on the retail sale of most new heavy-duty trucks (Government Printing Office 2012). In addition, sales taxes apply to sales of commercial vehicles in some states. There is also the federal Heavy Vehicle Use Tax (HVUT) for heavy-duty vehicles with a weight rating of 55,000 lb or greater (FHWA 2020). The amount depends on the unloaded weight and the maximum load customarily carried on the vehicle. For HDVs with a weight rating between 55,000 lb and 75,500 lb, the tax is $100, plus $22 per 1,000 lb over 55,000 lb. For vehicles exceeding 75,500 lb, the tax is $550. Some HDVs are exempt from the HVUT, such as government vehicles, non-profit emergency response vehicles, mass transit vehicles, and other vehicles in special cases.

The latest data collected on annual state-level commercial HDV registration fees was by the FHWA (2008), which estimated the national average for single-unit trucks and class 8 semi-tractors to be about $880 and $1425 per year, respectively (2019$). As commercial truck registration fees are typically based on either empty or gross vehicle weight, we used the FHWA data to estimate the annual fees on an empty weight-basis for single-unit trucks and semi-tractors to be, $0.14 and $0.10 per pound, respectively. Fees such as permits, licenses, and tolls paid by HDV operators depend on the state in which the HDV travels. In 2018, ATRI found commercial freight carriers spent about $0.05 per mile or $4,800 per year on these fees (Murray and Glidewell 2019). No per-vehicle data was available for public fleets, but they likely do not pay local fees.

In this analysis, the baseline operational weights for each vehicle come from Autonomie modeling, and represent a typical load for each size class. In the TCO analysis, these vehicles are then taxed appropriately based on their modeled sales price and loaded vehicle weight.

3.7. COSTS AND CONSIDERATIONS SPECIFIC TO COMMERCIAL VEHICLES

Commercial vehicle purchase decisions are largely driven by economics, but purchasers also consider a variety of "soft" costs and benefits that are difficult to quantify, such as driver retention, payload capacity, and corporate image. Several TCO calculators are publicly available, but many do not include cost data because they are developed for fleet purchasers and users are expected to have information specific to their operations. However, they do provide guidance on what parameters are most relevant to consumers. To identify and prioritize cost elements unique to commercial vehicles, we reviewed available TCO tools and conducted two virtual workshops with fleets and manufacturers. These workshops also provided insights on data sources, valuation methodologies, and experience with early production electrified commercial vehicles.

Section 3.7.1 provides a summary of the qualitative workshop findings. In Section 3.7.2, we identify priority cost elements, and describe recommended calculations for the comprehensive TCO calculations. Finally, Section 3.7.3 documents the key assumptions, derivations, and findings for these cost components specific to commercial vehicles.

3.7.1. Summary of Qualitative Workshop Findings

The study team conducted two virtual workshops, the first focusing on manufacturer perspectives and the second on fleet perspectives on TCO for commercial vehicles. Both workshops were well attended, demonstrating industry-wide interest in TCO for emerging technologies. This section summarizes the key points highlighted by the workshop participants, primarily focusing on cost differences that may arise between powertrain types.

3.7.1.1. Use of TCO and Methodology Issues

Participants indicated that TCO is a widely used criterion in manufacturers' product planning and fleet purchase decisions. However, manufacturers cautioned that using bottom-up cost estimation to determine future vehicle costs is misleading because it underestimates or neglects recovery of investment in R&D, training, marketing, etc., required to bring new technologies to market. Fleets and manufacturers both indicated that there is high variation and uncertainty in many variables and the appropriate value to use - average, maximum, fleet specific, etc. – depends on the purpose or application of the calculation.

While participants indicated that fleets desire equivalent performance in new technologies, this requirement can underestimate the adoption potential in applications for which certain technologies are best suited. Conversely, if future powertrains are evaluated using parameters for the most suitable applications, this approach discounts the value of versatility, which is an important feature for many commercial vehicles. In addition, many parameters are interrelated (e.g., range, vehicle utilization, and charging opportunity), and input assumptions must be consistent. This greatly complicates assessing TCO for unknown future vehicle configurations. Finally, while fleets value versatility and want one-to-one replacements for their current vehicles, in the longer term, vehicles may be purpose-built for specific duty cycles, especially if they can be kept in service longer at a lower TCO.

Stakeholders indicated that publicly available TCO tools should be comprehensive, with all possible costs included, but give the user the choice whether to value certain costs and the option to use their own values. This is particularly true for highly variable, uncertain, and soft costs. The developer should clearly indicate where values are uncertain. Stakeholders that have provided TCO calculators cautioned that users may apply the tool without careful attention to the caveats provided, yet still attribute their results to the tool developer.

3.7.1.2. Vehicle Utilization and VMT

Workshop attendees noted their belief that high vehicle utilization is important to offset purchase costs when adopting new technologies (i.e. to achieve early payback). Stakeholders' analyses of BEVs in China showed low utilization for electric trucks compared to diesel trucks, but it is unclear whether this is due to technology limits (range and charge time) or fear of using these trucks for more or different applications (range anxiety). When vehicle range or charging are real limits to operation, a fleet may need to buy more trucks to meet its business needs.

New operating regimes (e.g., drop and hook) may offer potential for high utilization by increasing daily usage, but may also reduce charging opportunities. Similarly, full automation could increase vehicle utilization since driver hours of service (HOS) regulations by the Federal Motor Carrier Safety Administration would no longer limit usage, but would also reduce charging opportunities since continuous usage would be possible for any fleet.

While high utilization may be needed to achieve short payback, if the new technology continues to be reliable and to save money, it may be kept in the original use profile longer than a conventional diesel would be, thereby increasing the life over which fuel cost savings are calculated.

3.7.1.3. Depreciation

In the commercial truck market, trucks are moved to shorter routes closer to their home base as they age and become less reliable, or for BEVs, as the battery and range degrade. Leasing companies and large fleets are able to move vehicles within their own operations, while smaller fleets will sell the vehicles to other fleets that specialize in shorter range operations. However, for larger long-haul fleets, commercial truck replacement may be driven more by the need to attract and retain drivers with comfortable up-to-date vehicles than shortcomings in on-road vehicle performance. Residual value therefore is a key factor in many fleets’ purchase decisions. The residual value of new technologies will depend on used truck buyers’ confidence in that technology. While building this confidence, depreciation for new technologies will initially be accelerated relative to mature diesel technology. This may be further accelerated by performance advances and cost reductions in each new generation that make new vehicles more attractive than used ones. The used market also could be depressed by a real or perceived lack of maintenance support infrastructure.

In the longer term, depreciation will depend on the value of new technology in the vehicle’s “second-life” application. However, some stakeholders raised the possibility that BEVs will change this lifecycle phenomenon and that fleets may keep them longer than conventional diesel trucks if they still show positive cash flow. This would reduce the availability of used vehicles, increase residual value, and change the appropriate ownership period to use in TCO calculations that support initial purchase decisions.

Finally, battery life and the development of a secondary market for used batteries is a factor in whether the battery has a positive or negative impact on BEV residual value. As discussed in Section 3.2.1.1, while future battery salvage value is still largely unknown, batteries of the size required for many MHDVs hold the potential for a sizeable salvage value for second-life application beyond use in the vehicle.

3.7.1.4. Refueling and Recharging

The time required to charge BEVs could result in lost revenue or the need for a larger fleet compared to diesel. This is likely a greater factor in needing more trucks than reduction in payload capacity. Given HOS rules, the time required to charge may reduce a truck's potential daily mileage. This impacts schedule and driver wages since many drivers are paid by the revenue-mile, especially in longer haul applications. While many analysts assume that trucks have time to charge overnight, many regional trucks are used in slip-seating / 2-shift operations. Data for one package delivery fleet show that 68% of the fleet's tractors were in long-run 2-shift operations. Stakeholders believe these operations are becoming more commonplace. Long haul trucks also may be driven by team drivers, which doubles the amount of time the trucks may be driven and decreases time available for charging.

The energy price for charging MHDVs is unknown and will depend on infrastructure upgrade costs, which utilities will need to recover, equipment costs, local utility rate structures, and charging station utilization rates. Utility upgrades and associated costs required to electrify a fleet are site-specific, variable, and largely unknown. As a result, electricity pricing will vary by site. Stakeholders reported that today, for low-scale deployment, cost may be around $100,000 / truck (as noted in Section 0), but costs are non-linear with the scale of deployment. In addition, the cost of smart charging software should be included in TCO.

3.7.1.5. Maintenance and Repair

There is little to no public data on powertrain repair, maintenance costs, and failure rates for MHDVs. While OEM's have warranty data and fleets have out-of-warranty data, it is considered proprietary. With this lack of data, stakeholders suggested using engineering judgement and inference from LDV experience.

Diesel technology is very mature, but technologies used to meet the 2007 and 2010 emissions regulations initially were plagued by reliability issues and increased emissions-related costs. Since 2010, reliability has increased dramatically and these costs have decreased, though the latter did not return to pre-regulation values. Through the elimination of the M&R associated with diesel engines and exhaust after-treatment, MHDV BEVs are expected to have lower M&R costs. However, stakeholders indicated that this has not been the experience to date. Similar to the diesel emissions control experience, stakeholders voiced expectations for elevated BEV M&R costs and lower reliability relative to diesel trucks during the learning phase. These costs will be driven by the initial high cost of major powertrain components and electronics, as well as lengthy downtime for repairs. In addition, servicing BEVs will require a significant skill set change, and there are significant challenges with high voltage that will require new procedures, training, and certification. As a result, stakeholders felt that maintenance initially will be outsourced and labor will be more expensive. While larger fleets likely will return to in-house service as the technology matures, smaller fleets and local repair shops may never be able to do so.

Fleets express concerns over battery lifetime, replacement cost, and residual value. Experience to date in the U.S. is limited to buses, as discussed in Section 3.5.5, but there is experience with trucks internationally. According to one stakeholder, battery degradation has been faster than anticipated, with a life of about 1,000 cycles and replacement required at about 3 years. Meanwhile, heavy diesel engines are typically designed for one million miles, which occurs in 13 to 14 years for the sleeper tractor mileage schedule used in this study.

Finally, M&R costs for trucks of all types could be reduced by application of telematics for diagnostics and preventative maintenance, but the industry is still learning how to tap that potential.

3.7.2. Commercial Vehicle Priorities

The wide variety of commercial vehicle configurations, applications, and duty cycles complicates the calculation of TCO. In addition, data for MHDVs is more scarce and often more proprietary compared to privately owned, passenger LDVs. Based on stakeholder feedback, analysis of vehicle population and energy use, new powertrain research activity, and data availability, the team identified and prioritized vehicle segments and cost elements to focus this study's efforts.

The MHDV market was segmented by gross vehicle weight rating (GVWR) class and body style as shown in Table 3.20. Highest priority was given to segments with high energy consumption and vehicle population, indicated by colored circles: green: high, yellow: medium, red: low, no color: very low. Green shading in population and fuel use columns indicates highest fractions within each. Unfortunately, data were not available for several high population or use segments, including dump trucks, specialty hauling (flatbeds, stake side, etc.), pickup trucks, and vans. In this graphic, "Other" includes emergency vehicles and motor homes. Fractions may not add to 100% due to rounding. Population and fuel use fractions were estimated by NREL using VIUS 2002 (U.S. Census 2004), 2013 R.L. Polk registration counts (R.L. Polk 2013), and other published fuel economy and VMT sources (Lustbader et al. 2021).

TABLE 3.20 MHDV market segmentation and prioritization

Body type / vocation		Weight Class							Fraction	
		2b	3	4	5	6	7	8	Population	Fuel use
Tractor	**Day Cab Tractor**	▨	▨	▨	▨	▨	🔴	🟢	14.3%	25.8%
	Sleeper Cab Tractor	▨	▨	▨	▨	▨	▨	🟢	14.3%	44.8%
Single Unit	Beverage	▨							0.5%	0.2%
	Box Reefer	▨							1.2%	0.8%
	Box Truck	▨				🟢		🟢	9.5%	4.0%
	Bus, School	▨					🟢		5.6%	1.8%
	Bus, Transit/Commuter	▨	▨	▨	▨			🟢	1.2%	2.9%
	Bus, Shuttle/other								0.0%	0.0%
	Concrete								1.1%	0.9%
	Dump								9.5%	3.7%
	Specialty Delivery								0.1%	0.0%
	Specialty Hauling								11.3%	3.3%
	Specialty Service								0.3%	0.1%
	Pickup	🟠	🟠	▨	▨	▨	▨	▨	10.3%	3.0%
	Refuse	▨	▨	▨	▨			🟢	1.5%	1.5%
	Step/Walk-in Van	▨					▨	▨	3.5%	1.6%
	Tanker	▨	▨	▨					2.8%	1.2%
	Tow	▨							1.7%	1.0%
	Utility Aerial	▨	🟢			🟢			3.8%	1.3%
	Utility Non-aerial	▨							2.4%	1.1%
	Van					▨	▨	▨	4.0%	0.8%
	Other								1.2%	0.2%

The study team then identified cost parameters unique to commercial vehicles that would vary by powertrain type, other new technologies, or other considerations, including vehicle segment or vocation, shown in Table 3.21.

TABLE 3.21 Costs unique to commercial vehicles

	Varies With		
Parameter	Power-train	Other Techs	Other*
Maintenance and repair			
Exhaust after-treatment	✓		✓
Downtime and reliability valuation	✓		✓
Maintenance employee training, expertise, availability	✓		
Maintenance facility upgrade	✓		
Tank inspection (gaseous fuels)	✓		
Battery health	✓		
Vehicle washing and interior cleaning		✓	
Vehicle / equipment purchase, replacement, removal			
Exhaust after-treatment			
Full-service lease	?		
Refrigerator unit			✓
Idle reduction device (e.g. APU)			✓
PTO / hydraulics	✓		✓
Business operations, administration			
Commercial vehicle taxes, registrations, licensing, etc.			✓
Idle time and fuel			✓
ELDs and data plans		✓	
Fueling infrastructure	✓		✓
Administrative (fleet)	✓		
Drivers, productivity – specifically as it relates to alternative powertrains			
Driver compensation		✓	✓
Driver training and turnover	✓	✓	✓
Driver licensing?			
Payload opportunity cost	✓		✓
Yard management (charging)	✓		
Out of route mileage, time to charge, foregone miles	✓		

3.7.3. Key Cost Elements

As noted in Section 2.2.1, ATRI annually publishes a report describing the operational costs of trucking (Murray and Glidewell 2019). Figure 3.35 shows how TCO cost elements have changed over the last decade, though this data is almost entirely based on conventional ICEV. Based on the cost parameter examination described above, the team identified several of the most important and quantifiable variable cost parameters specific to commercial vehicles, particularly those which may vary with the introduction of AFV MHDVs. These include driver compensation/labor costs, idling, payload capacity costs, and refueling/recharging costs. To estimate each of these costs, we formulated calculation methodologies by reviewing literature and collecting and analyzing real world data, as described in the following sections.

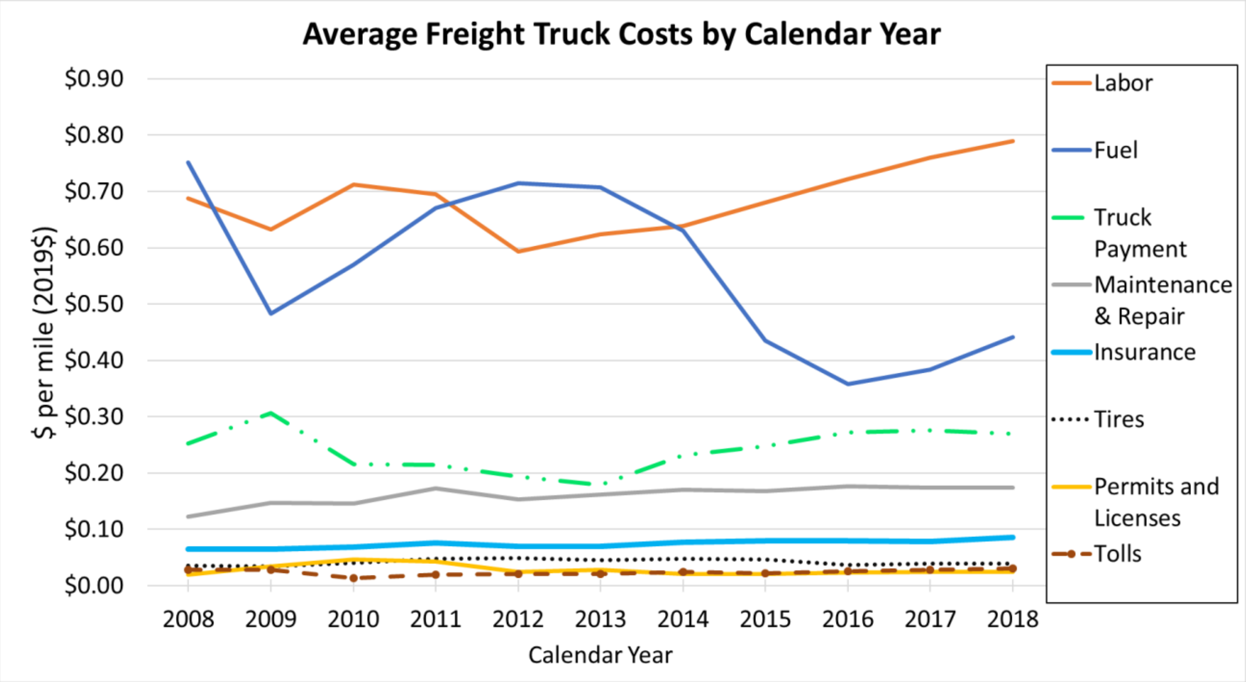


FIGURE 3.35 Average freight truck costs by calendar year, inflation adjusted (data adapted from Hooper and Murray 2017; Murray and Glidewell 2019)

3.7.3.1. Labor Costs

Driver wages and benefits for freight and passenger movement are key elements in a comprehensive TCO as, together, they constitute one of the largest cost components for many vocations. Estimates of driver wages and benefits are also required to quantify the cost of refueling time, which can be quite long for MHDV BEVs with large batteries, since current HOS rules dictate that fueling counts as working, so refueling/recharging counts against the total daily limit of vehicle operation (FMSCA 2015). Furthermore, labor/benefit rates would be required to assess possible cost savings for fully automated vehicles. As such, it is important to have an accurate data-based estimate.

ATRI (Murray and Glidewell 2019) reports total driver compensation as hourly and per mile values for tractor drivers in truckload (TL), less-than-truckload (LTL), and specialized hauling sectors. According to the ATRI data, salary accounts for about 77% of total driver compensation. The ATRI salary fraction was applied to additional hourly driver salaries obtained from online job listings for local, regional, and long haul truck drivers to scale up to the full compensation rate, which also includes benefits. Per-mile labor rates for these additional segments were developed using average duty cycle speeds from the Phase 2 fuel efficiency standards (EPA and NHTSA 2016). For service vehicles, such as utility bucket trucks, plumbers, etc., operating the vehicle is secondary to performing the service job and wages depend on the specific vocation. For this study, we assume that these vehicles must be able to complete these services during a normal work shift and charge overnight. Figure 3.36 shows a comparison of driver compensation for different tractor-trailer operation, measured both per-hour and per-mile.

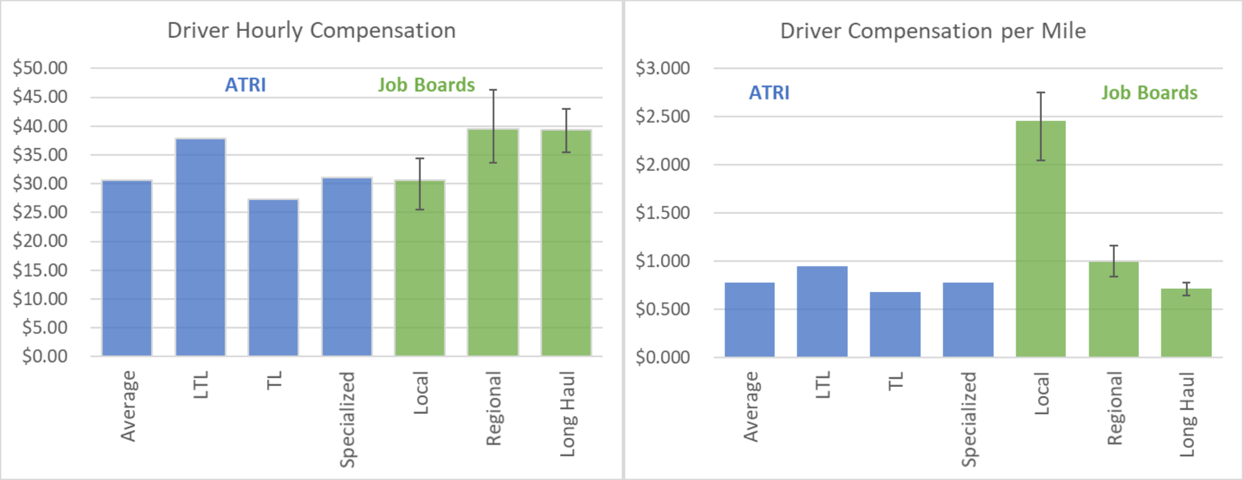


FIGURE 3.36 Hourly and per-mile compensation for drivers of different vehicle types. LTL: less-than-truckload service; TL: truckload service; specialized: includes tankers and flatbed carriers. Sources: ATRI (Murray and Glidewell 2019), Glassdoor (2020), Zip Recruiter (2020), Indeed.com (2020), Payscale.com (2020), and Neuvoo.com (2020).

We assume that tractor drivers, including sleepers and day cabs, are paid using a per-mile rate and drivers for all other vocations (Pick-up and Delivery, Vocational, Refuse, Bus) are paid by the hour. For the vocations paid by the mile, we assume a rate of $0.79/mile and for vocations paid by the hour, we assume a rate of $30/hour. To determine the total annual labor costs, we assume 2000 hours/year for the hourly rate vocations and use the applicable VMT schedule for the per-mile vocations.

3.7.3.2. Idling

In addition to fuel consumption from driving a commercial vehicle, considerable amounts of fuel can be consumed during idling, such as when a vehicle is temporarily parked during a delivery, in stop-and-go traffic, or during overnight hoteling for sleeper cabs. Figure 3.37 shows the roles of idling and PTO for utility truck activities from a study by NREL (Konan et al. 2017), showing idling can take 30% of total operation time and 10% of total energy use. The Autonomie fuel economy simulation results utilize duty cycles with a mix of highway and transient driving based on weighting factors found in the Phase 2 fuel efficiency standards (EPA and NHTSA 2016). The transient driving cycle includes a certain amount of on-road idling (though may underestimate idling for delivery trucks), but does not including idling during hoteling. Therefore, we focus on hoteling for sleeper cabs since it has the potential for the greatest amount of idling time and is not accounted for in the Autonomie duty cycle.

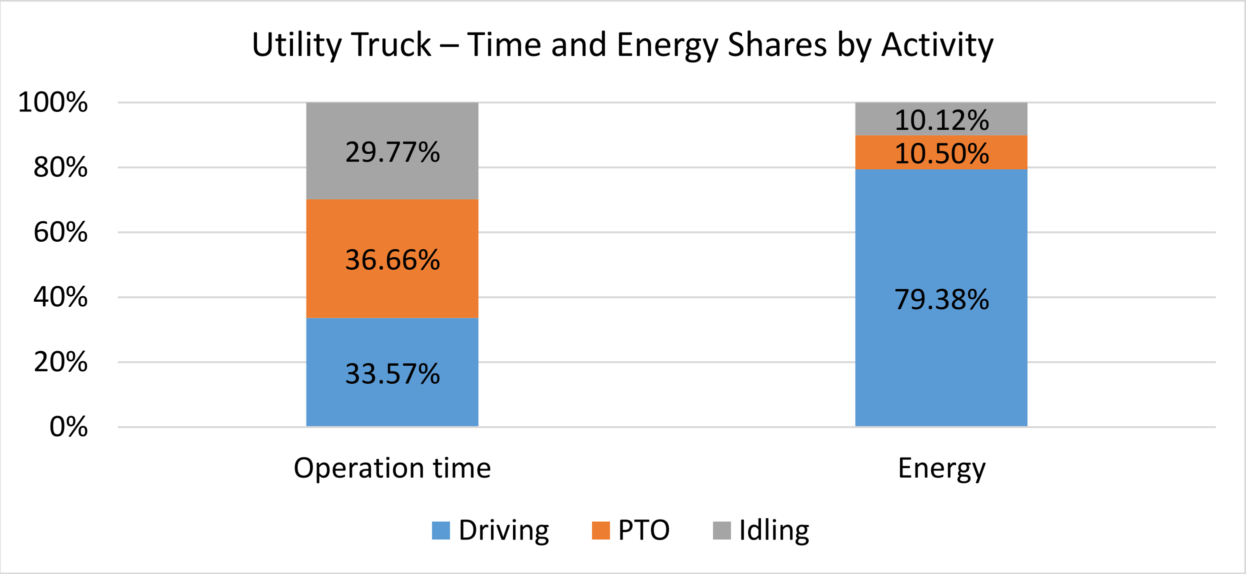


FIGURE 3.37 Time and energy shares of PTO and idling for utility trucks (data from Konan et al. 2017)

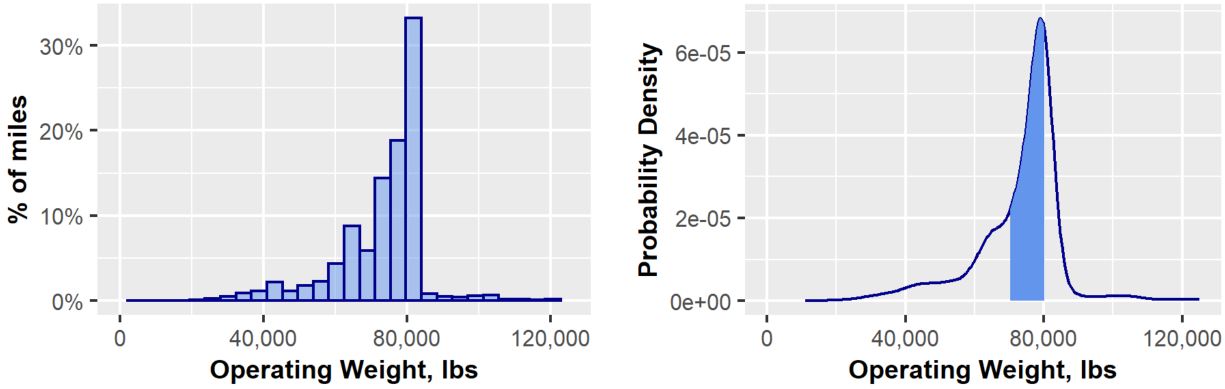
We assume that sleeper cabs support 1800 hours of hoteling annually (Gaines et al. 2006; Gaines and Weikersheimer 2015) and consume 0.8 gal/hour for both ICE and HEV diesel trucks. Fuel consumption due to idling is considered a fuel cost in our analysis as it inherently refers to the burning of fuel. For the other electrified powertrains, we assume that the onboard battery can be sufficient to power the climate control and other power needs due to hoteling. As a sensitivity analysis, we examine the role of Auxiliary Power Units (APUs), which can be used as an alternative to running the engine for more efficient idling/hoteling in sleepers. We assume that the APU consumes 0.2 gal/hour during idling over the same 1800 hours annually. In order to account for the initial cost of the APU, we include this as an additional cost in the price of the vehicle. While there is significant variation due to configurations and options, we use an average value of $8600 for an APU (Gaines and Weikersheimer 2016). At the fuel consumption rates above, it takes about 3 years to recover the cost of the APU in fuel savings, and also leads to lower emissions.

3.7.3.3. Payload Capacity Costs

Stakeholders identified potential loss in payload as a significant concern for BEVs, even though anecdotal evidence suggests that few truck trips are at gross vehicle weight rating (GVWR). One possible approach is to assume that no loss in capacity is acceptable. While this may be true for some fleets, it is unlikely to hold for all commercial vehicle buyers. Therefore, the study team identified four possible approaches to quantify the value of lost payload capacity, by evaluating the cost to (1) purchase additional trucks, (2) rent additional trucks, (3) buy capacity services at spot market rates, or (4) assume the fleet does nothing to compensate and forgoes the lost freight. The last option was considered infeasible because it means lost revenue in the short run and potential customer or market loss long term, which would equate to extremely high cost.

The first approach adds an operational cost equivalent to the value of buying a portion of a similar truck to fulfill the unmet needs of the fleet. This methodology first computes the levelized cost of purchasing the new option, then adds the fractional amount of additional trucks required. For example, if the BEV has 10% less payload, the capacity cost is 0.10 times the lifetime total cost without considering payload impacts. The second approach quantifies the cost for a fleet to rent a fraction of a similar truck to meet their needs. This is mathematically similar to the first option, but there are differences in capital depreciation, overhead charges, and taxes. The third approach quantifies the cost to buy cargo capacity services on the TL and LTL spot markets. LTL rates for marginal cargo capacity are significantly higher than the levelized cost of ownership of a fully-loaded truck, resulting in capacity costs as much as ten times higher. The study team decided that the first approach was the most tractable and reflects likely fleet behavior.

The next step is to determine whether to value the entire payload capacity loss as if the vehicle were always weight limited. Since this is reportedly seldom the case, the team adopted a probabilistic approach based on VIUS 2002 vehicle operating weight distributions (U.S. Census 2004). As shown in Figure 3.38(a), for tractors, the distribution in operating weight, expressed as a percentage of total tractor miles, can be used to establish how often trucks are likely to lose revenue as a result of reduced capacity. We first assume that tractors operating over the maximum GVWR of 80,000 lb already have a weight exemption and do not lose payload. Then the distribution to the left of 80,000 lb represents the probability of incurring a payload capacity cost. The shaded portion of Figure 3.38(b) illustrates the part of this distribution for which the capacity cost would apply for a 10,000 lb increase in the vehicle empty weight due to new powertrain technology.



(a) (b)

FIGURE 3.38 Operating weight distribution for class 7 and class 8 tractors

The expected payload loss is then:

$$E(PayLDLoss) = \int_{G-\Delta veh\_wt}^{G} P(w) * [w - (G - \Delta veh_{wt})]\, dw \qquad \text{Eq 3.14}$$

where

G = maximum gross vehicle weight rating

Δveh_wt = increase in empty vehicle weight due to technology

w = operating weight

P = probability density function based on operating weight distribution

To calculate the per-mile payload capacity cost, the expected payload loss is divided by the new vehicle payload capacity then multiplied by the per-ton-mile estimated TCO without considering payload capacity. However, nearly all states have enacted a 2,000 lb weight allowance for BEVs, which we subtract from the vehicle weight increase for BEVs. In this analysis, we find that a MY2025 BEV sleeper cab loses a total of 5100 lbs of cargo capacity relative to the ICEV (after accounting for the one-ton weight allowance), for an expected loss of 2300 lbs. This increases costs by 4.9%. However, in the Autonomie low-technology case, the MY2025 BEV sleeper cab loses a total of 8700 lbs relative to the ICEV, because the batteries have lower energy density (kWh/kg). In this case, the expected payload loss is 4400 lbs, resulting in a 10.3% increase in costs. In this analysis, we attribute all of these costs to the ‘payload’ cost item.

3.7.3.4. Refueling Labor Costs

Refueling advanced powertrains may incur two additional costs: (1) time and out-of-route mileage due to searching for refueling, and (2) dwell time costs. The first cost depends on the location and pervasiveness of refueling infrastructure and may be a transitional issue. The second cost depends on charge power or refill speed and storage capacity. Even trucks using public overnight charging could incur these costs if the facility is not located along their normal or optimum route. However, as illustrated in Figure 3.39, for fleets that install their own refueling infrastructure and only refuel between shifts, there are no additional refueling costs, assuming this does not represent a change in operations. Consistent with stakeholder feedback, the TCO tool allows analysis with and without considering dwell time and re-routing costs. However, scenarios should be defined with consistent assumptions about daily / annual mileage and charging opportunities.

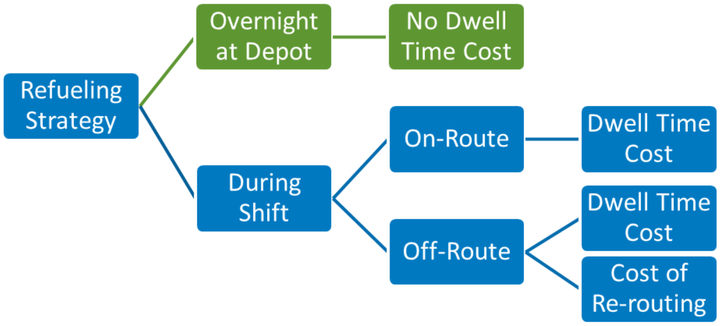


FIGURE 3.39 Schematic diagram representing refueling costs

The time to refuel may be valued using the cost of driver and administrative labor. Since conventional diesel trucks do require time to refuel, this cost, C_{refuel_dwell}, is evaluated as the increase in time times the labor rate. For BEVs, this can be calculated as:

$$C_{refuel\_dwell} = \left(\frac{BatCap}{ChargePower} - \frac{TankVol}{FillRate}\right) * LaborRate \qquad \text{Eq 3.15}$$

where:

$BatCap$ = battery capacity (kWh)
$ChargePower$ = EVSE charge power (kW)
$TankVol$ = diesel tank volume (gal)
$FillRate$ = diesel nozzle fill rate (30–60 gallons/min)
$LaborRate$ = loaded driver labor costs + administrative labor cost ($/hr)

Because the diesel fueling rate is so much faster than electric vehicle charging, we can generally focus on the electric charging aspect. At 45 gallons/minute, a typical ICEV costs approximately 0.1 cent/mile to fuel. Hypothetical charging rates for MHDV BEV are unknown, and estimates range from approximately 50 kW (equivalent to a fast charger for LDV today) to over 1 MW. Using Autonomie results, we find that even with megawatt-level charging, refueling would take over an hour for 500-mile range tractors. If we use the hourly labor rate described in Section 3.7.3.1 of $30/hour, this increases costs by 8 cents per mile, while 400 kW charging would increase costs by 20 cents per mile. In this analysis, refueling labor fits into the labor item of the TCO calculation. This is analyzed in greater detail in Section 4.2.6.

Re-routing can be valued using the per-mile TCO estimated prior to adding the cost to re-route. Much like the payload capacity cost, this increases the total use of the vehicle, acting as a multiplier to all costs. Because VMT increases with re-routing, the total VMT increases. When quantifying a levelized cost of driving, it is important to treat the metric as dollars-per-operational-mile, as the additional mileage is not earning revenue. Due to lack of information about how refueling for AFVs will change vehicle operation, we set the additional mileage parameter to zero in the baseline analysis.

4. RESULTS

Having developed a methodology for quantification of vehicle ownership costs and with a robust series of assumptions for each of the individual cost elements, we turn our attention to exploring economic results. In Section 4.1, we present results from our primary case, MY2025 vehicles across different LDV and MHDV size classes and powertrains. In Section 4.2, we present results from side cases of particular interest, while Section 4.3 presents a more detailed sensitivity analysis comparing the influence of uncertainties in different TCO cost parameters. Results are presented in tabular form in Appendix B for each of the graphics in Sections 4.1 and 4.2.

4.1. BASE CASE

As discussed in Section 2.3, total cost of ownership will be presented in terms of a discounted cash flow analysis and as a levelized cost of driving (LCOD) per mile. TCO is particularly important for comparing differences across alternative technologies in order to understand when a new technology can become cost-effective. Figure 4.1 shows a TCO comparison of six different powertrain technologies for a small SUV. This vehicle was modeled in Autonomie and is meant to be representative of a vehicle that could be available in 2025. A 15-year analysis window was assumed, along with a 1.2% discount rate and a 4.0 interest rate on a 63-month loan. The upper graphic is the total (discounted) cost of ownership, integrated over the entire 15-year analysis window. The lower graphic is the levelized cost of driving in $/mile, averaged across the full analysis timeframe.

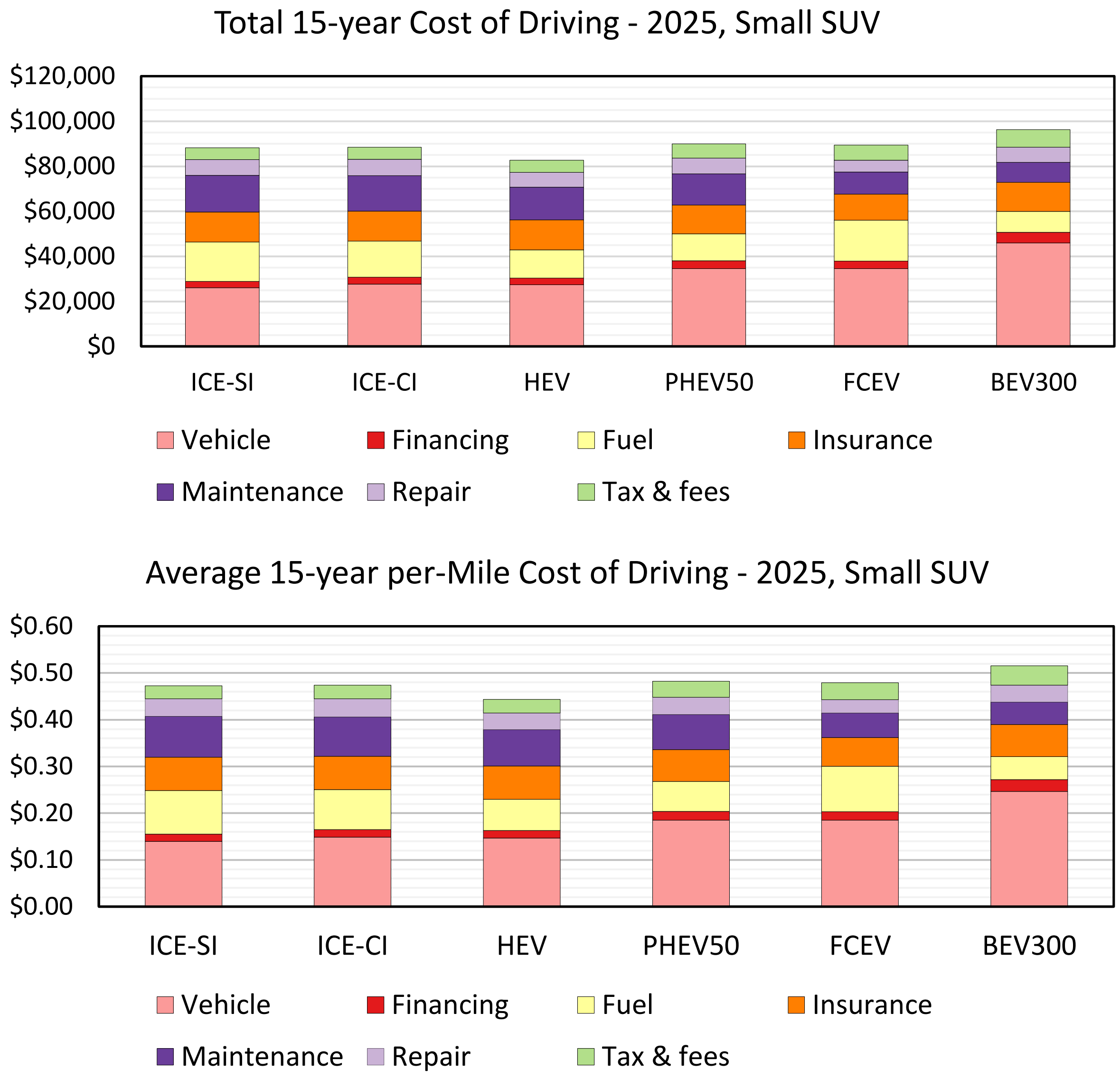


FIGURE 4.1 TCO and LCOD for small SUVs, MY2025

Comparing across powertrains, the HEV is the vehicle powertrain with the lowest cost of ownership over a 15-year span, at 44.6¢/mile. The ICE-SI, ICE-CI, FCEV, and PHEV50 all have costs around 48¢/mile. The BEV300 has the highest cost, at 51.8¢/mile, though the shorter-range BEV200 (not pictured) has a cost of 45.3¢/mile. The comparatively high costs for BEV300 come from assumed battery costs of $170/kWh in 2025 in the Autonomie model (Islam et al. 2020), though BEV would reach cost parity with HEV at a cost of $102/kWh. For all powertrains, the vehicle cost is the single most expensive cost over the 15-year analysis window. Maintenance and repair taken together is the second most expensive for all powertrain types except FCEV. For petroleum-fueled vehicles, this is followed by fuel, then insurance. For electric-fueled vehicles (both BEV and PHEV) and hybrids, reduced fuel costs lead to higher insurance costs than fuel costs. Hydrogen fuel cells have a different cost breakdown, where the cost of fuel is higher than maintenance and repair and insurance. This is due to the high price of hydrogen as described in Section 0.

Figure 4.2 demonstrates that the TCO depends on the size of the vehicle as well, as larger vehicles tend to be more expensive and less fuel efficient. We show the levelized TCO for the five LDV size classes for a MY2025 ICE-SI vehicle in Figure 4.2; the trend that larger vehicles are modeled as more expensive is true for all powertrain types. For a more direct comparison, all vehicles were assumed to drive exactly 12,000 miles per year, rather than using the different mileage schedules for the cars and light trucks.

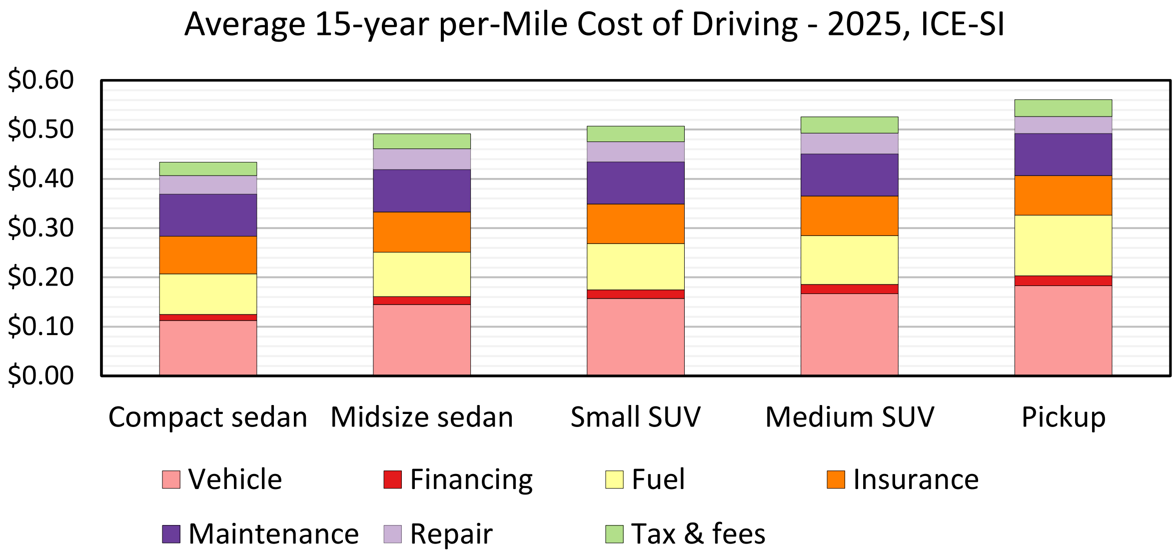


FIGURE 4.2 Comparison of LCOD for different LDV size classes of MY2025 conventional gasoline vehicles, 12,000 miles per year

Beyond light-duty vehicles, heavy-duty vehicles can be quantified in this framework. As with the LDV, we use Autonomie to model vehicles available today and in the near future based on technological advancements. In this analysis, we consider 7 different types of vehicles: Sleeper cab Class 8 tractor, Day cab Class 8 tractor, Class 8 Vocational, Class 6 - Pickup/Delivery, Class 4 - Pickup/Delivery, Class 8 Transit Bus, Class 8 Refuse. These vehicles are compared in Figure 4.3. As in Figure 4.1, both an aggregate cost of ownership and a levelized cost of driving are presented. Note that these vehicles have drastically different mileage schedules, and therefore the LCOD is a more direct way of comparing across these vehicles rather than the total 10-year discounted cost of ownership. For these commercial vehicles, we use a discount rate of 3.0%, highlighting both the enhanced value of investment capital in a commercial setting relative to households, and the desire for rapid payback by fleet operators.

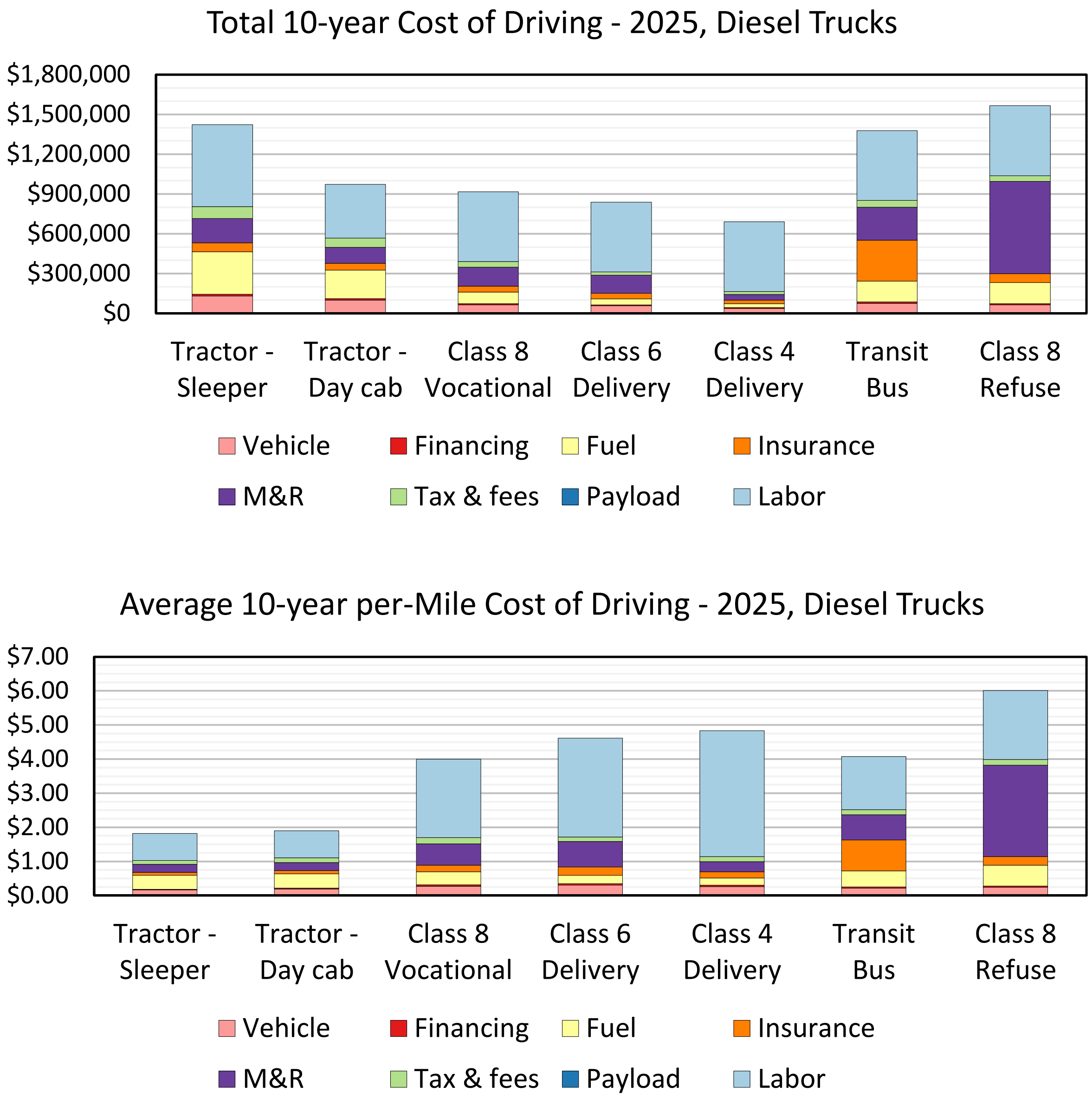


FIGURE 4.3 TCO and LCOD for medium-duty and heavy-duty trucks

Figure 4.3 shows that these vehicles do not have a definite rank order in terms of the most expensive cost component. For all of these, driver wages and benefits are a major expense for fleet operators, making up nearly half the cost for freight trucking, and an even greater fraction for MDV delivery vehicles. While a sleeper cab is the most expensive vehicle considered here, it has the lowest cost-per-mile due to the long driving distance (870,000 miles over the 10-year analysis window). For buses, the largest (non-labor) cost is for liability insurance, while refuse trucks have exceptionally high maintenance and repair costs, as described in Section 3.5.5. Over the lifetime of the tractor trailers, fuel costs are much higher than the initial vehicle purchase. Improving fuel economy is one pathway for economic freight operation. Figures 4.4 and 4.5 show cost of ownership for class 8 sleeper cabs and day cabs with different powertrains, excluding labor costs which are the same across powertrains.

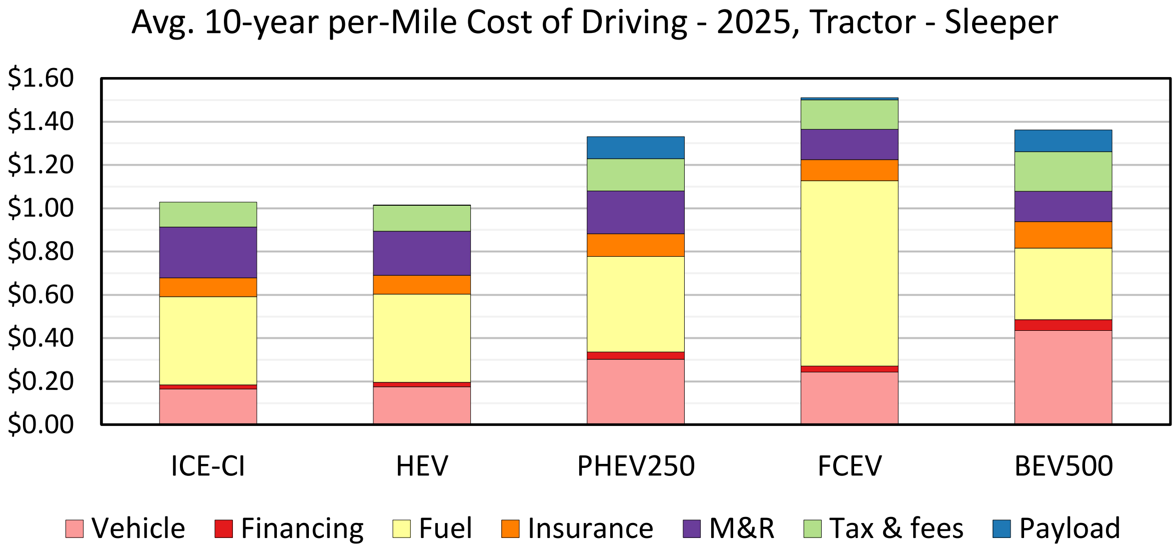


FIGURE 4.4 LCOD comparison across powertrains for MY2025 long-haul tractor trailers

For the Sleeper cabs, the traditional diesel-fueled vehicles have the lowest cost; the conventional ICE vehicle runs $1.03/mile while the HEV is $1.01/mile. Because highway driving comprises 95% of the driving cycle for these trucks, the fuel economy of the ICE, HEV, PHEV, and FCEV sleeper cabs are all modeled to be quite similar, while the high fuel economy of the BEV gives a modest benefit in lifetime fuel costs. The FCEV is forecast to be more expensive than the ICEV in 2025, while using much more expensive fuel. PHEV and BEV are more expensive to purchase owing to their very large lithium-ion batteries (670 and 1470 kWh, respectively, as compared to approximately 100 kWh for the largest LDV batteries). Also, the total weight for the PHEV and BEV are 5,200 and 7,100 lbs heavier than the ICE, respectively. This causes some trucks to weigh out, as described in Section 3.7.3.3, leading to a 5% increase in total costs for the BEV in 2025. We find marginal payload capacity costs on the order of $0.10/mile due to this term, comparable to costs for insurance or maintenance and repair. For day cabs, the HEV vehicles are still the cheapest option ($1.07/mile) followed by the ICEV ($1.10/mile). Because the capital costs are amortized over a shorter distance, these prices are higher than for the sleeper cab tractors. For AFV, the largest difference between the cost of operation of the day cabs and sleeper cabs comes from smaller battery sizes, leading to lower purchase costs and reduced payload capacity costs. Currently, BEVs receive a 2,000 lb weight exemption, greater than its 1,800 lb incremental weight, so the BEV day cab actually has greater room for payload than the ICEV in 2025.

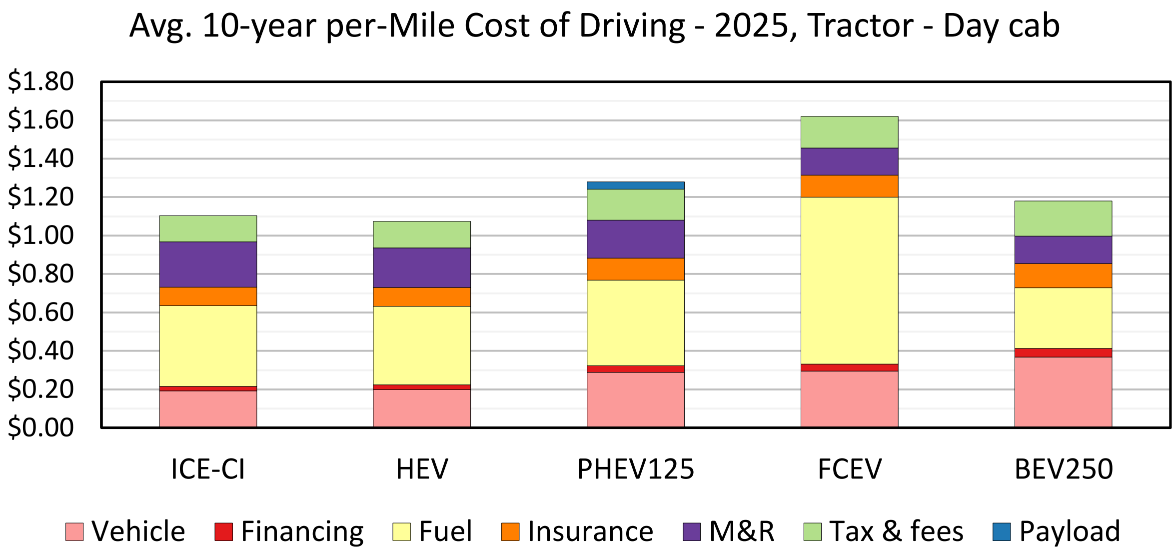


FIGURE 4.5 LCOD comparison across powertrains for MY2025 day cab tractor trailers

Figure 4.6 shows the comparison across powertrains for the class 4 delivery truck in 2025. In this case, the BEV is the lowest-cost option, with a total cost of $1.01/mile, followed by the HEV at $1.08. The largest difference in price comes from reduced fuel costs of using electricity in a more efficient vehicle. The BEV class 4 delivery vehicle was modeled to have a 150-mile range, lower than the class 8 tractors, at a battery cost of $150/kWh in Autonomie, before vehicle-specific markup (Vijayagopal et al. 2019). The class 6 delivery vehicle (data in the Appendix) exhibits similar cost behavior.

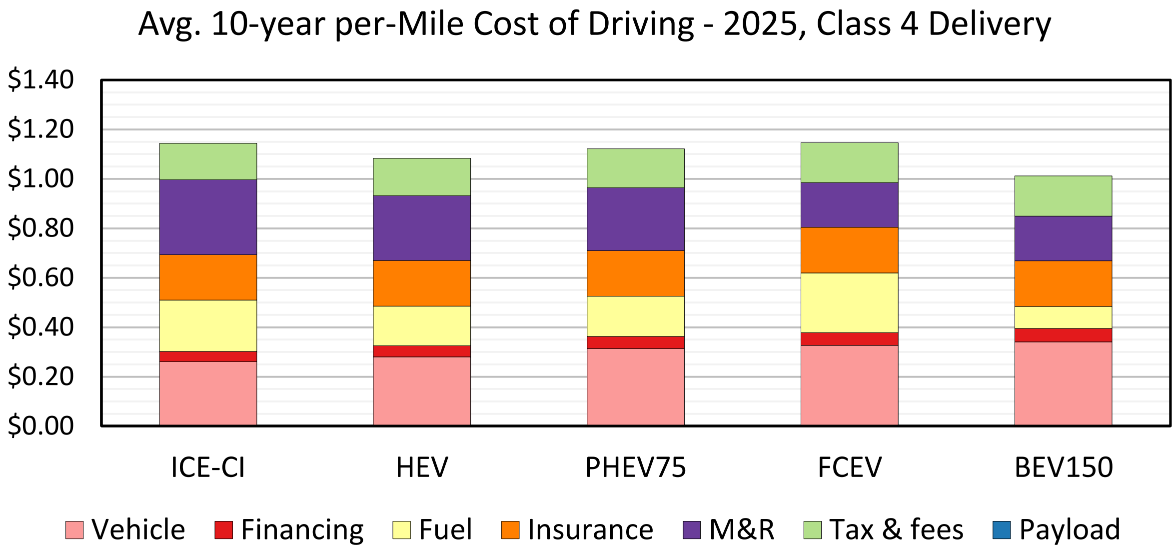


FIGURE 4.6 LCOD comparison across powertrains for MY2025 class 4 delivery trucks

4.2. SIDE CASES

4.2.1. Vehicle Technology Advancement

Looking toward the future, alternative powertrains make strides toward cost parity. Figure 4.7 shows the modeled reduction in TCO for the small SUV and the class 4 delivery truck for different powertrains from 2020 through 2050 as vehicle technology improves, using the high-tech progress cost modeling from Autonomie (Islam et al. 2020; Vijayagopal et al. 2019). While the HEV begins as the lowest cost powertrain for small SUV, FCEV are forecast to reach cost parity by 2030 when hydrogen prices reach $5/kg while BEV reaches cost parity with the HEV by 2035 at a battery cost of $98 per usable kWh of capacity, with these two technologies being the lowest cost in 2050. For the class 4 delivery truck, the BEV150 becomes the lowest cost vehicle by 2025, at a nominal $170/kWh of usable battery capacity. The FCEV tracks the BEV closely, being approximately 7 cents/mile more expensive through 2050. The conventional ICEV is the most costly powertrain by 2030. The largest cause for the cost reductions for both the BEV and the FCEV is the reduction in vehicle cost, which causes additional reductions in insurance and M&R expenses as well.

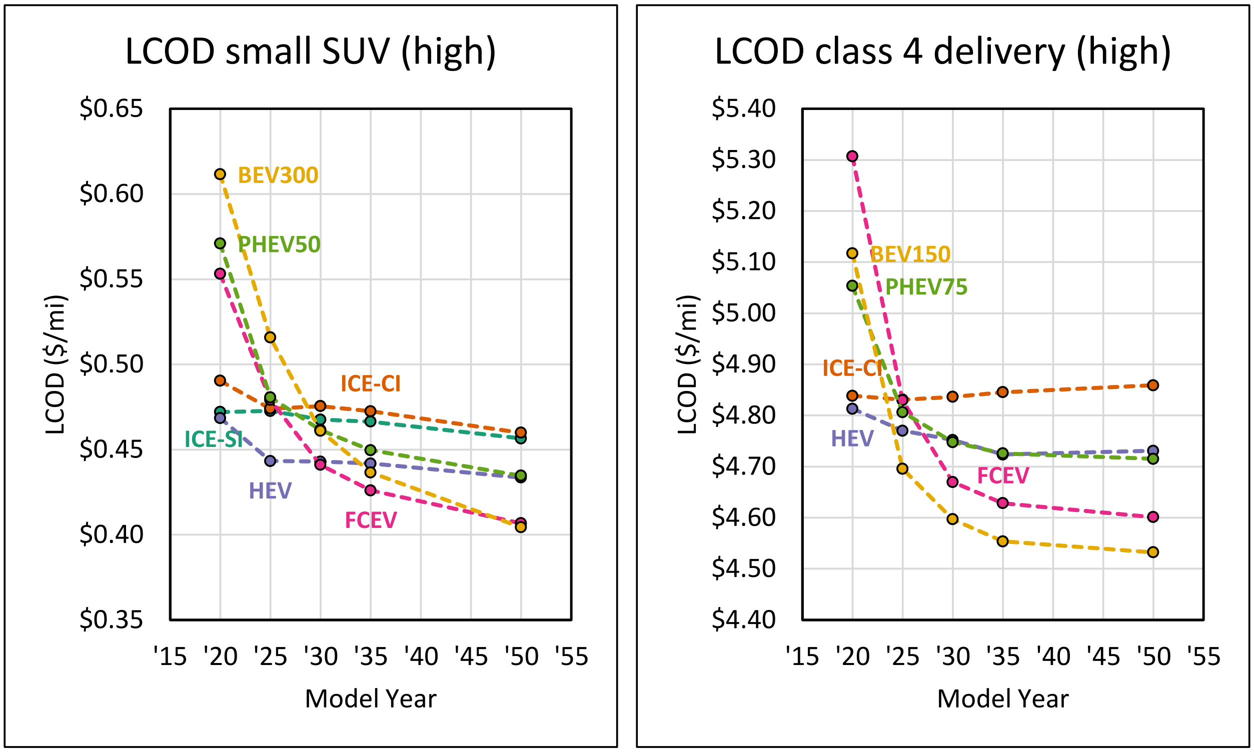


FIGURE 4.7 LCOD for small SUV and class 8 sleeper cab from MY2020 to MY2050, modeled using the Autonomie high technology progress case

Figure 4.8 shows the same curves as Figure 4.7, except for the class 8 sleeper cab and day cab tractors. For the class 8 sleeper cab tractor, the HEV and ICEV begin as the lowest cost powertrains, and the BEV500 reduces in cost from the most expensive to the least expensive by 2035. As shown in the cost breakdown in Appendix B, the rapid drop in costs for the BEV is caused both by reduction in vehicle costs (related to the cost of the battery) and reduction in payload-related operational costs (related to the energy density of the battery). Due to the high cost of hydrogen, the FCEV never reaches cost parity in this modeling. Cost modeling for the class 8 day cab shows the same trends as the sleeper cab, except that the BEV becomes the cheapest option before 2030.

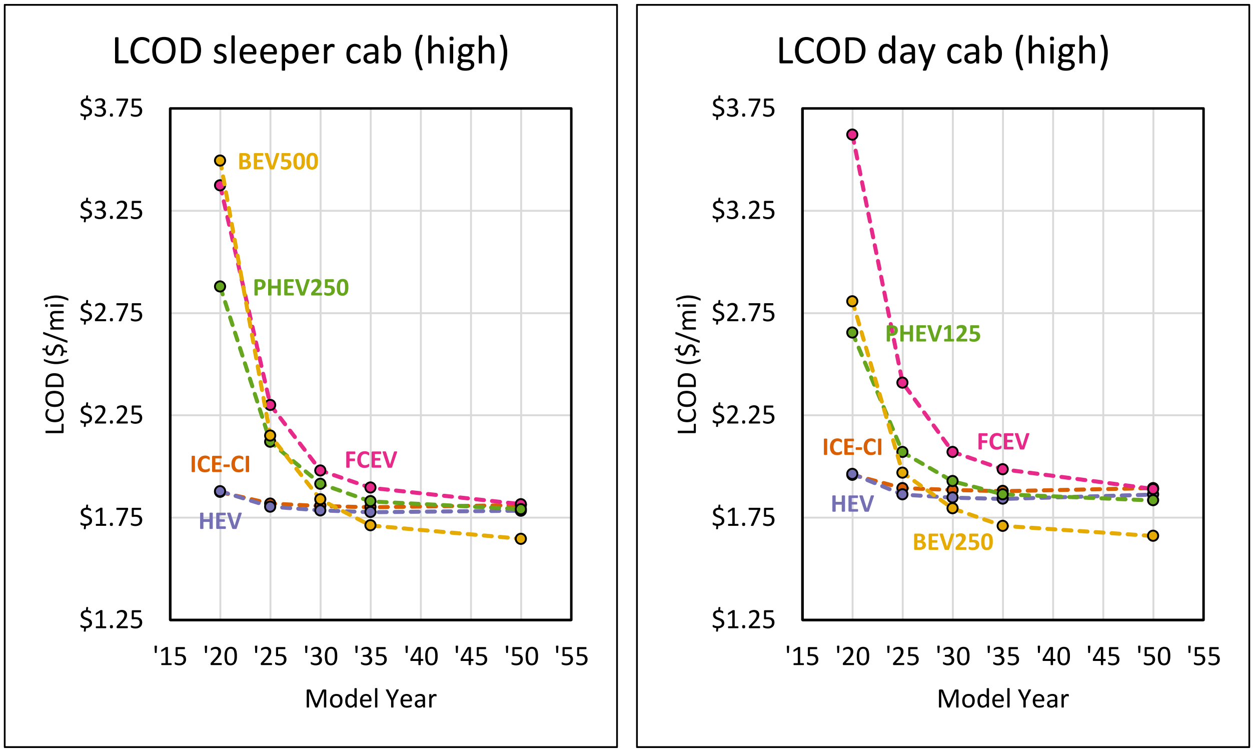


FIGURE 4.8 LCOD for class 8 sleeper cab and class 8 day cab from MY2020 to MY2050, modeled using the Autonomie high technology progress case

4.2.2. Current Vehicles

While most of the analysis presented here relies on Autonomie simulations, we can also consider vehicles that have been sold recently. Using real-world vehicles has the advantage of being naturally aligned with a true TCO that a consumer could pay today, though has the disadvantage in conflating characteristics of vehicles with differences across powertrains. Figure 4.9 shows LCOD calculations for a sales-weighted average LDV that were sold in 2019, as discussed in Section 3.2.3. HEV are the cheapest cost alternative, followed by BEV300, based on the actual MSRP of these vehicles. We do not consider the $7500 tax credit for PEVs, as this is not uniform across all electric vehicles, though a $7500 incentive would be sufficient for the BEV300 to have lower LCOD than the HEV.

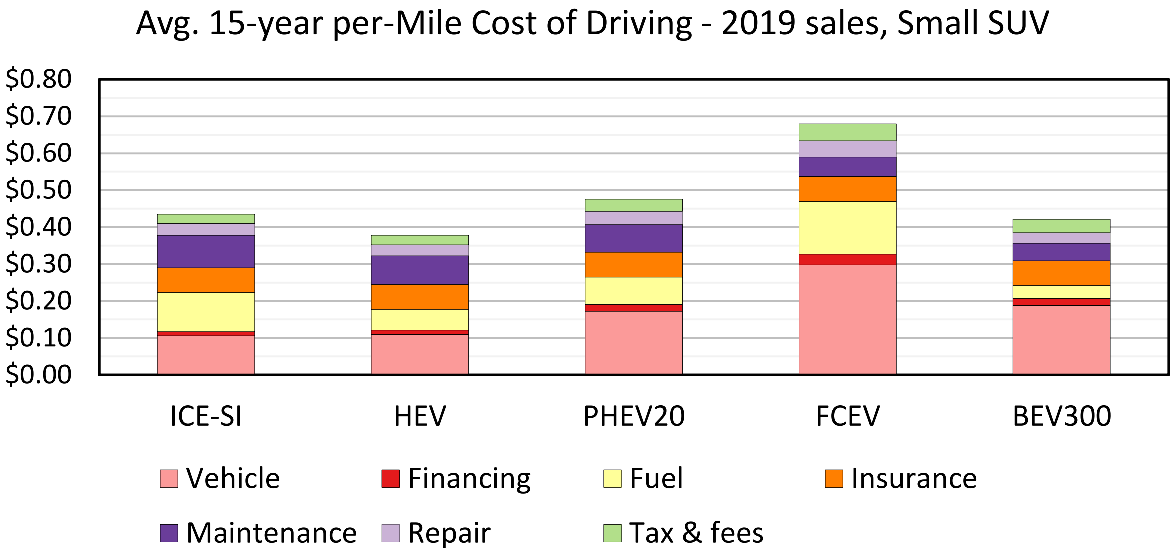


FIGURE 4.9 Average cost of driving across powertrain, small SUV sold in 2019

4.2.3. Vehicle Ownership Period

Most of the analysis presented in Section 4.1 uses a 15-year analysis window for LDV and a 10-year analysis window for MHDV. While this corresponds to typical use over the lifetime of the vehicle, we can also consider a first-owner analysis. For a passenger vehicle, this is approximately 5 years, while 3 years is a common period of ownership for a heavy duty truck. Figure 4.10 shows comparison of TCO across powertrains for a small SUV and for a day cab tractor trailer with a reduced analysis window. These can be directly compared with Figures 4.1 and 4.4. While the AFVs are more expensive upfront, they also maintain a larger residual value, and so there is little substantive difference in the rank ordering of technologies. HEV maintain their position as the cheapest LDV choice, while ICEV are marginally cheaper than HEV for the sleeper cabs, implying a technology payback period of 3 years.

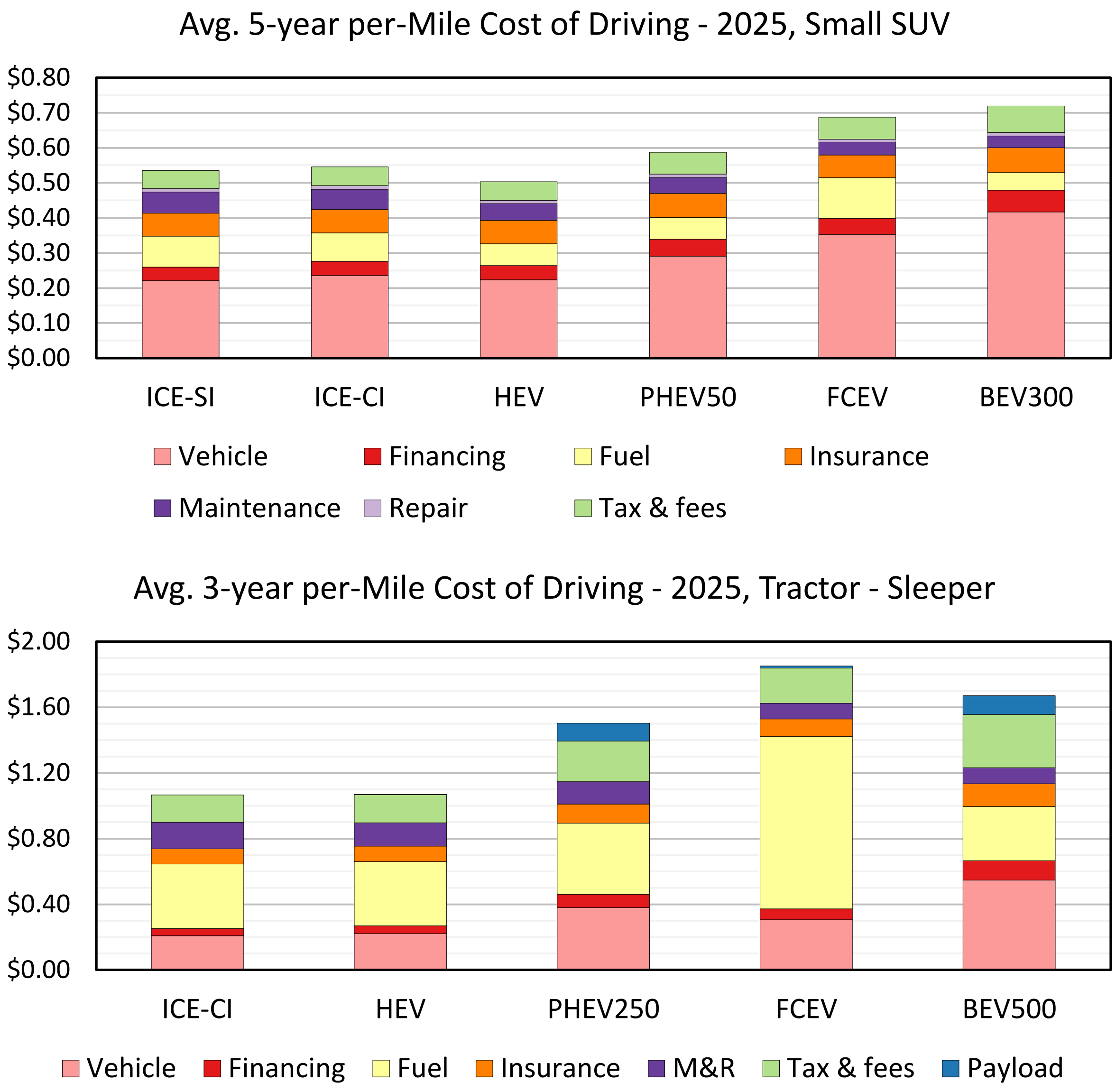


FIGURE 4.10 Short-ownership LCOD analysis for small SUVs and class 8 sleeper cab tractors in MY2025

4.2.4. Component Replacement

As a side case in this analysis, we consider replacement of major powertrain components during the vehicle's life. As discussed in Section 2.3.2, replacement of major vehicle components will change the residual value of the vehicle. To minimize the impacts of vehicle refurbishment on residual value, we assume the replacements to happen halfway through the vehicle life. For the SUV presented here that is at 100,700 miles. That is relatively early for estimated failure for any of these components and so this can be seen as an upper bound of major vehicle repair costs, and not viewed as representative of all vehicles. Data from the Production Engine Remanufacturers Association and from the Automotive Engine Rebuilders Association each estimate on the order of 2 million engines being remanufactured per year, or less than 20% over the vehicle lifetime, and largely focused on high-power applications (PERA 2021; Kaufman 2015). The replacement of high-voltage batteries in the HEV, BEV, and PHEV are just outside typical warranty periods, making this an unlikely out-of-pocket replacement for the vehicle owner.

For internal combustion engine vehicles we consider replacement of the combustion engine; for HEV we consider replacement of the high-voltage battery and the integrated starter generator; for BEV and PHEV we consider replacement of the high-voltage battery; for FCEV we consider replacement of the fuel cell stack. These costs come from Autonomie modeling, with a 50% retail markup over the manufacturing costs, as described in Section 3.2. Given the forecasted reduction in prices of the core components for AFVs, this may be an overestimate of costs for the parts but we do neglect labor costs, so these two simplifying assumptions should somewhat offset each other. Figure 4.11 shows the costs per mile amortized over the lifetime of the vehicle for each of these six powertrains. Rather than comparing across powertrains it may be more informative to compare with Figure 4.1; the sum values from the base case are included as diamond overlays. We see that the lifetime per-mile cost of the gasoline ICEV increases by 1.6 cent/mile, 2.0 cent/mile for the diesel ICEV, 1.5 cent/mile for the HEV, 2.8 cent/mile for the PHEV, 3.4 cent/mile for the FCEV, and 11.8 cent/mile for the BEV300.

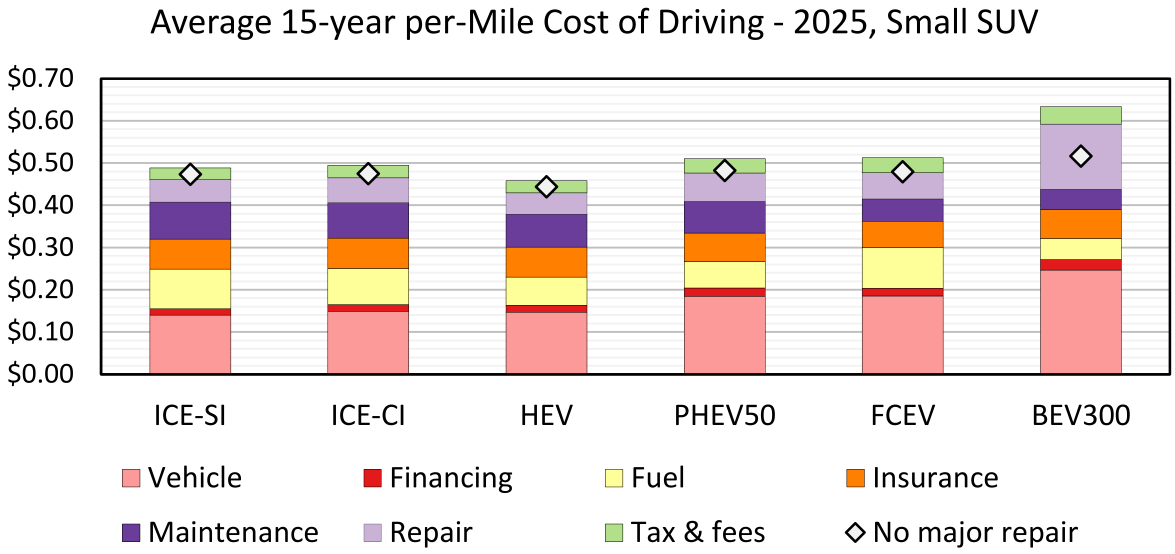


FIGURE 4.11 Change in LCOD from major powertrain repair or replacement for small SUVs in MY2025

4.2.5. Taxi Cabs

Taxi cabs and rideshare vehicles, such as Uber and Lyft, represent an interesting use case for LDV, as they are typically driven with much higher intensity than personally owned vehicles. In this side analysis, we consider small SUVs used as taxicabs. We add $150/year in ridehailing insurance, though dedicated taxicabs may have different commercial insurance policies. We estimate VMT using information from the New York Taxicab and Limousine Commission on the age of vehicles and their mileage (NYC 2014; NYC 2020). Unlike the light-duty passenger vehicles, the mileage schedules that were generated inherently include removal of these vehicles from the taxi fleet. This survivability factor represents typical fleet use; while a ten-year old taxi may still drive 50,000 miles per year, very few vehicles are still used as taxis at that age, and no 15-year old taxis are still in service in New York. For an analysis looking at this vehicle in use as a taxi, it is not necessary to consider how the vehicle may be used after being a taxi, other than to account for any residual value that the vehicle has when it is sold, which we assume to be $0 in this analysis due to the high VMT. Due to lack of data availability and the fact that the taxicab is already a side analysis, no further variations in this mileage schedule were considered. Figure 4.12 shows a comparison across powertrains; we see that AFVs are cost-effective choices for taxicabs, due to their lower operating cost and intensive driving patterns. The cheapest choice is the HEV, followed by the PHEV. As shown in Table B.12, the modeled BEV200 has an even lower cost, aligning with results from the University of California, Berkeley (Bauer et al. 2018), though with assumed vehicle mileage schedule exceeding 200 miles per day, low-cost public charging would be required. Relative to personally owned vehicles (Figure 4.1), M&R and insurance costs are increased, while the cost of the vehicle itself is reduced in importance.

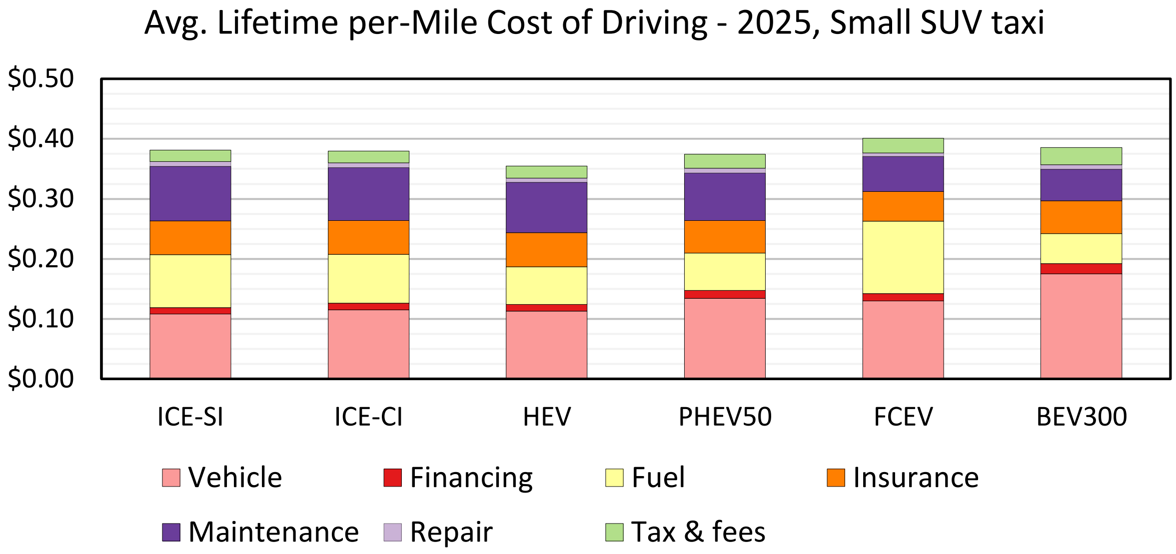


FIGURE 4.12 LCOD comparison across powertrains for MY2025 small SUV taxi

4.2.6. Labor Costs while Fueling

Charging of MHDV electric vehicles can add an additional labor cost which is not incurred by ICEV. As described in Section 3.7.3.1, current HOS rules say that fueling counts as working, so time for charging would reduce available time in a day for driving. At a reasonable charging rate of 50 kW, equivalent to typical LDV fast charging today, the driver would spend more time charging than driving, causing labor costs to become the dominant vehicle expense. 400 kW represents the charging rate analyzed as extremely fast charging for LDV by Burnham et al. (2017). Beyond this rate would require dedicated high-power charging for MHDV. Figure 4.13 shows the TCO for class 8 sleeper cab tractor trailers for ICEV and BEV at several different charging profiles, accounting for this additional cost. For each of these electricity rates, the same price of approximately $0.12/kWh is used, though it is possible that infrastructure for high-power charging will increase the cost of delivered electricity. The extra costs are clearly much higher than any other cost element at low power rates, but can be manageable at higher rates, showing that on-road charging of long-haul BEV will not be feasible without either increased charging power, some kind of depot-based charging independent of the presence of the vehicle driver, or federal policy changes allowing unmanned, overnight vehicle charging.

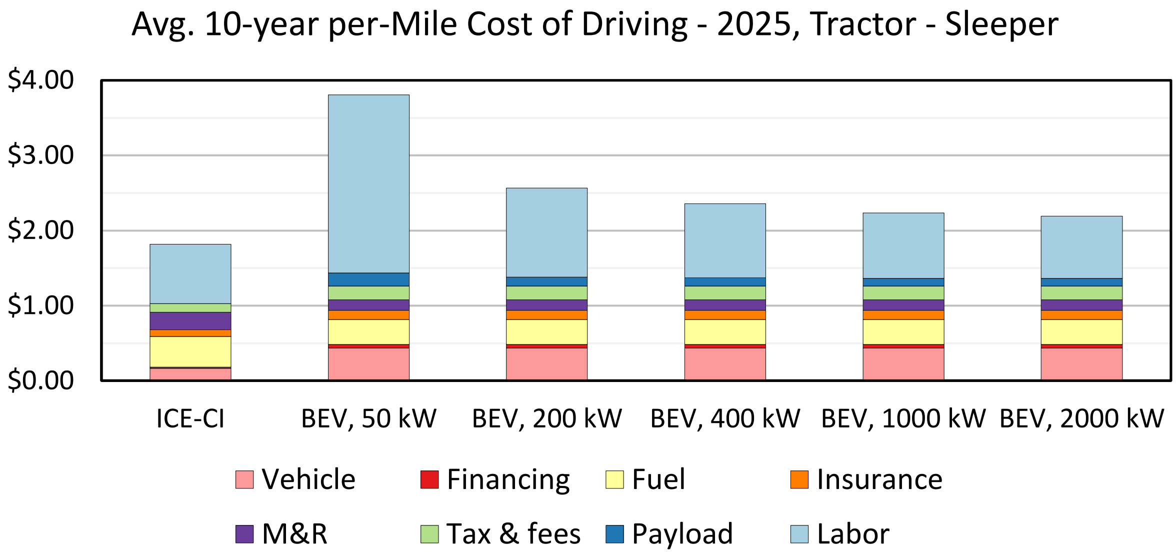


FIGURE 4.13 TCO for class 8 sleeper cab comparison of ICEV and different BEV charging rates in MY2025

4.3. SENSITIVITY ANALYSIS

The TCO results for the base case (Section 4.1) are based on the best available data for the many inputs on which the various cost elements depend, but many of these inputs are uncertain or vary widely between vehicles and drivers. We assessed the influence of uncertainty in many of these inputs on the TCO for a number of LDVs and MHDVs. In order to do so, we analyzed the ranges of TCO for conventional ICEV, HEV, and BEV by sequentially adjusting over 20 parameters. We plotted these results in tornado charts, so termed because the varied parameters are sorted by magnitude to identify the most impactful variables. One such chart is presented in Figure 4.14, showing the LCOD for the MY2025 small SUV BEV. The baseline case is 51.6 cents/mile, and each of the bars represents how the LCOD changes by changing a single parameter of the calculation.

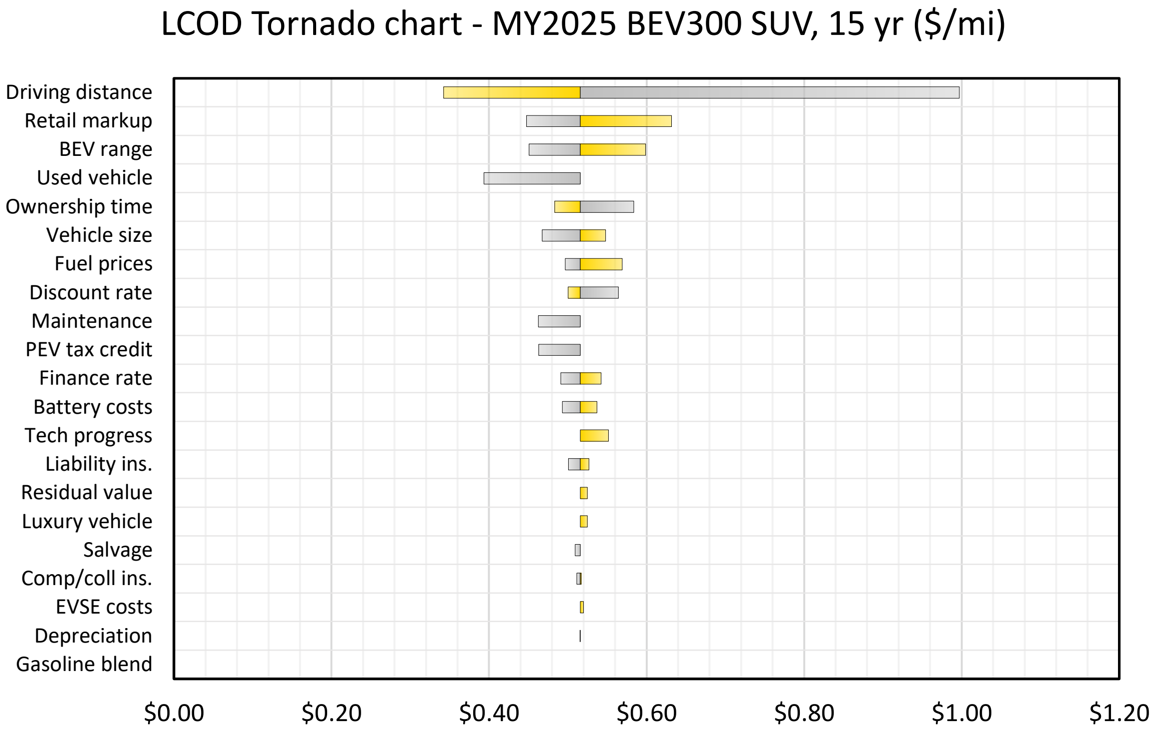


FIGURE 4.14 Tornado chart for LCOD of MY2025 small SUV BEV300

In this graphic, the gold bars represent changes that increase the total lifetime vehicle cost, while silver bars represent changes that decrease the total vehicle cost over the analysis window, with each starting from the baseline of 51.6 cents/mile. Note that the colors in Figure 4.14 are reversed for variations in driving distance, ownership time, and discount rate, showing that amortizing costs over a greater distance reduces per-mile costs.

In order to properly compare the impacts of multiple different variables, we aim to have comparable adjustments across all parameters. Where possible, we select values that are one standard deviation, σ, from the baseline case, or approximately the 15th and 85th percentiles. For other non-categorical variables, we selected values that represent a broad range of possible scenarios while generally avoiding outliers and unlikely extremal cases. Table 4.1 summarizes the basis of the choice of the low and high values used in assessing sensitivity for LDV.

TABLE 4.1 Input variables examined in LDV TCO sensitivity analysis

Variable	Low case	Baseline	High case	Basis
Driving distance	~5800 mi/yr	~13,400 mi/yr	~25,400 mi/yr	15/85 percentile VMT
Ownership time	10 yr	15 yr	20 yr	±1σ of vehicle scrappage
Used vehicle	5 yr old	New		Default loan term for first owner
Vehicle size	Midsize sedan	Small SUV	Medium SUV	Adjacent size classes modeled
Luxury vehicle		Small SUV	Luxury Small SUV	Autonomie modeling performance variant
BEV range	200 mi	300 mi	400 mi	Next-largest / smallest battery sizes modeled
Tech progress		High tech	Low tech	Autonomie modeling cases
Retail markup	1.2x	1.5x	2x	Values from Kelly (2020)
Battery costs	\$150/kWh	\$170/kWh	\$190/kWh	Interpolated Autonomie 2023/2027 costs
PEV tax credit	\$7500	\$0		Currently available credit
Discount rate	5%	1.20%	0%	Typical discount rate cases
Finance rate	0%	4%	8%	0% APR loans common; 8% avg. prime & subprime
Depreciation	15% confidence interval	Eq. 3.6	85% confidence interval	15/85 percentile
Residual value		Eq. 3.6	Total (100%) depreciation	No-resale scenario
Salvage	Vehicle or Battery	Vehicle only	None	Possible scenarios, see Section 3.2.1.2
Fuel prices	~\$2.10/gal, ~8 cent/kWh	~\$2.88/gal, ~12.9c/kWh	~\$4.33/gal, ~27 cent/kWh	AEO low/high oil cases; Borlaug low/high electric
Gasoline blend		Regular gasoline	Premium gasoline	Possible ICEV fuels
EVSE costs		\$0	\$800	Typical cost
Liability insurance	\$400/yr	\$600/yr	\$750/yr	15/85 percentile
Comp/coll. insurance	5%	10%	15%	Reasonable scenarios
Maintenance	Harto 2020a	Scheduled		Alternative M&R calculation

Development of the bounds in Table 4.1 is discussed in more detail in the subsections describing the data and analysis of these cost components. While only one variable was changed at a time, in practice, these ranges can be combined to generate a more complex scenario, so far as the variables in question are independent from each other (as per Table 2.4). Note that the LCOD calculation is not affected by all potential variables: for example, a change in gasoline prices does not impact the cost of an electric-fueled BEV.

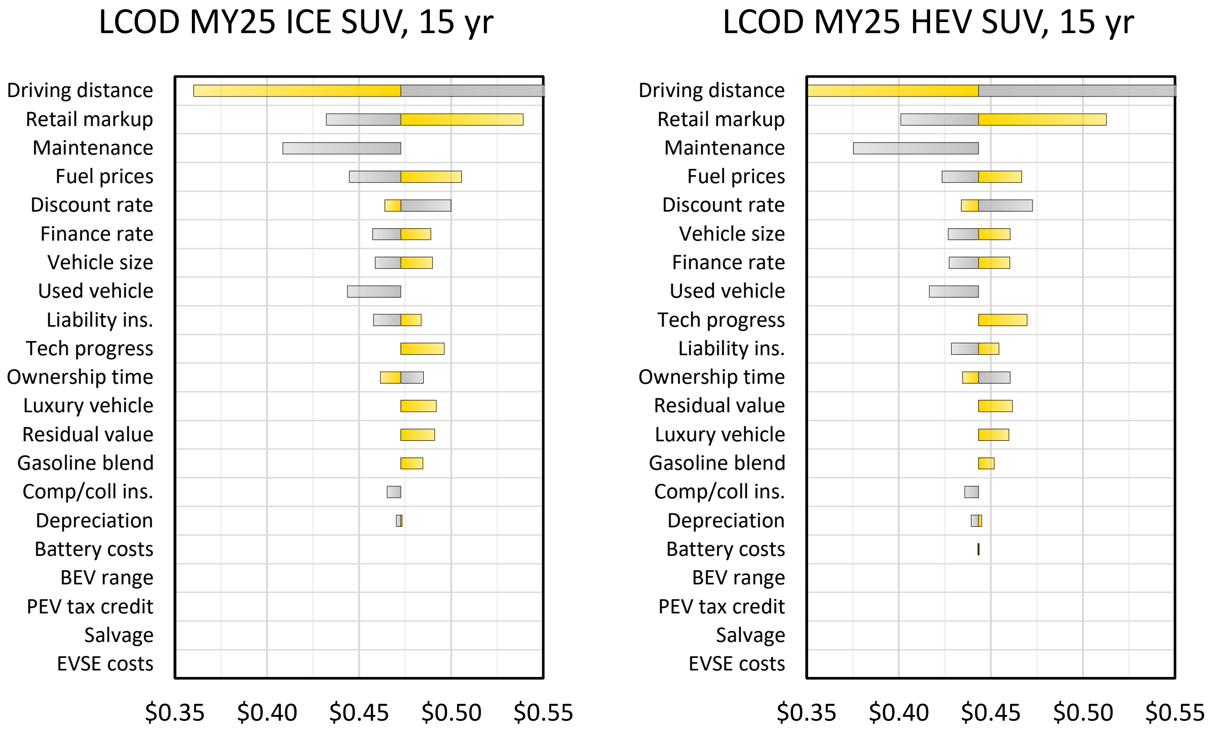


FIGURE 4.15 Tornado chart for LCOD of MY2025 small SUV ICEV and HEV

Figure 4.15 shows tornado charts for the MY2025 ICEV and HEV small SUVs. Note that the order of the specific input parameters is not the same across Figures 4.14 and 4.15. This shows that particular parameters may be more/less relevant when considering alternative powertrains. Like the BEV tornado chart, the largest cost uncertainty by far comes from variations in typical driving distances (truncated on Figure 4.15 for space). The TCO of the 85th percentile VMT MY2025 ICEV was approximately twice that of the 15th percentile VMT (VMT varied by a factor of four over the 15-year ownership period), as was the LCOD, or per-mile TCO. The sensitivity of TCO to VMT over 15 years was slightly lower for the BEV small SUV, due to the lower fuel cost and higher purchase price. The cumulative TCO of the BEV increased by about 50% when VMT increased by a little over a factor of four. For the same VMT increase, the TCO *per mile* of the BEV *decreased* by a factor of three, due to the greater amortization of the vehicle. For each vehicle, the next most impactful factor in cost uncertainty is the amount of retail markup. The TCO per mile is sensitive to the assumed value of the RPE factor (ratio of purchase price to manufacturing cost) as the vehicle purchase price is a large component of TCO.

Because of the higher MSRP of the BEV, it is more sensitive to cost parameters that are directly related to vehicle depreciation early in the vehicle life, such as the length of vehicle ownership and purchasing a vehicle used rather than new. To consider TCO of used vehicles, we model a used vehicle here by setting the ownership period to 5–15 years (5-year-old vehicle is purchased and owned for 10 years). The TCO of used vehicles is notably lower than that of new vehicles, and the difference is higher for BEVs than for ICEVs or HEVs, owing to the higher depreciation of BEVs in the first five years. The TCO per mile for the used BEV300 is lower than that of the used ICEV and the used HEV. Likewise, since operational costs such as fuel, insurance, and maintenance are a larger portion of the TCO for ICEV, variations in these operating costs are more impactful for the ICEV. Additionally, financing, comprehensive insurance, repair costs, and taxes are assumed to scale with purchase price, and this increases the dependence of TCO on the RPE factor. LCOD for all three powertrains is reduced by considering the maintenance costs published by Consumer Reports (Harto 2020a), though the difference is similar across powertrains.

We found TCO to be largely insensitive to parameters which focus on late in the vehicle lifetime. This can be seen by looking at the asymmetry in the 'Ownership time' bars, where the reduction in costs from extending the vehicle lifetime are smaller than the additional per-mile costs from shortening the lifetime. Likewise, variations in vehicle and battery salvage and alternative considerations for C&C insurance are less impactful parameters.

In Appendix C, tornado charts are shown with different baseline scenarios, namely having a baseline ownership period of only five years (similar to a first-owner analysis), and considering a vehicle purchased at five years old (i.e., a second-owner analysis). These side cases were selected for further examination because they both change the baseline vehicle ownership parameters (from Table 2.4); as nearly all other cost parameters depend on these factors, these are among the least 'additive' parameters. An additional side case presents analysis for vehicles representative of those sold in 2019, adjusting the vehicle cost and fuel economy to match the sales-weighted average.

Table 4.2 shows the key input parameters examined in the analysis of MHDV. This section considers class 8 sleeper cab tractors, class 8 day cab tractors, and class 4 delivery trucks, with additional cases considered in Appendix C as well. Note that several cost elements can be considered or not considered in a typical fleet-oriented TCO calculation; these parameters (such as idling costs, labor costs, and payload capacity) are explicitly removed from the calculation in the side cases. Additionally, several of these costs are only relevant to the sleeper cab, and are removed from the calculation for other vehicles. For M&R and insurance, the range of ±10% represents the historical annual variation in average costs for this component since 2008 (Murray and Glidewell 2019).

TABLE 4.2 Input variables examined in MHDV TCO sensitivity analysis

Variable	Low case	Baseline	High case	Basis
Driving distance	~7k mi/yr MDV delivery; ~20k mi/yr day cab; ~49k mi/yr, sleeper cab	~16k mi/yr MDV delivery; ~57k mi/yr day cab; ~87k mi/yr, sleeper cab	~32k mi/yr MDV delivery; ~94k mi/yr day cab; ~120k mi/yr, sleeper cab	15/85 percentile VMT
Ownership time	5 yr	10 yr	15 yr	±1σ of vehicle scrappage
Used vehicle	5 yr old	New		Default loan term for first owner
Tech progress		High tech	Low tech	Autonomie modeling cases
Retail markup	1.2x	1.5x	1.875x	Reasonable values from Kelly 2020
Battery costs	\$130/kWh	\$150/kWh	\$170/kWh	Interpolated Autonomie 2023/2027 costs
Discount rate	5%	3%	0%	Typical discount rate cases
Finance rate	0%	4%	8%	Same as LDV
Residual value		Eq. 3.6	Total (100%) depreciation	No-resale scenario
Fuel prices	~\$2.40/gal, ~10.2 cent/kWh	~\$3.37/gal, ~12.4c/kWh	~\$4.96/gal ~34 cent/kWh	AEO low/high oil cases; Borlaug low/high electric
EVSE costs		\$0	\$4000 MDV; \$50k day cab; \$120k sleeper	Typical cost, see Section 0
Insurance	-10%	0%	10%	±1σ across last decade
Fixed insurance		Insurance proportional to residual value	Constant insurance by year	Reasonable scenarios
M&R by powertrain	xEV much lower than ICEV	xEV modestly lower than ICEV	xEV equal ICEV	Reasonable values, derived from Blynn 2018
M&R variance	-10%	0%	10%	±1σ across last decade
Idling costs	Exclude costs	APU	No APU	Alternate scenarios
Payload capacity	Don’t include	Include		Alternate scenarios
Weight exemption	2 tons	1 ton	None	Reasonable values
Drive to charger		+0%	+3% for BEV	Ten-minute detour to fuel
Labor costs		Don’t include	Include	Alternate scenarios
Charging labor		Don’t include	include	Alternate scenarios

Figures 4.16, 4.17, and 4.18 show tornado charts for costs for the class 8 sleeper cab tractor. Including labor costs or not is the single biggest impact on expenses (not shown), though this choice impacts all powertrains nearly equally. Additionally, driving distance is a major factor in estimating the cost for each of the powertrains, as is the factor for vehicle cost markup. For the BEV and HEV, the assumption that electrified powertrains have lower maintenance costs than conventional powertrains is one of the largest cost factors. For most cases, we find the HEV to be slightly cheaper than the ICEV for the class 8 sleeper cab tractor, but that is not true if maintenance is ignored.

For the ICEV and HEV, fuel is a major cost component for the class 8 sleeper cab, and so uncertainty in fuel prices can result in different analytical results. For the BEV, high-price electricity or middling progress on cost reductions for batteries are major potential threats for lowering costs, with worst-case scenario costs nearly as large as labor costs for the driver. Ownership expenses for the BEV gradually decrease over time, as the vehicle depreciation is much larger than for the ICEV or HEV. For the ICEV and HEV, however, costs increase over time. This means that the powertrains exhibit different characteristics as a function of vehicle age, where a used BEV tractor trailer is more cost-effective than new, but a new ICEV is more cost effective than an old one. The cost of EVSE for the BEV truck ($120,000 assumed for electric sleeper cabs) increases the TCO per mile by $0.16/mi. This may be an overestimate if the costs of the charging facility can be amortized over multiple vehicles. Appendix C presents a comparative analysis between the three powertrains for an initial ownership period of 3 years.

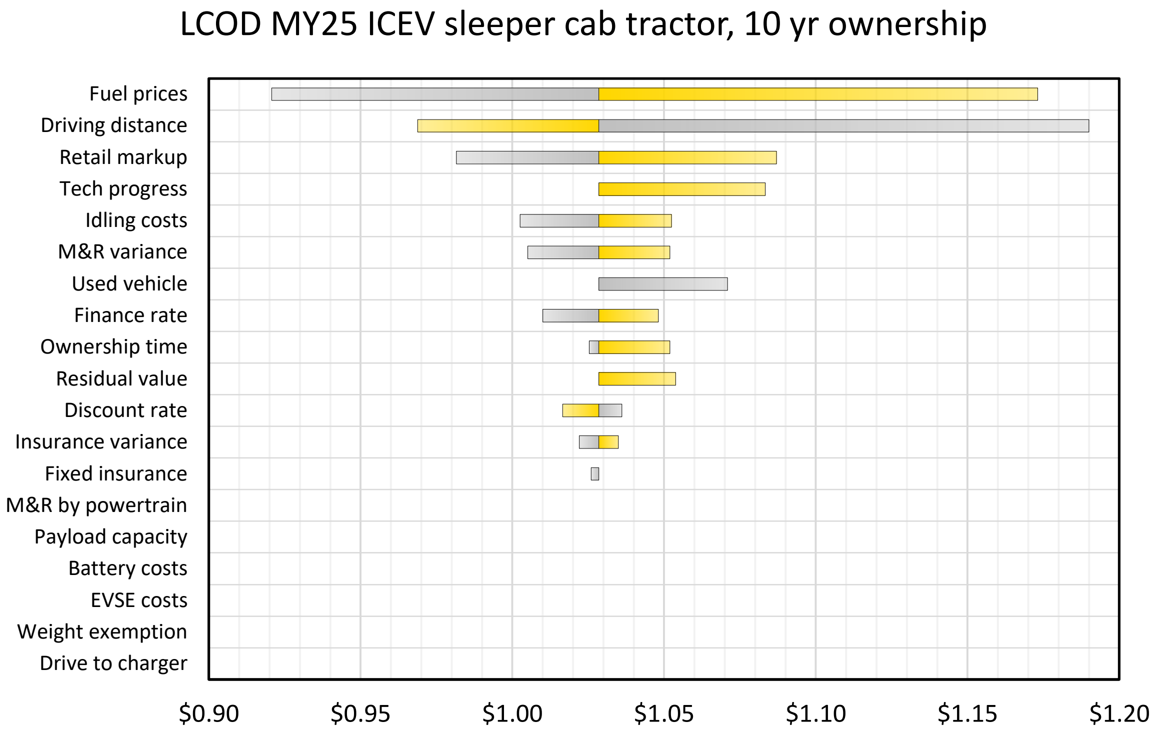


FIGURE 4.16 Tornado chart for LCOD of MY2025 sleeper cab ICEV, 10 year analysis window

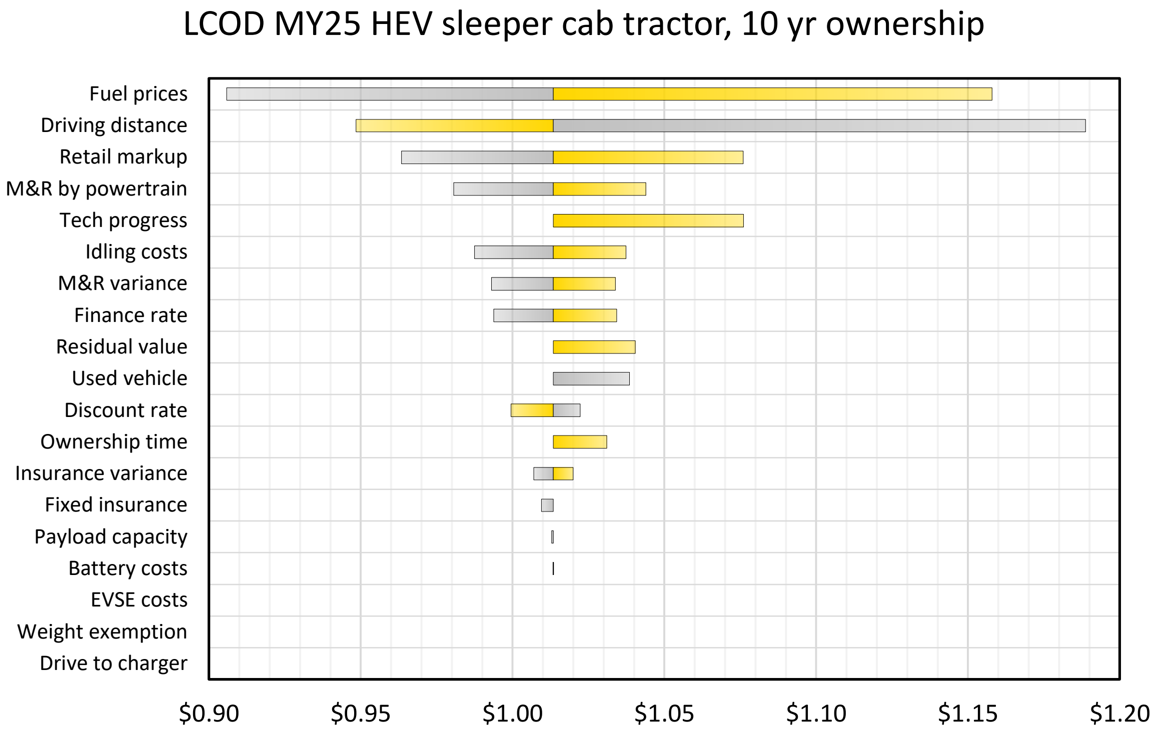


FIGURE 4.17 **Tornado chart for LCOD of MY2025 sleeper cab HEV, 10 year analysis window**

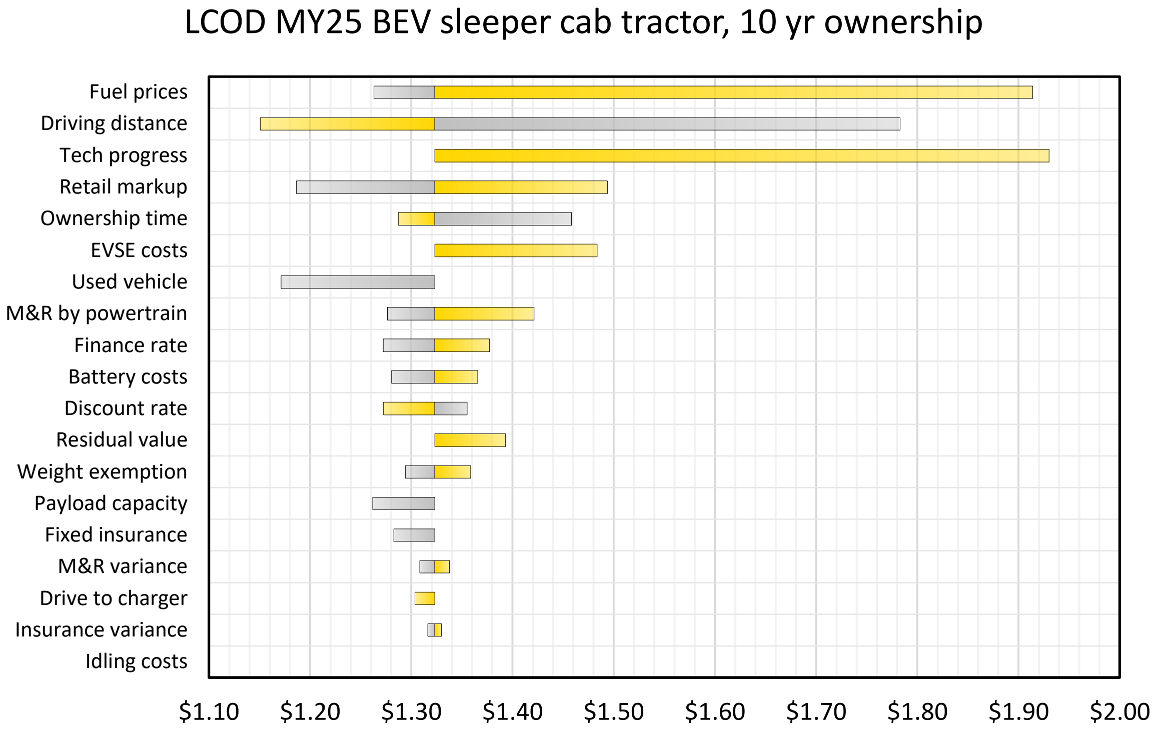


FIGURE 4.18 **Tornado chart for LCOD of MY2025 sleeper cab BEV, 10 year analysis window**

Figures 4.19, 4.20, and 4.21 show tornado charts for costs for the class 8 day cab tractor for ICEV, HEV, and BEV. For the BEV, the factor with the largest potential spread in TCO is the driving distance, with an even larger spread than the cost of labor, included on these graphics for comparison. This underscores the desire for fleet managers to keep their vehicles on the road as much as possible, while showing the breadth of driving applications for medium- and heavy-duty vehicles. Fuel prices are important for all vehicles, while continued research and development will help bring operating costs down as well. The BEV is the vehicle most impacted by variations in driving distance; a battery electric vehicle traveling about 65% more than average (one standard deviation above the mean) is cheaper than an HEV or ICEV. At 260 miles per day, this vehicle is on the cusp on being range-limited for a typical day's trip, but optimized trip management can make this a feasible, cost-effective choice for a fleet.

Used vehicles exhibit interesting behavior for these day cab tractors. Much like the sleeper cab tractors, vehicle costs gradually increase with age for ICEV due to maintenance and repair costs. This has the effect of making a used BEV cost competitive with the lowest-price HEV, rather than being the most expensive as is true for the remaining sensitivities. Appendix C presents a comparative analysis between the three powertrains for an initial ownership period of 3 years.

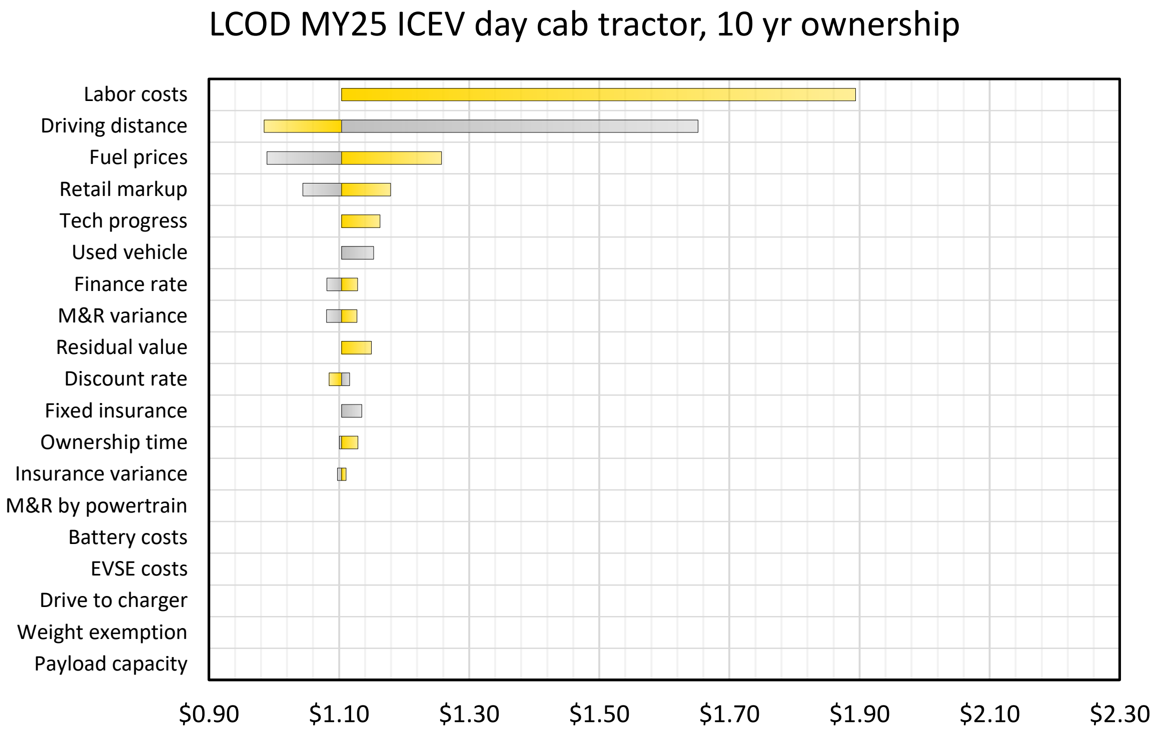


FIGURE 4.19 Tornado chart for LCOD of MY2025 class 8 day cab ICEV, 10 year analysis window

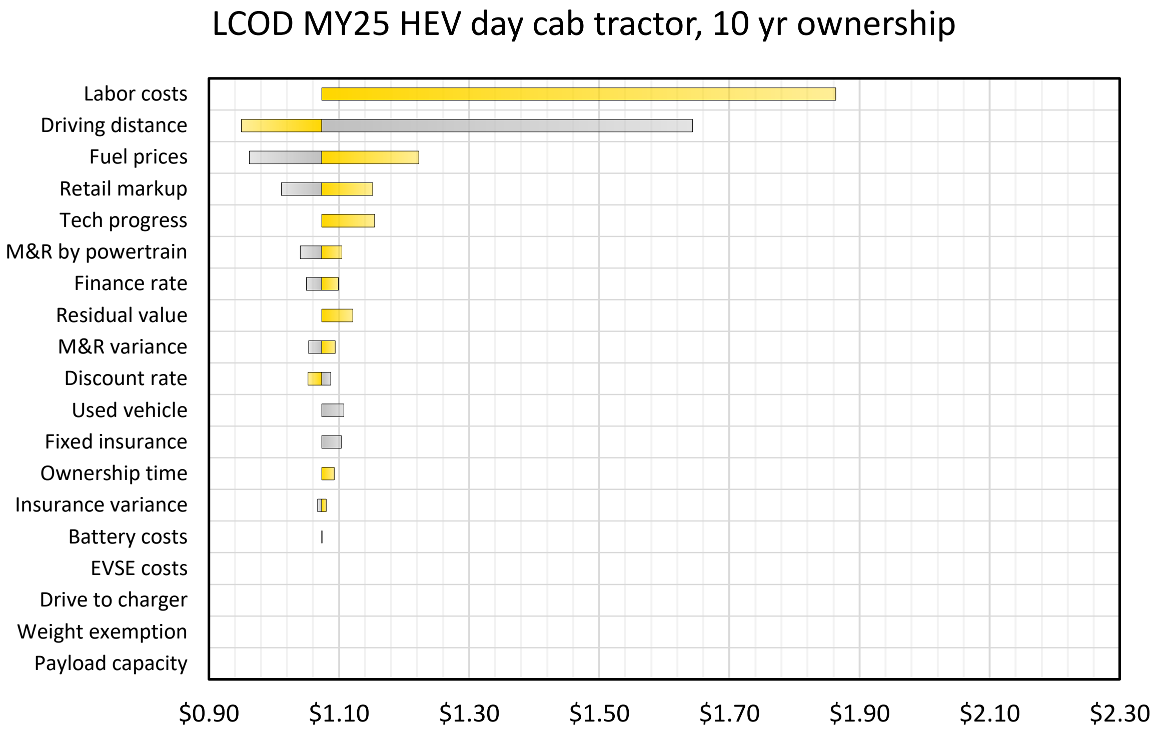


FIGURE 4.20 Tornado chart for LCOD of MY2025 class 8 day cab HEV, 10 year analysis window

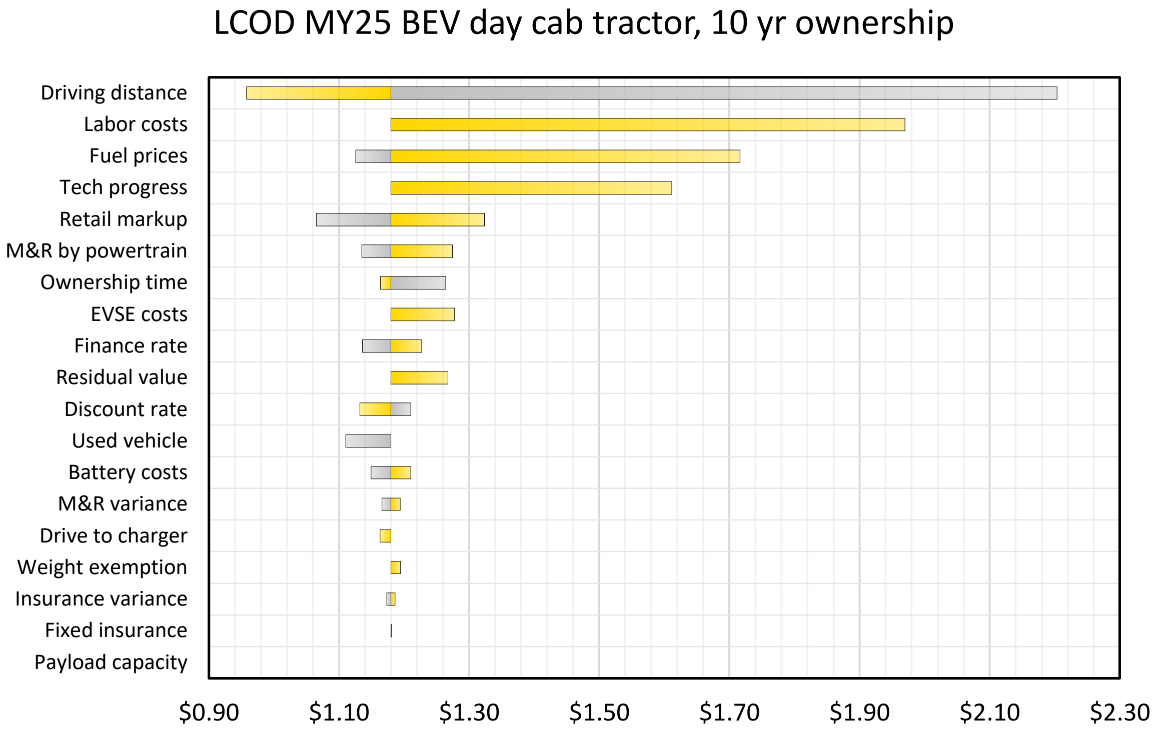


FIGURE 4.21 Tornado chart for LCOD of MY2025 class 8 day cab BEV, 10 year analysis window

Figures 4.22, 4.23, and 4.24 show tornado charts for costs for the class 4 delivery truck. In nearly all cases, the BEV is the cheapest vehicle powertrain. If differences in M&R costs across powertrains are not considered, then the HEV is slightly less expensive than the BEV, but both are still cheaper than the ICEV. Similarly, if the cost of electricity is very high, then the BEV may not be the most cost-effective option. For each of these powertrains, it is more expensive to own and operate a used vehicle than a new one. Even if the BEV RPE factor is 25% higher than the ICEV, the BEV still has a lower cost of operation over 10 years. All of this is predicated on continued improvement in BEV energy efficiency and reduction of battery costs, as the low-technology-progress case (effectively $170/kWh for the battery) finds the BEV to be the most expensive vehicle.

Because AFVs are most cost-competitive within the class 4 delivery truck segment, Appendix C presents a side case where the class 4 delivery trucks are owned for only 3 years to see if AFVs have a sufficiently low breakeven time to be considered by fleet managers. This analysis shows that in the baseline case, that BEV still manage to be the lowest cost powertrain, even at under 3 years before resale of the vehicle.

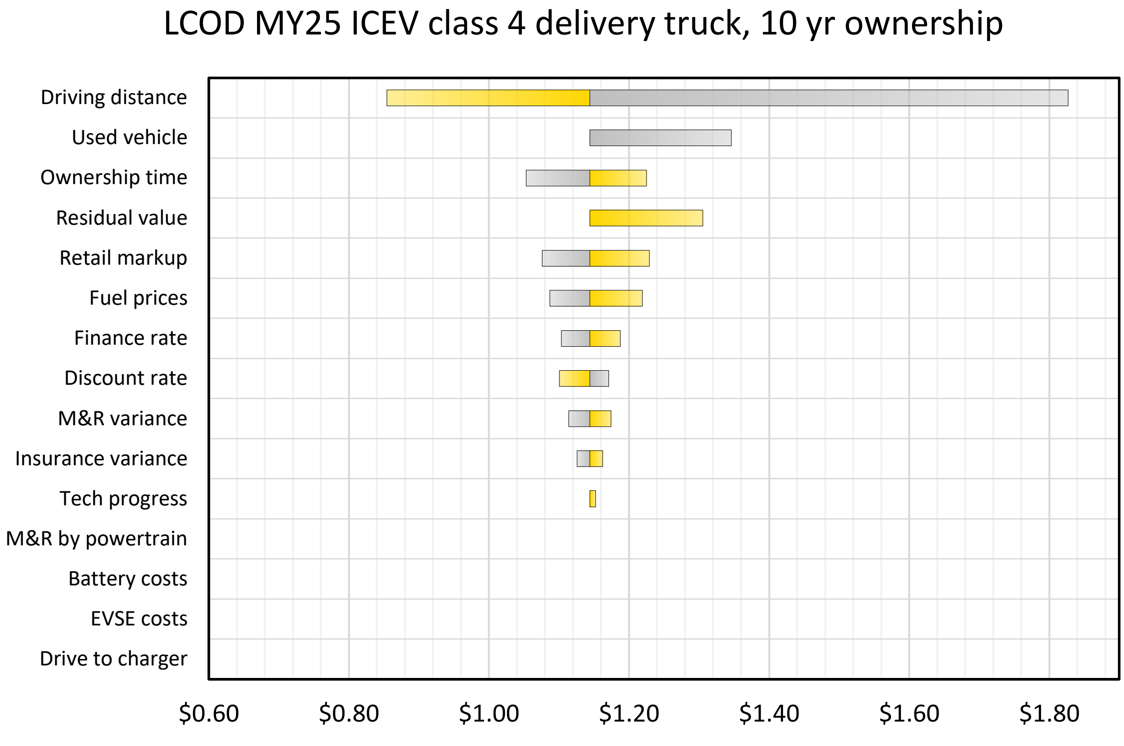


FIGURE 4.22 Tornado chart for LCOD of MY2025 class 4 delivery ICEV, 10 year analysis window

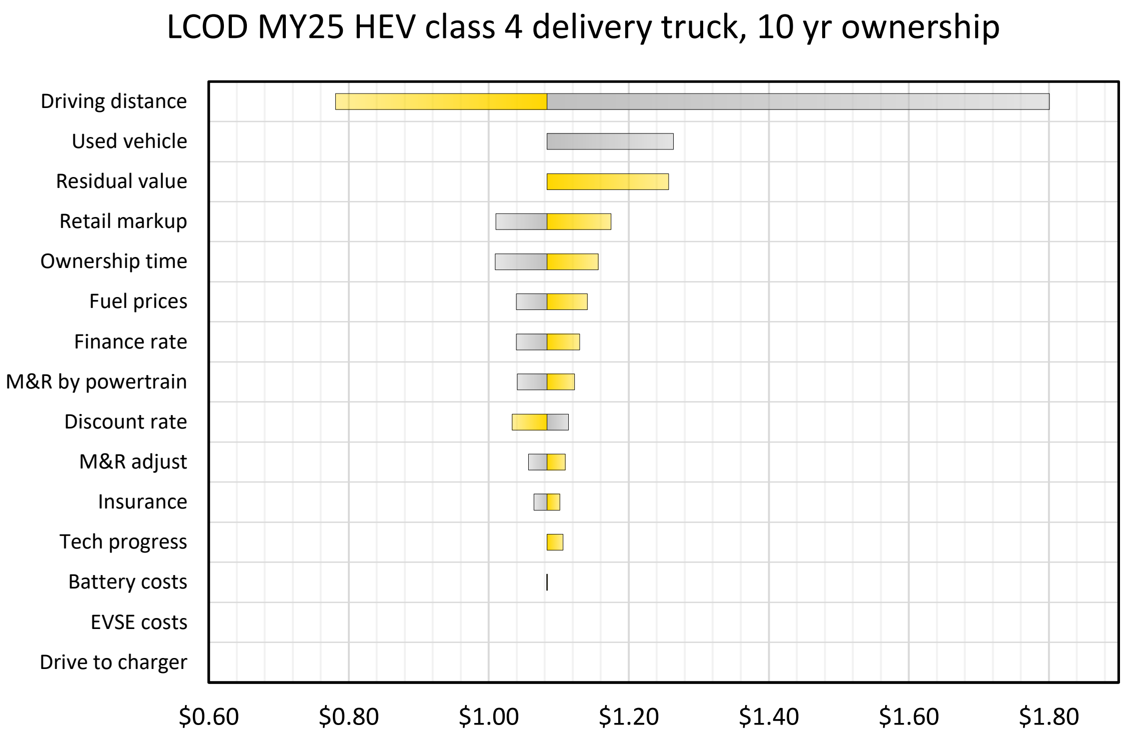


FIGURE 4.23 Tornado chart for LCOD of MY2025 class 4 delivery HEV, 10 year analysis window

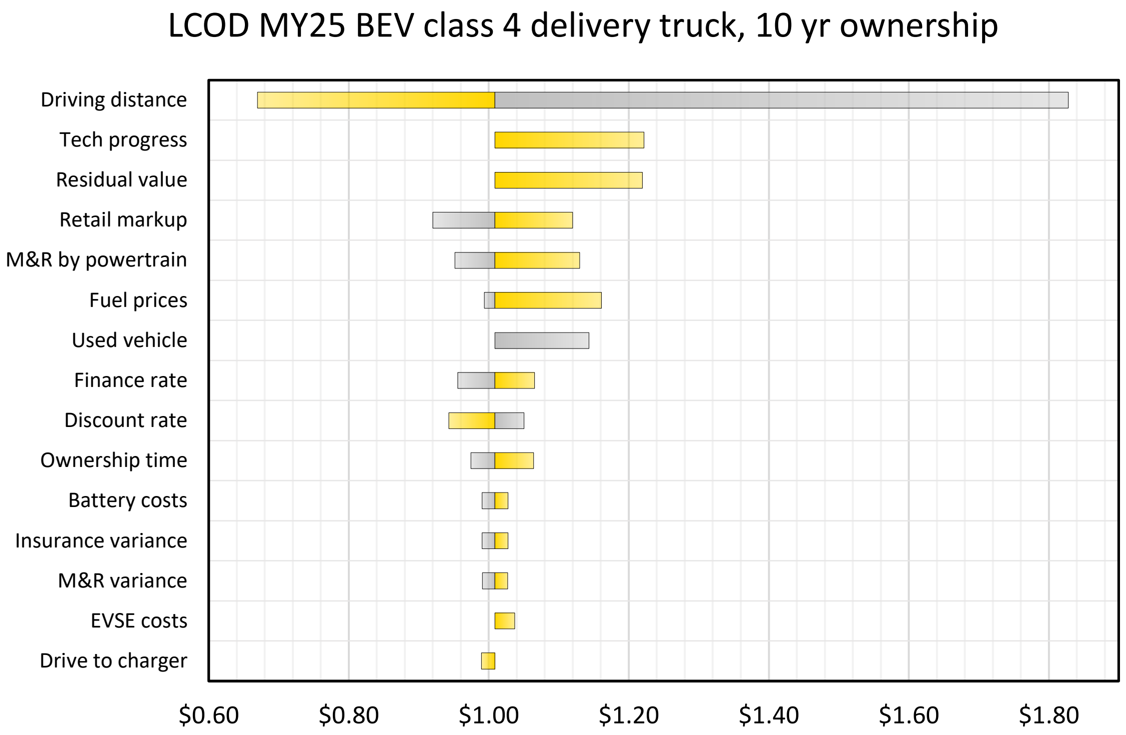


FIGURE 4.24 Tornado chart for LCOD of MY2025 class 4 delivery BEV, 10 year analysis window

5. DISCUSSION AND CONCLUSIONS

In this report, we have put forward a comprehensive, internally-consistent quantification of the total cost of ownership of light-duty, medium-duty, and heavy-duty vehicles. Prior to this study, there have been many reports and peer-reviewed articles published on the costs of vehicle operation and ownership. We present here what we believe to be the most comprehensive calculation for TCO for both LDV and MHDV, based on a thorough analysis of each of the cost elements which comprise TCO. A summary of the new analysis and our key findings from this research is presented below.

For LDV, our cost elements include the net vehicle cost (purchase less final sale), financing, fuel use, insurance, maintenance, repair, and taxes & fees. For MHDV, our cost elements include the net vehicle cost, financing, fuel use, insurance, maintenance & repair, taxes & fees, costs of operational changes, and labor. In this analysis, we find that insurance and M&R are particularly important factors which are often neglected in studies of vehicle technology. These terms can vary across powertrains, and their inclusion (or lack thereof) can change the rank order of technology LCOD.

We do find that TCO for AFVs is generally forecast to drop in the coming years. DOE invests in multiple sustainable technologies, and there are viable paths forward for each of them, though the segment in which they compete depends on operational details. In general HEV are modeled to be cost-competitive within five years, with FCEV and BEV shortly behind, depending on reductions in the price of hydrogen fuel and batteries.

Depreciation

- New analysis: Systematic analysis of depreciation by powertrain (LDVs), development of multi-variable HDV depreciation model.
- Key findings: Cars depreciate faster than light trucks. MY13-16 electric vehicles have a greater depreciation rate than newer PEVs.

Insurance

- New analysis: In-depth analysis of liability, comprehensive and collision insurance costs for LDVs by powertrain for selected size classes, development of simple MHDV insurance cost model from several sources for a range of vocations.
- Key findings: LDV insurance costs show comparable costs for different powertrains, lower costs for larger size classes. MHDV insurance costs vary significantly by vocation.

Maintenance and Repair (M&R)

- New analysis: Systematic analysis of LDV maintenance and repair costs: maintenance schedule for LDVs by powertrain for selected size classes, model for LDV repair costs by powertrain for selected size classes. Developed estimates for MHDV M&R costs.
- Key findings: Electric and electrified powertrains have lower maintenance and repair costs than ICE powertrains for all vehicle sizes, relative to vehicle price. MHDV M&R costs depend heavily on vocation and duty cycle.

Taxes, fees, parking, tolls, etc.

- New analysis: Development of consistent costs for both LDVs and MHDVs by size class and powertrain, covering a comprehensive range of relevant taxes and fee-related costs.
- Key findings: LDV taxes and fees are comparable across powertrain types and size classes; marginally higher registration fees for AFVs. MHDV costs depend on the vocation, weight rating, and state.

Costs unique to commercial vehicles

- New analysis: Models developed to estimate labor costs of BEV charging and heavy-duty payload capacity costs.
- Key findings: Many vehicles would be affected by additional battery weight, reducing the available payload capacity, and this cost can be substantial. BEV charging can be time-consuming; labor rates can cause this cost to dominate TCO. Auxiliary Power Units to minimize idling are cost effective ways to minimize fuel consumption.

Financial analysis

- New analysis: Examination of discount rates, inflation rates, and loan terms.
- Key findings: Real loan terms of 4% for 5.25 years are appropriate for analysis along with a 1.2% discount rate for households, 3% for businesses.

Because this analysis focuses on the ownership and operation costs of an individual vehicle, it is distinct from segmentation-type analyses which aim to identify market opportunities for specific technologies (e.g. Morrison et al. 2018; Hunter et al. 2021 forthcoming). Likewise, this analysis does not attempt to model market adoption to estimate future sales shares of different vehicle technologies, as these analyses depend on consumer behavior which is not completely tied to vehicle cost of ownership (e.g. Stephens et al. 2020; Brooker et al. 2021 forthcoming). That noted, the results from this output can be used to supplement those types of analyses, as this report includes rigorous and self-consistent analysis of many of the costs that comprise a TCO calculation. Furthermore, forecasting costs into the future is challenging. For AFV along with their energy infrastructure, variations in the rate of technical improvement can change which vehicles are most affordable and when. Combining vehicle-level cost modeling with technoeconomic analysis of fueling/charging infrastructure and market analysis and modeling can strengthen assumptions used across analyses.

While the analysis presented here is sufficient for a robust analysis, there are still gaps in the available data. AFVs are nascent technologies, and have smaller market share, which leads to a lack of information about insurance and M&R costs, particularly for MHDV. Beyond looking at an average TCO for each vocation, we can consider the distributions of TCO within a broader population. Geographic differences in fuel prices, insurance requirements, and labor rates can lead to differences in TCO throughout the country, while socioeconomic factors can impact vehicle choice and travel behavior.

The authors hope that the information presented here can be used by the research community broadly. Beyond the tables of data which are available in Appendices B and C, the authors have developed a web-based tool for calculating TCO (Wiryadinata and Lehrer 2021).

Details of the comprehensive literature review will also be published alongside this report (Delucchi 2021, ANL 2021a).

This research was supported by the Vehicle Technologies Office in the Office of Energy Efficiency and Renewable Energy at the U.S. Department of Energy, and the authors express their thanks to VTO, and in particular Jacob Ward, Raphael Isaac, and Mark Smith, for guidance and helpful discussion. The authors thank members of the U.S. DRIVE government-industry partnership Integrated Systems Analysis Technical Team for insightful discussions. The authors also thank attendees and panelists of the Total Cost of Ownership workshops for medium- and heavy-duty vehicles, held in April 2020, for their valuable insights and perspectives. In particular, the authors would like to thank Mike Tunnell (American Transportation Research Institute), Mike Roeth (North American Council for Freight Efficiency), Scott Phillippi (UPS), Dawn Fenton (Volvo Group NA), Alan Mace (Ballard Power Systems), and Randal Kaufman (Black & Veatch) for being panelists. The authors especially thank Sandra Loi of NREL for her invaluable assistance in reorganizing and hosting the workshops as virtual events after the implementation of nationwide travel restrictions due to COVID-19.

APPENDIX A: COMPARISON OF PRIVATE AND SOCIETAL TCO

The majority of this report addresses a complete, quantitative, data-based estimation of the cost of ownership of different on-road vehicles having a range of vehicle fuels and powertrain technologies, from the perspective of a private individual or firm. However, there are key distinctions between this private calculation and a societal benefits calculation, as shown in Table 2.1. This appendix will look deeper into the differences between a social lifetime cost analysis and a quantitative private-cost analysis, and show that one cannot estimate social lifetime cost merely by adding external costs to private costs.

A lifetime-cost analysis can provide anything from detailed cost models to simple estimates of total cost, which can be used to: i) evaluate the costs and benefits of transportation projects, policies, and long-range scenarios; ii) help establish efficient prices for and ensure efficient use of transportation services and commodities; iii) compare the costs and benefits of different kinds of vehicles; and iv) prioritize research and funding to reduce transportation costs and maximize benefits. Table A.1 presents key cost elements for TCO calculations, and examines how their treatment differs depending on which perspective and calculation approach is being used – societal-quantitative, private-quantitative, or private-qualitative.

TABLE A.1 Cost elements and parameters that vary by vehicle fuel or powertrain

Perspective/approach → Cost element ↓	***Societal***	***Private-quantitative***	***Private-qualitative***
Vehicle cost	Included	Combined into full vehicle *retail price* (cost+profit+taxes+incentive) and considered jointly with vehicle loan payments	
Automaker profit	**Not included**, because is an *intra-society* transfer from consumers to producers		
Vehicle sales tax	**Not included**, because taxes are an *intra-society* transfer from consumers to government		
Purchase incentives	**Not included**, because they are designed to manipulate demand, not recover costs		
Vehicle loan payments	Includes only the cost of administering the loan; principal is part of "vehicle cost;" loan interest is a transfer from consumers to lenders; social discount rate accounts for opportunity cost of resources used to make vehicle)	An ordinary periodic cost to be discounted by the relevant *discount* rate	Considered qualitatively, rather than in a full, explicit financial accounting
Vehicle resale value	Includes only the actual (very small) transaction costs; the rest is a transfer between consumers	Considered quantitatively	Considered qualitatively
Period of first ownership (when vehicle is resold)	Relevant only via (trivial) effect on timing of resale transaction cost		
Average vehicle lifetime to scrappage	Included quantitatively (this is the only relevant lifetime)	If vehicle is resold, lifetime to scrappage is reflected in resale value; otherwise, it is considered quantitatively or qualitatively	
Battery replacement	Included quantitatively		Considered qualitatively
Vehicle energy use			

TABLE A.1 (Cont.)

<table>
<tr><th><i>Perspective</i> →
Cost element ↓</th><th><i>Societal</i></th><th><i>Private-quantitative</i></th><th><i>Private-qualitative</i></th></tr>
<tr><td>Energy cost – retail cost of dispensed fuel</td><td>Included</td><td rowspan="3">Included quantitatively based on full energy <i>prices</i> (including cost, profit, and taxes)</td><td rowspan="3">Considered qualitatively, based on full energy <i>prices</i> (including cost, profit, and taxes), in conjunction with vehicle efficiency</td></tr>
<tr><td>Energy firm profit</td><td>Not included, because producer surplus is an <i>intra-society</i> transfer from consumers to producers</td></tr>
<tr><td>Energy (excise) taxes</td><td>Not included, because taxes are an <i>intra-society</i> transfer from consumers and producers to government</td></tr>
<tr><td>Corporate income taxes</td><td>Not included, because taxes are an <i>intra-society</i> transfer from producers to government</td><td>Included quantitatively based on actual prices</td><td>Considered qualitatively, based on actual prices</td></tr>
<tr><td>Insurance</td><td>Includes only actual administrative cost; excludes industry true profit (producer surplus) in premiums</td><td>Included based on actual premiums paid</td><td rowspan="2">Perhaps considered qualitatively</td></tr>
<tr><td>Maintenance and repair</td><td colspan="2">Included; must avoid double-counting repair costs covered by warranties and insurance premiums; costs must be consistent with vehicle usage and lifetime; costs for EVs will decrease with scale and learning</td></tr>
<tr><td>Engine oil</td><td colspan="2" rowspan="4">Included</td><td rowspan="3">Probably not explicitly considered in purchase or use decisions</td></tr>
<tr><td>Inspection fees</td></tr>
<tr><td>Replacement tires</td></tr>
<tr><td>Paid driver time</td><td>Not applicable</td></tr>
<tr><td>External costs (e.g., air pollution, climate change, energy security</td><td>Included (note that estimates should use discount rate consistent with rate assumed for present-value calculations)</td><td colspan="2">Not included</td></tr>
</table>

TABLE A.1 (Cont.)

<table>
<tr><th><i>Perspective</i> → Cost element↓</th><th><i>Societal</i></th><th><i>Private-quantitative</i></th><th><i>Private-qualitative</i></th></tr>
<tr><td>Parking</td><td colspan="2" rowspan="2">Included</td><td rowspan="4">Probably not explicitly considered in purchase or use decisions</td></tr>
<tr><td>Accessories</td></tr>
<tr><td>Tolls and fines</td><td rowspan="2">Not included, because they are a transfer from consumers to government</td><td rowspan="2">Included</td></tr>
<tr><td>Registration fees*</td></tr>
<tr><td>Annual VMT, base-line travel benefits**</td><td colspan="2" rowspan="2">Included</td><td rowspan="2">Perhaps considered qualitatively</td></tr>
<tr><td>Inflation, cost escalation</td></tr>
<tr><td>Discount rate</td><td>Social discount rate; mainly the opportunity cost of foregone productivity growth</td><td>Interest foregone on short-to-medium term, relatively safe savings and investments</td><td><i>Implicit</i> discounting of the future due to risk aversion, uncertainty, and limited time to fully enjoy benefits of transportation</td></tr>
<tr><td>Motor-vehicle road infrastructure and public services</td><td colspan="3">Not included, because they do not vary appreciably*** by vehicle technology; they would be included in a cost-benefit analysis comparing motor-vehicles with other transport modes, such as trains</td></tr>
</table>

* Registration fees can vary slightly from state to state, by powertrain.

** This is the annual VMT corresponding to the access benefits of travel in the current conventional petroleum-fuel vehicle baseline. This baseline, fundamental benefit of travel is the same for all vehicles. Table 2.6 lists ways in which VMT can vary by vehicle type and affect costs but not baseline benefits. See the text for further discussion.

*** Because road wear is a function of vehicle weight, changes in powertrains that affected average in-use vehicle weight would affect road wear.

An important point to make here is that, contrary to common (if not heretofore universal) practice, one can *not* produce an estimate of the *social* lifetime cost simply by adding estimates of external costs to estimates of private costs. As summarized in Table A.1, and described in greater detail in Table A.2, there are a number of non-trivial differences between the societal-quantitative and the private-quantitative perspective/approach other than the treatment of external costs (or, more generally, non-market costs):

1) The difference between price-times-quantity payments (private-quantitative) and the area under the long-run marginal-cost curve (societal-quantitative). This difference potentially is quite large. For example, Delucchi (2004) estimates that tax and fee payments by motor-vehicle users towards the use of public highway infrastructure and services (PHIS) (mainly fuel taxes, registration and license fees, tolls and fines) are 20% to 31% of the costs "usually included in GNP-type accounts" (see top part of column 2 of Table A.2) and 12% to 17% of the sum of: *i)* priced-private sector costs (column 2 of Table A.2) and *ii)* the cost of motor-vehicle goods and services provided by the public sector (column 4 of Table 2). Because these tax and fee payments towards PHIS "have no straightforward relevance in an analysis of social costs or efficient pricing" (Delucchi 2007, 988), they should be treated as transfers and excluded from a social-cost analysis (which would estimate separately the *actual* cost of the PHIS – column 4 of Table 2). And one cannot reasonably choose not to estimate and deduct tax and fee payments on the grounds that doing so would not change the *relative* social costs of alternative transportation options, because the claim is false: tax and fee payments are potentially different, in relative as well as absolute terms, between, say, electric and gasoline vehicles, and certainly are different between motor-vehicles and other transportation options.

   Moreover, Delucchi's (2004) estimate of tax and fee payments for PHIS do not include sales taxes, corporate income taxes, property taxes, or personal income taxes related to the production and use of motor vehicles, motor fuels, and public roads. Delucchi and Murphy (2008) estimate that in total these taxes could amount to several tens of billions of dollars. Delucchi and Murphy (2008) also estimate the associated "tax subsidy," defined as the difference between the actual tax payments and the amount that would have been paid had the entities been taxed at a national average rate: on the order of $10 to $50 billion in the year 2000. We point this out not because the tax subsidy is a social cost – it is *not* – but because it speaks to and invalidates the tempting argument that embedded taxes need not be removed in a social cost analysis because removing them would not change *relative* social costs. The only way to get a proper picture of relative and absolute social costs is to remove all taxes from an estimate of the private cost.

   Finally, Sun et al (2019) estimate that producer surplus is about 40% of total price-times-quantity payments for gasoline in the US over the period 2005 to 2030. In an illustrative calculation, they estimate that failing to deduct producer surplus from price-times-quantity payments *overstates* the present value of lifetime social costs for a single gasoline vehicle by about $7,000.

2) <u>The difference between considering the period of first ownership, depreciation, and resale value and ignoring these</u>. As discussed in the background report, this difference – i.e., the absolute, unambiguous error that results from incorrectly assuming that social costs = business costs + external costs – is potentially quite large, at least several thousand dollars, and perhaps over $20,000. For example, assuming a $30,000 dollar vehicle (based on Table 3.1), the annual VMT schedule for SUVs from the NHTSA & EPA (2020) LDV rulemaking, an 18-year vehicle life to scrappage, a real discount rate of 1.2% (Table 2.5), and resale of the vehicle after 7 years with a resale value of 34% of the initial cost (Figure 3-11), then the difference in the net present value of annualized vehicle costs between the societal

perspective and the private-quantitative perspective is $13,400. This figure increases if the lifetime to scrappage is longer or if the resale value percentage for a given year is lower.

This entire error comes into play when comparing the social cost of different modes. But there also is an absolute and relative error here when comparing the social cost of vehicles with different powertrains. Note that difference increases linearly with the initial cost. This means that, for a given depreciation schedule, assuming that social costs = private costs + external costs not only introduces a very large error, the error is greater for more costly vehicles. From the standpoint of society, ownership aspects are irrelevant; what matters are actual vehicle lifetime to scrappage and actual M&R costs over the entire lifetime.

3) The difference between loan rates and discount rates pertinent to individuals and firms and the much lower discount rate for society. There are two aspects to this. First, the private-quantitative case includes loan interest payments that from the perspective of society are transfers from borrowers to lenders, assuming that *who* holds the interest portion – which banks or companies or public entities – makes no difference economically. The social cost of a loan, then is only the cost of administering the loan.

   Second, a financial discount rate perhaps is a bit higher than the social discount rate. Loss aversion, budget constraints, and pertain only to individuals and perhaps companies, but not to society; thus the social discount rate includes only a national productivity component.

   The difference due to the treatment of loans is not trivial: for example, the difference between *i)* the stream of payments on a loan to finance 90% of the cost of a $25,000 vehicle at an annual rate of 5% over 5 years, and *ii)* the stream of payments at 0% has a present value of about $2000.

TABLE A.2 Detailed description of costs related to motor vehicle use

Personal	**Private sector**		**Public sector**	**Externalities (except 6b)**	
MPC or MPV might be mis-estimated, because of poor information or irrational behavior	Prices are not optimal because of imperfect standards (MCC ≠ MDC), distortionary taxes, subsidies, price controls, quotas, imperfect competition (P ≠ MPC), or poor information	Bundling decision can be distorted or determined by regulations, taxes, poor information	User taxes and fees ≠ MPC, and B/C not maximized, because of non-efficiency objectives	These are unpriced (MPC ≠ MSC in markets with externalities) because of the absence of fully enforced individual or collective property rights, or the absence of optimal Pigovian taxes	
Nonmonetary	**Monetary costs**				**Nonmonetary costs**
(1) Personal non-monetary costs of MV use	**(2) MV goods and services produced and priced in private sector (net of PS, taxes and fees)**	**(3) MV goods bundled in the private sector**	**(4) MV goods and services from government**	**(5) Monetary externalities of MV use**	**(6a) Nonmonetary externalities of MV use**
• Travel time, excluding travel delay imposed by other drivers, that displaces unpaid activities • Accident costs inflicted on oneself: pain, suffering, death, and lost nonmarket productivity • Personal time spent working on MVs and garages, refueling MVs, and buying and disposing of MVs and parts • MV noise and air pollution inflicted on oneself	*These kinds of costs usually are included in GNP-type accounts:* • Motor vehicles: annualized cost of the fleet (excluding vehicles replaced as a result of motor-vehicle accidents) • Used vehicles*:* cost of transactions • Parts, supplies, maintenance, repair, cleaning, storage, renting, towing, etc. (excluding parts and services in repair of vehicles damaged in accidents) • Motor fuel and lubricating oil, excluding cost of fuel use attributable to delays • Motor-vehicle insurance: administrative and management costs • Parking: priced private commercial and residential, excluding parking taxes (continued on next page)	• Parking: annualized cost of non-residential off-street, included in the price of goods and services or offered as an employee benefit • Parking: annualized cost of off-street residential included in the price of housing • Roads: annualized cost provided or paid for by the private sector and recovered in the price of structures, goods, or services	• Roads: annualized cost of public highways, including on-street parking • Parking: annualized cost of municipal and institutional off-street • Highway patrol and safety • Regulation and control of MV air, water, and solid waste pollution • Research and development support for MVs and fuel	• Travel delay, imposed by other drivers: extra fuel consumption and foregone paid work (including costs of paid drivers) • Accident costs not accounted for by economically responsible party: property damage, medical, productivity, and legal and administrative costs • Oil price shocks: macroeconomic adjustment losses of GDP • Pecuniary externality of oil use: increased payments to foreign countries for non-transport oil, due to ordinary price effect of using petroleum for motor vehicles (continued on next page)	• Travel delay, imposed by other drivers, that displaces unpaid activities • Accident costs not accounted for by the economically responsible party: pain, suffering, death, and lost nonmarket productivity • Air pollution: effects on human health, crops, materials, and visibility** • Climate change due to life-cycle emissions of greenhouse gases • Noise from motor vehicles • Water pollution: effects of leaking storage tanks, oil spills, urban runoff, road deicing • Fires and net crimes* related to using or having MV goods, services, or infrastructure: nonmonetary costs • Air pollution: damages to ecosystems other than forests • Others: costs of motor-vehicle waste, vibration damages, fear of MVs and MV-related crime

TABLE A.2 (Cont.)

(1) Personal non-monetary costs of MV use	**(2) MV goods and services produced and priced in private sector (net of PS, taxes and fees)**	**(3) MV goods bundled in the private sector**	**(4) MV goods and services from govern-ment**	**(5) Monetary externalities of MV use**	**(6a) Nonmonetary externalities of MV use**
	Usually not included in GNP-type account: • Travel time, excluding travel delay imposed by other drivers, that displaces paid work (includes cost of paid drivers) • Accident costs: private monetary costs, including user payments for cost of motor-vehicle accidents inflicted on others, but excluding insurance administration costs • Overhead expenses of business and government fleets			• Fires and net crimes* related to using or having MV goods, services, or infrastructure: monetary, non-public-sector costs	
			• Police protection (excl. highway patrol), court and corrections system (net of cost of substitute crimes) • Fire protection • Other agencies, motor-vehicle related costs • Military expenditures related to the use of Persian-Gulf oil by motor vehicles • Strategic Petroleum Reserve , annualized cost		**(6b) Nonmonetary impacts of the MV infrastructure**[#]
					• Land-use damage: habitat, species loss due to highways, MV infrastructure • Roads as physical barriers: the socially divisive in communities • Aesthetics of highways, vehicle and service establishments

Notes:
MPC = marginal private cost; MPV = marginal private value; P = price, MCC = marginal control cost; MDC = marginal damage cost; B/C = dollar benefit/cost ratio of investment; MSC = marginal social cost; MV = motor vehicle; GNP = gross national product; R&D = research and development; PS = producer surplus.

* These really should be classified not as external costs, within an economic framework, but rather as costs of illegal or immoral behavior, within a framework that encompasses more than just economic criteria. However, regardless of how these are *classified*, they in fact are related to using or having motor-vehicle goods, services, or infrastructure. See Delucchi (2021) for further discussion

** The cost of crop loss, and some of the components of other costs of air pollution (e.g., the cost of medical treatment of sickness caused by motor-vehicle air pollution), probably should be classified as monetary externalities.

[#] Although these are nonmonetary environmental and social costs of total motor-vehicle use, they are not costs of marginal motor-vehicle use, and hence technically are not externalities.

APPENDIX B: TABULAR TCO AND LCOD DATA

This appendix presents the figures of Section 4 in tabular form, presenting the lifetime TCO and the per-mile LCOD by cost element, as described in Section 2.3. A more comprehensive set of results including additional side cases is published online accompanying this report (ANL 2021a). For LDV, ‘Payload’ and ‘Labor’ costs are always zero, while for MHDV, ‘Repair’ is zero because it is incorporated into the combined ‘M&R’.

The following powertrains were analyzed:

- ICE-SI: Internal Combustion Engine, Spark Ignition
  - Fueled by gasoline
- ICE-CI: Internal Combustion Engine, Compression Ignition
  - Fueled by diesel
- HEV: Hybrid Electric Vehicle
  - Fueled by gasoline for light-duty vehicles
  - Fueled by diesel for medium- and heavy-duty vehicles
- PHEVxx: Plug-in Hybrid Electric Vehicle with an all-electric range of xx miles
  - Fueled by gasoline and electricity for light-duty vehicles
  - Fueled by diesel and electricity for medium- and heavy-duty vehicles
- FCEV: Fuel Cell Electric Vehicle
  - Fueled by hydrogen
- BEVxx: Battery Electric Vehicle with an all-electric range of xx miles
  - Fueled by electricity

Light-duty vehicle size classes ranging from compact sedans to pickup trucks were considered, with the primary focus on small sport utility vehicles. The following medium- and heavy-duty vocations were analyzed:

- Class 8 sleeper-cab tractor trailer
- Class 8 day-cab tractor trailer
- Class 8 vocational truck
- Class 6 pickup and delivery truck
- Class 4 pickup and delivery truck
- Class 8 transit bus
- Class 8 refuse truck

Vehicle costs and fuel economy were modeled using the Autonomie model. The BEV range was assumed to be 500 miles for class 8 sleeper-cab tractor trailers, 250 miles for class 8 day-cab tractor trailers, 200 miles for class 8 vocational vehicles, and 150 miles for the other four vocations. MHDV PHEV were modeled to have exactly half this range. Further information about the modeling assumptions for the vehicles can be found in (Islam et al. 2020) and (Vijayagopal et al. 2019).

TABLE B.1 Small SUV, MY2025; Figures 4.1 and ES-5

Lifetime Costs	ICE-SI	ICE-CI	HEV	PHEV50	FCEV	BEV300	BEV200
Vehicle	$26,051	$27,744	$27,419	$34,505	$34,515	$46,031	$37,621
Financing	$2,884	$3,072	$3,019	$3,584	$3,465	$4,672	$3,818
Fuel	$17,488	$15,939	$12,433	$11,981	$18,118	$9,254	$8,770
Insurance	$13,289	$13,357	$13,376	$12,667	$11,495	$12,870	$12,349
Maintenance	$16,302	$15,714	$14,518	$13,968	$9,829	$8,920	$8,920
Repair	$6,990	$7,270	$6,543	$6,959	$5,288	$6,808	$5,694
Tax & fees	$5,244	$5,409	$5,460	$6,356	$6,763	$7,741	$6,991
Total	**$88,248**	**$88,505**	**$82,768**	**$90,020**	**$89,474**	**$96,295**	**$84,164**
Per-Mile Costs	**ICE-SI**	**ICE-CI**	**HEV**	**PHEV50**	**FCEV**	**BEV300**	**BEV200**
Vehicle	$0.1395	$0.1486	$0.1469	$0.1848	$0.1849	$0.2465	$0.2015
Financing	$0.0154	$0.0165	$0.0162	$0.0192	$0.0186	$0.0250	$0.0205
Fuel	$0.0937	$0.0854	$0.0666	$0.0642	$0.0970	$0.0496	$0.0470
Insurance	$0.0712	$0.0715	$0.0716	$0.0678	$0.0616	$0.0689	$0.0661
Maintenance	$0.0873	$0.0842	$0.0778	$0.0748	$0.0526	$0.0478	$0.0478
Repair	$0.0374	$0.0389	$0.0350	$0.0373	$0.0283	$0.0365	$0.0305
Tax & fees	$0.0281	$0.0290	$0.0292	$0.0340	$0.0362	$0.0415	$0.0374
Total	**$0.4727**	**$0.4740**	**$0.4433**	**$0.4822**	**$0.4792**	**$0.5158**	**$0.4508**

TABLE B.2 Gasoline LDV, MY2025; Figure 4.2

Lifetime Costs	Compact sedan	Midsize sedan	Small SUV	Medium SUV	Pickup
Vehicle	$18,626	$24,055	$26,051	$27,714	$30,366
Financing	$2,054	$2,652	$2,884	$3,068	$3,362
Fuel	$13,605	$14,902	$15,631	$16,392	$20,422
Insurance	$12,715	$13,605	$13,289	$13,356	$13,216
Maintenance	$14,202	$14,202	$14,202	$14,202	$14,202
Repair	$6,244	$7,077	$6,760	$7,025	$5,747
Tax & fees	$4,514	$5,040	$5,244	$5,406	$5,664
Total	**$71,960**	**$81,534**	**$84,061**	**$87,165**	**$92,978**
Per-Mile Costs	**Compact sedan**	**Midsize sedan**	**Small SUV**	**Medium SUV**	**Pickup**
Vehicle	$0.1123	$0.1451	$0.1571	$0.1672	$0.1831
Financing	$0.0124	$0.0160	$0.0174	$0.0185	$0.0203
Fuel	$0.0821	$0.0899	$0.0943	$0.0989	$0.1232
Insurance	$0.0767	$0.0821	$0.0802	$0.0806	$0.0797
Maintenance	$0.0857	$0.0857	$0.0857	$0.0857	$0.0857
Repair	$0.0377	$0.0427	$0.0408	$0.0424	$0.0347
Tax & fees	$0.0272	$0.0304	$0.0316	$0.0326	$0.0342
Total	**$0.4340**	**$0.4918**	**$0.5070**	**$0.5257**	**$0.5608**

TABLE B.3 Class 8 diesel truck, MY2025; Figure 4.3 and ES-6

Lifetime Costs	Sleeper	Day cab	Vocational	6-Delivery	4-Delivery	Transit Bus	Refuse
Vehicle	$129,699	$98,661	$62,928	$55,890	$37,223	$74,612	$63,467
Financing	$14,793	$12,081	$9,559	$7,229	$5,962	$11,240	$9,618
Fuel	$318,806	$215,658	$87,920	$44,954	$29,661	$157,578	$158,676
Insurance	$67,898	$49,989	$43,931	$43,931	$26,358	$307,514	$65,896
M & R	$183,575	$121,090	$144,162	$135,383	$43,216	$248,708	$697,718
Tax & fees	$90,484	$69,765	$41,428	$24,413	$21,149	$51,061	$43,255
Payload	$0	$0	$0	$0	$0	$0	$0
Labor	$618,509	$405,871	$527,167	$527,167	$527,167	$527,167	$527,167
Total	**$1,423,765**	**$973,116**	**$917,095**	**$838,967**	**$690,737**	**$1,377,878**	**$1,565,797**
Per-Mile Costs	**Sleeper**	**Day cab**	**Vocational**	**6-Delivery**	**4-Delivery**	**Transit Bus**	**Refuse**
Vehicle	$0.1657	$0.1920	$0.2740	$0.3077	$0.2603	$0.2206	$0.2436
Financing	$0.0189	$0.0235	$0.0416	$0.0398	$0.0417	$0.0332	$0.0369
Fuel	$0.4072	$0.4197	$0.3828	$0.2475	$0.2074	$0.4660	$0.6089
Insurance	$0.0867	$0.0973	$0.1913	$0.2419	$0.1843	$0.9093	$0.2529
M & R	$0.2345	$0.2357	$0.6276	$0.7453	$0.3022	$0.7354	$2.6776
Tax & fees	$0.1156	$0.1358	$0.1804	$0.1344	$0.1479	$0.1510	$0.1660
Payload	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$2.2951	$2.9023	$3.6869	$1.5588	$2.0231
Total	**$1.8185**	**$1.8940**	**$3.9927**	**$4.6188**	**$4.8309**	**$4.0744**	**$6.0089**

TABLE B.4 Class 8 sleeper cab tractor, MY2025; Figure 4.4

Lifetime Costs	ICE-CI	HEV	PHEV250	FCEV	BEV500
Vehicle	$129,699	$137,834	$236,316	$191,000	$341,088
Financing	$14,793	$15,721	$26,953	$21,785	$38,903
Fuel	$318,806	$318,297	$345,926	$669,896	$258,583
Insurance	$67,898	$68,982	$82,097	$76,062	$96,050
M & R	$183,575	$159,710	$154,203	$110,145	$110,145
Tax & fees	$90,484	$92,510	$117,036	$105,751	$143,129
Payload	$0	$747	$78,947	$8,595	$77,972
Labor	$618,509	$618,509	$618,509	$618,509	$618,509
Total	**$1,423,765**	**$1,412,311**	**$1,659,988**	**$1,801,742**	**$1,684,380**
Per-Mile Costs	**ICE-CI**	**HEV**	**PHEV250**	**FCEV**	**BEV500**
Vehicle	$0.1657	$0.1760	$0.3018	$0.2439	$0.4356
Financing	$0.0189	$0.0201	$0.0344	$0.0278	$0.0497
Fuel	$0.4072	$0.4065	$0.4418	$0.8556	$0.3303
Insurance	$0.0867	$0.0881	$0.1049	$0.0971	$0.1227
M & R	$0.2345	$0.2040	$0.1970	$0.1407	$0.1407
Tax & fees	$0.1156	$0.1182	$0.1495	$0.1351	$0.1828
Payload	$0.0000	$0.0010	$0.1008	$0.0110	$0.0996
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$1.8185**	**$1.8038**	**$2.1202**	**$2.3012**	**$2.1513**

TABLE B.5 Class 8 day cab tractor, MY2025; Figure 4.5

Lifetime Costs	**ICE-CI**	**HEV**	**PHEV125**	**FCEV**	**BEV250**
Vehicle	$98,661	$102,594	$148,398	$151,759	$189,365
Financing	$12,081	$12,563	$18,171	$18,583	$23,187
Fuel	$215,658	$209,582	$228,365	$446,172	$161,522
Insurance	$49,989	$50,658	$58,443	$59,014	$65,405
M & R	$121,090	$105,348	$101,716	$72,654	$72,654
Tax & fees	$69,765	$70,817	$83,063	$83,962	$94,017
Payload	$0	$0	$19,562	$0	$0
Labor	$405,871	$405,871	$405,871	$405,871	$405,871
Total	**$973,116**	**$957,433**	**$1,063,587**	**$1,238,013**	**$1,012,022**
Per-Mile Costs	**ICE-CI**	**HEV**	**PHEV125**	**FCEV**	**BEV250**
Vehicle	$0.1920	$0.1997	$0.2888	$0.2954	$0.3686
Financing	$0.0235	$0.0245	$0.0354	$0.0362	$0.0451
Fuel	$0.4197	$0.4079	$0.4445	$0.8684	$0.3144
Insurance	$0.0973	$0.0986	$0.1137	$0.1149	$0.1273
M & R	$0.2357	$0.2050	$0.1980	$0.1414	$0.1414
Tax & fees	$0.1358	$0.1378	$0.1617	$0.1634	$0.1830
Payload	$0.0000	$0.0000	$0.0381	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$1.8940**	**$1.8635**	**$2.0701**	**$2.4096**	**$1.9698**

TABLE B.6 Class 4 delivery truck, MY2025; Figure 4.6

Lifetime Costs	**ICE-CI**	**HEV**	**PHEV75**	**FCEV**	**BEV150**
Vehicle	$37,223	$40,101	$44,760	$46,615	$48,638
Financing	$5,962	$6,423	$7,169	$7,466	$7,790
Fuel	$29,661	$22,821	$23,261	$34,522	$12,744
Insurance	$26,358	$26,358	$26,358	$26,358	$26,358
M & R	$43,216	$37,598	$36,302	$25,930	$25,930
Tax & fees	$21,149	$21,618	$22,515	$23,070	$23,315
Payload	$0	$0	$0	$0	$0
Labor	$527,167	$527,167	$527,167	$527,167	$527,167
Total	**$690,737**	**$682,087**	**$687,532**	**$691,128**	**$671,942**
Per-Mile Costs	**ICE-CI**	**HEV**	**PHEV75**	**FCEV**	**BEV150**
Vehicle	$0.2603	$0.2805	$0.3130	$0.3260	$0.3402
Financing	$0.0417	$0.0449	$0.0501	$0.0522	$0.0545
Fuel	$0.2074	$0.1596	$0.1627	$0.2414	$0.0891
Insurance	$0.1843	$0.1843	$0.1843	$0.1843	$0.1843
M & R	$0.3022	$0.2630	$0.2539	$0.1813	$0.1813
Tax & fees	$0.1479	$0.1512	$0.1575	$0.1613	$0.1631
Payload	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$3.6869	$3.6869	$3.6869	$3.6869	$3.6869
Total	**$4.8309**	**$4.7704**	**$4.8085**	**$4.8336**	**$4.6994**

TABLE B.7a Small SUV, gasoline HEV, MY2020–2050; Figures 4.7 and ES-8

Lifetime Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$28,660	$27,419	$27,172	$27,359	$26,553
Financing	$3,156	$3,019	$2,992	$3,012	$2,924
Fuel	$15,403	$12,433	$12,707	$12,240	$11,819
Insurance	$13,427	$13,376	$13,365	$13,373	$13,340
Maintenance	$14,518	$14,518	$14,518	$14,518	$14,518
Repair	$6,733	$6,543	$6,506	$6,534	$6,414
Tax & fees	$5,580	$5,460	$5,436	$5,454	$5,376
Total	**$87,476**	**$82,768**	**$82,696**	**$82,491**	**$80,943**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.1535	$0.1469	$0.1455	$0.1465	$0.1422
Financing	$0.0169	$0.0162	$0.0160	$0.0161	$0.0157
Fuel	$0.0825	$0.0666	$0.0681	$0.0656	$0.0633
Insurance	$0.0719	$0.0716	$0.0716	$0.0716	$0.0714
Maintenance	$0.0778	$0.0778	$0.0778	$0.0778	$0.0778
Repair	$0.0361	$0.0350	$0.0348	$0.0350	$0.0344
Tax & fees	$0.0299	$0.0292	$0.0291	$0.0292	$0.0288
Total	**$0.4685**	**$0.4433**	**$0.4429**	**$0.4418**	**$0.4335**

TABLE B.7b Small SUV, electric BEV300, MY2020–2050; Figures 4.7 and ES-8

Lifetime Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$57,480	$46,031	$39,091	$36,103	$32,658
Financing	$5,834	$4,672	$3,967	$3,664	$3,314
Fuel	$11,030	$9,254	$8,692	$8,149	$6,998
Insurance	$13,482	$12,870	$12,392	$12,305	$11,929
Maintenance	$8,920	$8,920	$8,920	$8,920	$8,920
Repair	$8,682	$6,808	$5,875	$5,514	$5,125
Tax & fees	$8,762	$7,741	$7,122	$6,855	$6,548
Total	**$114,190**	**$96,295**	**$86,060**	**$81,511**	**$75,492**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.3079	$0.2465	$0.2094	$0.1934	$0.1749
Financing	$0.0312	$0.0250	$0.0212	$0.0196	$0.0178
Fuel	$0.0591	$0.0496	$0.0466	$0.0436	$0.0375
Insurance	$0.0722	$0.0689	$0.0664	$0.0659	$0.0639
Maintenance	$0.0478	$0.0478	$0.0478	$0.0478	$0.0478
Repair	$0.0465	$0.0365	$0.0315	$0.0295	$0.0274
Tax & fees	$0.0469	$0.0415	$0.0381	$0.0367	$0.0351
Total	**$0.6116**	**$0.5158**	**$0.4609**	**$0.4366**	**$0.4043**

TABLE B.7c Small SUV, hydrogen FCEV, MY2020–2050; Figures 4.7 and ES-8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$35,568	$34,515	$31,844	$31,419	$29,861
Financing	$3,570	$3,465	$3,196	$3,154	$2,997
Fuel	$30,528	$18,118	$14,784	$12,551	$10,980
Insurance	$11,518	$11,495	$11,153	$11,144	$11,111
Maintenance	$9,829	$9,829	$9,829	$9,829	$9,829
Repair	$5,406	$5,288	$5,000	$4,955	$4,796
Tax & fees	$6,856	$6,763	$6,527	$6,490	$6,352
Total	**$103,275**	**$89,474**	**$82,333**	**$79,542**	**$75,926**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.1905	$0.1849	$0.1706	$0.1683	$0.1599
Financing	$0.0191	$0.0186	$0.0171	$0.0169	$0.0161
Fuel	$0.1635	$0.0970	$0.0792	$0.0672	$0.0588
Insurance	$0.0617	$0.0616	$0.0597	$0.0597	$0.0595
Maintenance	$0.0526	$0.0526	$0.0526	$0.0526	$0.0526
Repair	$0.0290	$0.0283	$0.0268	$0.0265	$0.0257
Tax & fees	$0.0367	$0.0362	$0.0350	$0.0348	$0.0340
Total	**$0.5531**	**$0.4792**	**$0.4410**	**$0.4260**	**$0.4067**

TABLE B.7d Small SUV, gasoline ICEV, MY2020–2050; Figures 4.7 and ES-8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$23,520	$26,051	$26,824	$27,154	$26,380
Financing	$2,604	$2,884	$2,970	$3,006	$2,921
Fuel	$20,931	$17,488	$15,451	$14,754	$14,009
Insurance	$13,187	$13,289	$13,320	$13,334	$13,302
Maintenance	$16,302	$16,302	$16,302	$16,302	$16,302
Repair	$6,592	$6,990	$7,117	$7,171	$7,044
Tax & fees	$4,998	$5,244	$5,320	$5,352	$5,276
Total	**$88,134**	**$88,248**	**$87,303**	**$87,071**	**$85,234**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.1260	$0.1395	$0.1437	$0.1454	$0.1413
Financing	$0.0139	$0.0154	$0.0159	$0.0161	$0.0156
Fuel	$0.1121	$0.0937	$0.0828	$0.0790	$0.0750
Insurance	$0.0706	$0.0712	$0.0713	$0.0714	$0.0712
Maintenance	$0.0873	$0.0873	$0.0873	$0.0873	$0.0873
Repair	$0.0353	$0.0374	$0.0381	$0.0384	$0.0377
Tax & fees	$0.0268	$0.0281	$0.0285	$0.0287	$0.0283
Total	**$0.4721**	**$0.4727**	**$0.4676**	**$0.4664**	**$0.4565**

TABLE B.7e Small SUV, gasoline/electric PHEV50, MY2020–2050; Figures 4.7 and ES-8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$44,420	$34,505	$32,281	$31,443	$30,377
Financing	$4,613	$3,584	$3,353	$3,266	$3,155
Fuel	$14,168	$11,704	$11,195	$10,126	$8,788
Insurance	$13,546	$12,667	$12,592	$12,563	$12,527
Maintenance	$13,968	$13,968	$13,968	$13,968	$13,968
Repair	$8,632	$6,959	$6,631	$6,511	$6,362
Tax & fees	$7,261	$6,356	$6,153	$6,077	$5,980
Total	**$106,609**	**$89,743**	**$86,172**	**$83,954**	**$81,157**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.2379	$0.1848	$0.1729	$0.1684	$0.1627
Financing	$0.0247	$0.0192	$0.0180	$0.0175	$0.0169
Fuel	$0.0759	$0.0627	$0.0600	$0.0542	$0.0471
Insurance	$0.0726	$0.0678	$0.0674	$0.0673	$0.0671
Maintenance	$0.0748	$0.0748	$0.0748	$0.0748	$0.0748
Repair	$0.0462	$0.0373	$0.0355	$0.0349	$0.0341
Tax & fees	$0.0389	$0.0340	$0.0330	$0.0325	$0.0320
Total	**$0.5710**	**$0.4807**	**$0.4615**	**$0.4497**	**$0.4347**

TABLE B.7f Class 4 delivery truck, diesel HEV, MY2020–2050; Figure 4.7

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$40,616	$40,101	$38,959	$36,981	$37,566
Financing	$6,505	$6,423	$6,240	$5,923	$6,017
Fuel	$28,324	$22,821	$21,719	$20,254	$20,507
Insurance	$26,358	$26,358	$26,358	$26,358	$26,358
M & R	$37,598	$37,598	$37,598	$37,598	$37,598
Tax & fees	$21,638	$21,564	$21,399	$21,114	$21,199
Payload	$0	$0	$0	$0	$0
Labor	$527,167	$527,167	$527,167	$527,167	$527,167
Total	**$688,206**	**$682,032**	**$679,440**	**$675,396**	**$676,412**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.2841	$0.2805	$0.2725	$0.2586	$0.2627
Financing	$0.0455	$0.0449	$0.0436	$0.0414	$0.0421
Fuel	$0.1981	$0.1596	$0.1519	$0.1417	$0.1434
Insurance	$0.1843	$0.1843	$0.1843	$0.1843	$0.1843
M & R	$0.2630	$0.2630	$0.2630	$0.2630	$0.2630
Tax & fees	$0.1513	$0.1508	$0.1497	$0.1477	$0.1483
Payload	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$3.6869	$3.6869	$3.6869	$3.6869	$3.6869
Total	**$4.8132**	**$4.7700**	**$4.7519**	**$4.7236**	**$4.7307**

TABLE B.7g Class 4 delivery truck, electric BEV150, MY2020–2050; Figure 4.7

Lifetime Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$92,693	$48,638	$38,611	$34,433	$32,946
Financing	$14,847	$7,790	$6,184	$5,515	$5,277
Fuel	$15,555	$12,744	$11,658	$10,944	$9,817
Insurance	$26,358	$26,358	$26,358	$26,358	$26,358
M & R	$25,930	$25,930	$25,930	$25,930	$25,930
Tax & fees	$29,137	$22,793	$21,349	$20,747	$20,533
Payload	$0	$0	$0	$0	$0
Labor	$527,167	$527,167	$527,167	$527,167	$527,167
Total	**$731,686**	**$671,420**	**$657,257**	**$651,093**	**$648,028**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.6483	$0.3402	$0.2700	$0.2408	$0.2304
Financing	$0.1038	$0.0545	$0.0433	$0.0386	$0.0369
Fuel	$0.1088	$0.0891	$0.0815	$0.0765	$0.0687
Insurance	$0.1843	$0.1843	$0.1843	$0.1843	$0.1843
M & R	$0.1813	$0.1813	$0.1813	$0.1813	$0.1813
Tax & fees	$0.2038	$0.1594	$0.1493	$0.1451	$0.1436
Payload	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$3.6869	$3.6869	$3.6869	$3.6869	$3.6869
Total	**$5.1173**	**$4.6958**	**$4.5968**	**$4.5536**	**$4.5322**

TABLE B.7h Class 4 delivery truck, hydrogen FCEV, MY2020–2050; Figure 4.7

Lifetime Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$72,749	$46,615	$35,878	$33,035	$31,570
Financing	$11,652	$7,466	$5,747	$5,291	$5,057
Fuel	$68,690	$34,522	$25,650	$23,447	$21,489
Insurance	$26,358	$26,358	$26,358	$26,358	$26,358
M & R	$25,930	$25,930	$25,930	$25,930	$25,930
Tax & fees	$26,265	$22,502	$20,956	$20,546	$20,335
Payload	$0	$0	$0	$0	$0
Labor	$527,167	$527,167	$527,167	$527,167	$527,167
Total	**$758,810**	**$690,559**	**$667,684**	**$661,775**	**$657,905**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.5088	$0.3260	$0.2509	$0.2310	$0.2208
Financing	$0.0815	$0.0522	$0.0402	$0.0370	$0.0354
Fuel	$0.4804	$0.2414	$0.1794	$0.1640	$0.1503
Insurance	$0.1843	$0.1843	$0.1843	$0.1843	$0.1843
M & R	$0.1813	$0.1813	$0.1813	$0.1813	$0.1813
Tax & fees	$0.1837	$0.1574	$0.1466	$0.1437	$0.1422
Payload	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$3.6869	$3.6869	$3.6869	$3.6869	$3.6869
Total	**$5.3070**	**$4.8297**	**$4.6697**	**$4.6283**	**$4.6013**

TABLE B.7i Class 4 delivery truck, diesel ICEV, MY2020–2050; Figure 4.7

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$34,445	$37,223	$37,909	$38,546	$39,349
Financing	$5,517	$5,962	$6,072	$6,174	$6,302
Fuel	$34,370	$29,661	$29,548	$30,026	$30,936
Insurance	$26,358	$26,358	$26,358	$26,358	$26,358
M & R	$43,216	$43,216	$43,216	$43,216	$43,216
Tax & fees	$20,749	$21,149	$21,248	$21,340	$21,455
Payload	$0	$0	$0	$0	$0
Labor	$527,167	$527,167	$527,167	$527,167	$527,167
Total	**$691,822**	**$690,737**	**$691,518**	**$692,827**	**$694,784**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.2409	$0.2603	$0.2651	$0.2696	$0.2752
Financing	$0.0386	$0.0417	$0.0425	$0.0432	$0.0441
Fuel	$0.2404	$0.2074	$0.2067	$0.2100	$0.2164
Insurance	$0.1843	$0.1843	$0.1843	$0.1843	$0.1843
M & R	$0.3022	$0.3022	$0.3022	$0.3022	$0.3022
Tax & fees	$0.1451	$0.1479	$0.1486	$0.1492	$0.1501
Payload	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$3.6869	$3.6869	$3.6869	$3.6869	$3.6869
Total	**$4.8385**	**$4.8309**	**$4.8364**	**$4.8455**	**$4.8592**

TABLE B.7j Class 4 delivery truck, diesel/electric PHEV75, MY2020–2050; Figure 4.7

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$67,348	$44,760	$39,326	$37,405	$37,094
Financing	$10,787	$7,169	$6,299	$5,991	$5,941
Fuel	$26,983	$23,261	$21,957	$21,283	$20,209
Insurance	$26,358	$26,358	$26,358	$26,358	$26,358
M & R	$36,302	$36,302	$36,302	$36,302	$36,302
Tax & fees	$25,487	$22,235	$21,452	$21,175	$21,131
Payload	$2,156	$0	$0	$0	$0
Labor	$527,167	$527,167	$527,167	$527,167	$527,167
Total	**$722,587**	**$687,252**	**$678,861**	**$675,680**	**$674,202**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.4710	$0.3130	$0.2750	$0.2616	$0.2594
Financing	$0.0754	$0.0501	$0.0441	$0.0419	$0.0416
Fuel	$0.1887	$0.1627	$0.1536	$0.1488	$0.1413
Insurance	$0.1843	$0.1843	$0.1843	$0.1843	$0.1843
M & R	$0.2539	$0.2539	$0.2539	$0.2539	$0.2539
Tax & fees	$0.1783	$0.1555	$0.1500	$0.1481	$0.1478
Payload	$0.0151	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$3.6869	$3.6869	$3.6869	$3.6869	$3.6869
Total	**$5.0537**	**$4.8065**	**$4.7478**	**$4.7256**	**$4.7153**

TABLE B.8a Class 8 sleeper cab tractor, diesel HEV, MY2020–2050; Figure 4.8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$134,709	$137,834	$139,019	$142,223	$146,127
Financing	$15,364	$15,721	$15,856	$16,221	$16,667
Fuel	$376,717	$318,297	$303,077	$291,275	$291,150
Insurance	$68,566	$68,982	$69,140	$69,566	$70,086
M & R	$159,710	$159,710	$159,710	$159,710	$159,710
Tax & fees	$91,732	$92,510	$92,805	$93,603	$94,575
Payload	$5,899	$747	$0	$0	$0
Labor	$618,509	$618,509	$618,509	$618,509	$618,509
Total	**$1,471,207**	**$1,412,311**	**$1,398,116**	**$1,391,108**	**$1,396,824**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.1721	$0.1760	$0.1776	$0.1816	$0.1866
Financing	$0.0196	$0.0201	$0.0203	$0.0207	$0.0213
Fuel	$0.4811	$0.4065	$0.3871	$0.3720	$0.3719
Insurance	$0.0876	$0.0881	$0.0883	$0.0889	$0.0895
M & R	$0.2040	$0.2040	$0.2040	$0.2040	$0.2040
Tax & fees	$0.1172	$0.1182	$0.1185	$0.1196	$0.1208
Payload	$0.0075	$0.0010	$0.0000	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$1.8790**	**$1.8038**	**$1.7857**	**$1.7767**	**$1.7840**

TABLE B.8b Class 8 sleeper cab tractor, electric BEV500, MY2020–2050; Figure 4.8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$777,681	$341,088	$236,096	$189,322	$173,091
Financing	$88,699	$38,903	$26,928	$21,593	$19,742
Fuel	$316,266	$258,583	$233,901	$214,088	$190,829
Insurance	$154,193	$96,050	$82,068	$75,839	$73,677
M & R	$110,145	$110,145	$110,145	$110,145	$110,145
Tax & fees	$251,859	$143,129	$116,982	$105,333	$101,291
Payload	$419,357	$77,972	$15,137	$5,407	$1,686
Labor	$618,509	$618,509	$618,509	$618,509	$618,509
Total	**$2,736,709**	**$1,684,380**	**$1,439,766**	**$1,340,236**	**$1,288,968**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.9933	$0.4356	$0.3015	$0.2418	$0.2211
Financing	$0.1133	$0.0497	$0.0344	$0.0276	$0.0252
Fuel	$0.4039	$0.3303	$0.2987	$0.2734	$0.2437
Insurance	$0.1969	$0.1227	$0.1048	$0.0969	$0.0941
Maintenance	$0.1407	$0.1407	$0.1407	$0.1407	$0.1407
Tax & fees	$0.3217	$0.1828	$0.1494	$0.1345	$0.1294
Payload	$0.5356	$0.0996	$0.0193	$0.0069	$0.0022
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$3.4954**	**$2.1513**	**$1.8389**	**$1.7118**	**$1.6463**

TABLE B.8c Class 8 sleeper cab tractor, hydrogen FCEV, MY2020–2050; Figure 4.8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$294,489	$191,000	$147,198	$135,036	$129,165
Financing	$33,588	$21,785	$16,789	$15,402	$14,732
Fuel	$1,311,377	$669,896	$493,030	$445,609	$390,896
Insurance	$89,844	$76,062	$70,229	$68,609	$67,827
M & R	$110,145	$110,145	$110,145	$110,145	$110,145
Tax & fees	$131,524	$105,751	$94,842	$91,813	$90,351
Payload	$52,170	$8,595	$0	$0	$0
Labor	$618,509	$618,509	$618,509	$618,509	$618,509
Total	**$2,641,646**	**$1,801,742**	**$1,550,743**	**$1,485,123**	**$1,421,626**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.3761	$0.2439	$0.1880	$0.1725	$0.1650
Financing	$0.0429	$0.0278	$0.0214	$0.0197	$0.0188
Fuel	$1.6749	$0.8556	$0.6297	$0.5691	$0.4993
Insurance	$0.1148	$0.0971	$0.0897	$0.0876	$0.0866
M & R	$0.1407	$0.1407	$0.1407	$0.1407	$0.1407
Tax & fees	$0.1680	$0.1351	$0.1211	$0.1173	$0.1154
Payload	$0.0666	$0.0110	$0.0000	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$3.3739**	**$2.3012**	**$1.9806**	**$1.8968**	**$1.8157**

TABLE B.8d Class 8 sleeper cab tractor, diesel ICEV, MY2020–2050; Figure 4.8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$124,630	$129,699	$132,853	$136,780	$141,718
Financing	$14,215	$14,793	$15,153	$15,601	$16,164
Fuel	$370,985	$318,806	$305,272	$294,923	$295,865
Insurance	$67,223	$67,898	$68,318	$68,841	$69,499
M & R	$183,575	$183,575	$183,575	$183,575	$183,575
Tax & fees	$89,222	$90,484	$91,270	$92,248	$93,477
Payload	$0	$0	$0	$0	$0
Labor	$618,509	$618,509	$618,509	$618,509	$618,509
Total	**$1,468,360**	**$1,423,765**	**$1,414,950**	**$1,410,477**	**$1,418,807**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.1592	$0.1657	$0.1697	$0.1747	$0.1810
Financing	$0.0182	$0.0189	$0.0194	$0.0199	$0.0206
Fuel	$0.4738	$0.4072	$0.3899	$0.3767	$0.3779
Insurance	$0.0859	$0.0867	$0.0873	$0.0879	$0.0888
M & R	$0.2345	$0.2345	$0.2345	$0.2345	$0.2345
Tax & fees	$0.1140	$0.1156	$0.1166	$0.1178	$0.1194
Payload	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$1.8754**	**$1.8185**	**$1.8072**	**$1.8015**	**$1.8121**

TABLE B.8e Class 8 sleeper cab tractor, diesel/electric PHEV250, MY2020–2050; Figure 4.8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$465,573	$236,316	$181,651	$159,116	$152,517
Financing	$53,102	$26,953	$20,718	$18,148	$17,396
Fuel	$435,472	$345,926	$310,102	$287,559	$272,314
Insurance	$112,628	$82,097	$74,817	$71,816	$70,937
M & R	$154,203	$154,203	$154,203	$154,203	$154,203
Tax & fees	$174,131	$117,036	$103,422	$97,810	$96,167
Payload	$240,692	$78,947	$36,362	$25,871	$20,234
Labor	$618,509	$618,509	$618,509	$618,509	$618,509
Total	**$2,254,310**	**$1,659,988**	**$1,499,785**	**$1,433,032**	**$1,402,276**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.5946	$0.3018	$0.2320	$0.2032	$0.1948
Financing	$0.0678	$0.0344	$0.0265	$0.0232	$0.0222
Fuel	$0.5562	$0.4418	$0.3961	$0.3673	$0.3478
Insurance	$0.1439	$0.1049	$0.0956	$0.0917	$0.0906
M & R	$0.1970	$0.1970	$0.1970	$0.1970	$0.1970
Tax & fees	$0.2224	$0.1495	$0.1321	$0.1249	$0.1228
Payload	$0.3074	$0.1008	$0.0464	$0.0330	$0.0258
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$2.8792**	**$2.1202**	**$1.9155**	**$1.8303**	**$1.7910**

TABLE B.8f Class 8 day cab tractor, diesel HEV, MY2020–2050; Figures 4.8 and ES-8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$101,664	$102,594	$104,167	$106,848	$113,076
Financing	$12,449	$12,563	$12,755	$13,083	$13,846
Fuel	$258,992	$209,582	$199,272	$192,058	$193,009
Insurance	$50,500	$50,658	$50,925	$51,381	$52,439
M & R	$105,348	$105,348	$105,348	$105,348	$105,348
Tax & fees	$70,568	$70,817	$71,238	$71,954	$73,620
Payload	$3,362	$0	$0	$0	$0
Labor	$405,871	$405,871	$405,871	$405,871	$405,871
Total	**$1,008,754**	**$957,433**	**$949,576**	**$946,543**	**$957,210**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.1979	$0.1997	$0.2027	$0.2080	$0.2201
Financing	$0.0242	$0.0245	$0.0248	$0.0255	$0.0269
Fuel	$0.5041	$0.4079	$0.3879	$0.3738	$0.3757
Insurance	$0.0983	$0.0986	$0.0991	$0.1000	$0.1021
M & R	$0.2050	$0.2050	$0.2050	$0.2050	$0.2050
Tax & fees	$0.1374	$0.1378	$0.1387	$0.1400	$0.1433
Payload	$0.0065	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$1.9634**	**$1.8635**	**$1.8482**	**$1.8423**	**$1.8631**

TABLE B.8g Class 8 day cab tractor, electric BEV250, MY2020–2050; Figures 4.8 and ES-8

Lifetime Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$409,108	$189,365	$140,393	$119,996	$113,370
Financing	$50,095	$23,187	$17,191	$14,693	$13,882
Fuel	$202,193	$161,522	$148,040	$135,941	$121,197
Insurance	$102,753	$65,405	$57,082	$53,616	$52,489
M & R	$72,654	$72,654	$72,654	$72,654	$72,654
Tax & fees	$152,768	$94,017	$80,923	$75,470	$73,698
Payload	$47,064	$0	$0	$0	$0
Labor	$405,871	$405,871	$405,871	$405,871	$405,871
Total	**$1,442,507**	**$1,012,022**	**$922,153**	**$878,241**	**$853,161**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.7963	$0.3686	$0.2733	$0.2336	$0.2207
Financing	$0.0975	$0.0451	$0.0335	$0.0286	$0.0270
Fuel	$0.3935	$0.3144	$0.2881	$0.2646	$0.2359
Insurance	$0.2000	$0.1273	$0.1111	$0.1044	$0.1022
M & R	$0.1414	$0.1414	$0.1414	$0.1414	$0.1414
Tax & fees	$0.2973	$0.1830	$0.1575	$0.1469	$0.1434
Payload	$0.0916	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$2.8076**	**$1.9698**	**$1.7948**	**$1.7094**	**$1.6606**

TABLE B.8h Class 8 day cab tractor, hydrogen FCEV, MY2020–2050; Figures 4.8 and ES-8

Lifetime Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$238,600	$151,759	$114,871	$106,306	$100,209
Financing	$29,216	$18,583	$14,066	$13,017	$12,270
Fuel	$913,227	$446,172	$329,640	$299,455	$259,322
Insurance	$73,773	$59,014	$52,744	$51,289	$50,253
M & R	$72,654	$72,654	$72,654	$72,654	$72,654
Tax & fees	$107,180	$83,962	$74,099	$71,809	$70,179
Payload	$20,204	$0	$0	$0	$0
Labor	$405,871	$405,871	$405,871	$405,871	$405,871
Total	**$1,860,726**	**$1,238,013**	**$1,063,945**	**$1,020,402**	**$970,758**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.4644	$0.2954	$0.2236	$0.2069	$0.1950
Financing	$0.0569	$0.0362	$0.0274	$0.0253	$0.0239
Fuel	$1.7775	$0.8684	$0.6416	$0.5828	$0.5047
Insurance	$0.1436	$0.1149	$0.1027	$0.0998	$0.0978
M & R	$0.1414	$0.1414	$0.1414	$0.1414	$0.1414
Tax & fees	$0.2086	$0.1634	$0.1442	$0.1398	$0.1366
Payload	$0.0393	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$3.6216**	**$2.4096**	**$2.0708**	**$1.9861**	**$1.8894**

TABLE B.8i Class 8 day cab tractor, diesel ICEV, MY2020–2050; Figures 4.8 and ES-8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$93,344	$98,661	$101,774	$104,882	$109,497
Financing	$11,430	$12,081	$12,462	$12,843	$13,408
Fuel	$257,579	$215,658	$206,216	$198,720	$198,901
Insurance	$49,086	$49,989	$50,518	$51,047	$51,831
M & R	$121,090	$121,090	$121,090	$121,090	$121,090
Tax & fees	$68,344	$69,765	$70,598	$71,429	$72,662
Payload	$0	$0	$0	$0	$0
Labor	$405,871	$405,871	$405,871	$405,871	$405,871
Total	**$1,006,743**	**$973,116**	**$968,528**	**$965,880**	**$973,259**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.1817	$0.1920	$0.1981	$0.2041	$0.2131
Financing	$0.0222	$0.0235	$0.0243	$0.0250	$0.0261
Fuel	$0.5013	$0.4197	$0.4014	$0.3868	$0.3871
Insurance	$0.0955	$0.0973	$0.0983	$0.0994	$0.1009
M & R	$0.2357	$0.2357	$0.2357	$0.2357	$0.2357
Tax & fees	$0.1330	$0.1358	$0.1374	$0.1390	$0.1414
Payload	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$1.9595**	**$1.8940**	**$1.8851**	**$1.8799**	**$1.8943**

TABLE B.8j Class 8 day cab tractor, diesel/electric PHEV125, MY2020–2050; Figures 4.8 and ES-8

Lifetime Costs	2020	2025	2030	2035	2050
Vehicle	$268,537	$148,398	$122,609	$112,958	$111,283
Financing	$32,882	$18,171	$15,013	$13,832	$13,626
Fuel	$296,104	$228,365	$207,743	$192,727	$182,009
Insurance	$78,861	$58,443	$54,060	$52,419	$52,135
M & R	$101,716	$101,716	$101,716	$101,716	$101,716
Tax & fees	$115,185	$83,063	$76,168	$73,588	$73,140
Payload	$64,491	$19,562	$7,675	$4,531	$2,727
Labor	$405,871	$405,871	$405,871	$405,871	$405,871
Total	**$1,363,646**	**$1,063,587**	**$990,855**	**$957,641**	**$942,507**
Per-Mile Costs	**2020**	**2025**	**2030**	**2035**	**2050**
Vehicle	$0.5227	$0.2888	$0.2386	$0.2199	$0.2166
Financing	$0.0640	$0.0354	$0.0292	$0.0269	$0.0265
Fuel	$0.5763	$0.4445	$0.4043	$0.3751	$0.3543
Insurance	$0.1535	$0.1137	$0.1052	$0.1020	$0.1015
M & R	$0.1980	$0.1980	$0.1980	$0.1980	$0.1980
Tax & fees	$0.2242	$0.1617	$0.1483	$0.1432	$0.1424
Payload	$0.1255	$0.0381	$0.0149	$0.0088	$0.0053
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$2.6541**	**$2.0701**	**$1.9286**	**$1.8639**	**$1.8345**

TABLE B.9 Small SUV, sales-weighted U.S. sales in 2019; Figure 4.9

Lifetime Costs	ICE-SI	HEV	PHEV20	FCEV	BEV300	BEV200
Vehicle	$19,734	$20,392	$32,206	$55,514	$35,025	$36,259
Financing	$2,185	$2,245	$3,345	$5,572	$3,555	$3,680
Fuel	$19,766	$10,463	$13,880	$26,596	$6,747	$7,208
Insurance	$12,510	$12,560	$12,589	$12,523	$12,274	$12,310
Maintenance	$16,302	$14,518	$13,968	$9,829	$8,920	$8,920
Repair	$6,039	$5,565	$6,620	$8,220	$5,389	$5,532
Tax & fees	$4,630	$4,779	$6,147	$8,615	$6,759	$6,869
Total	**$81,165**	**$70,522**	**$88,755**	**$126,870**	**$78,668**	**$80,778**
Per-Mile Costs	**ICE-SI**	**HEV**	**PHEV20**	**FCEV**	**BEV300**	**BEV200**
Vehicle	$0.1057	$0.1092	$0.1725	$0.2973	$0.1876	$0.1942
Financing	$0.0117	$0.0120	$0.0179	$0.0298	$0.0190	$0.0197
Fuel	$0.1059	$0.0560	$0.0743	$0.1424	$0.0361	$0.0386
Insurance	$0.0670	$0.0673	$0.0674	$0.0671	$0.0657	$0.0659
Maintenance	$0.0873	$0.0778	$0.0748	$0.0526	$0.0478	$0.0478
Repair	$0.0323	$0.0298	$0.0355	$0.0440	$0.0289	$0.0296
Tax & fees	$0.0248	$0.0256	$0.0329	$0.0461	$0.0362	$0.0368
Total	**$0.4347**	**$0.3777**	**$0.4754**	**$0.6795**	**$0.4214**	**$0.4327**

TABLE B.10a Small SUV, 5-year ownership, MY2025; Figure 4.10

Lifetime Costs	ICE-SI	ICE-CI	HEV	PHEV50	FCEV	BEV300	BEV200
Vehicle	$16,620	$17,701	$16,798	$21,890	$26,508	$31,375	$25,643
Financing	$2,884	$3,072	$3,019	$3,584	$3,465	$4,672	$3,818
Fuel	$6,658	$6,115	$4,733	$4,682	$8,689	$3,742	$3,547
Insurance	$4,929	$4,969	$4,988	$5,123	$4,924	$5,313	$5,132
Maintenance	$4,562	$4,376	$3,635	$3,492	$2,798	$2,558	$2,558
Repair	$708	$737	$663	$705	$536	$690	$577
Tax & fees	$3,859	$4,024	$4,012	$4,650	$4,726	$5,758	$5,007
Total	**$40,221**	**$40,992**	**$37,849**	**$44,126**	**$51,646**	**$54,108**	**$46,283**
Per-Mile Costs	**ICE-SI**	**ICE-CI**	**HEV**	**PHEV50**	**FCEV**	**BEV300**	**BEV200**
Vehicle	$0.2210	$0.2354	$0.2234	$0.2911	$0.3525	$0.4173	$0.3410
Financing	$0.0384	$0.0409	$0.0402	$0.0477	$0.0461	$0.0621	$0.0508
Fuel	$0.0885	$0.0813	$0.0629	$0.0623	$0.1156	$0.0498	$0.0472
Insurance	$0.0656	$0.0661	$0.0663	$0.0681	$0.0655	$0.0707	$0.0683
Maintenance	$0.0607	$0.0582	$0.0484	$0.0464	$0.0372	$0.0340	$0.0340
Repair	$0.0094	$0.0098	$0.0088	$0.0094	$0.0071	$0.0092	$0.0077
Tax & fees	$0.0513	$0.0535	$0.0534	$0.0618	$0.0629	$0.0766	$0.0666
Total	**$0.5349**	**$0.5452**	**$0.5034**	**$0.5869**	**$0.6869**	**$0.7196**	**$0.6155**

TABLE B.10b Class 8 sleeper cab tractor, 3-year ownership, MY2025; Figure 4.10

Lifetime Costs	ICE-CI	HEV	PHEV250	FCEV	BEV500
Vehicle	$69,292	$73,638	$126,252	$102,042	$182,226
Financing	$14,793	$15,721	$26,953	$21,785	$38,903
Fuel	$130,414	$130,205	$144,327	$349,071	$110,130
Insurance	$30,845	$31,431	$38,527	$35,262	$46,076
M & R	$53,685	$46,706	$45,095	$32,211	$32,211
Tax & fees	$55,600	$57,626	$82,153	$70,867	$108,245
Payload	$0	$327	$36,250	$4,189	$37,882
Labor	$262,666	$262,666	$262,666	$262,666	$262,666
Total	**$617,295**	**$618,319**	**$762,223**	**$878,091**	**$818,339**
Per-Mile Costs	**ICE-CI**	**HEV**	**PHEV250**	**FCEV**	**BEV500**
Vehicle	$0.2084	$0.2215	$0.3797	$0.3069	$0.5480
Financing	$0.0445	$0.0473	$0.0811	$0.0655	$0.1170
Fuel	$0.3922	$0.3916	$0.4341	$1.0498	$0.3312
Insurance	$0.0928	$0.0945	$0.1159	$0.1060	$0.1386
M & R	$0.1615	$0.1405	$0.1356	$0.0969	$0.0969
Tax & fees	$0.1672	$0.1733	$0.2471	$0.2131	$0.3255
Payload	$0.0000	$0.0010	$0.1090	$0.0126	$0.1139
Labor	$0.7900	$0.7900	$0.7900	$0.7900	$0.7900
Total	**$1.8565**	**$1.8596**	**$2.2924**	**$2.6409**	**$2.4612**

TABLE B.11 Small SUV with major component replacement, MY2025; Figure 4.11

Lifetime Costs	ICE-SI	ICE-CI	HEV	PHEV50	FCEV	BEV300	BEV200
Vehicle	$26,051	$27,744	$27,419	$34,505	$34,515	$46,031	$37,621
Financing	$2,884	$3,072	$3,019	$3,584	$3,465	$4,672	$3,818
Fuel	$17,488	$15,939	$12,433	$11,704	$18,118	$9,254	$8,770
Insurance	$13,289	$13,357	$13,376	$12,667	$11,495	$12,870	$12,349
Maintenance	$16,302	$15,714	$14,518	$13,968	$9,829	$8,920	$8,920
Repair	$9,905	$11,019	$9,377	$12,445	$11,577	$28,783	$19,493
Tax & fees	$5,244	$5,409	$5,460	$6,356	$6,763	$7,741	$6,991
Total	**$91,163**	**$92,255**	**$85,601**	**$95,229**	**$95,763**	**$118,271**	**$97,963**
Per-Mile Costs	**ICE-SI**	**ICE-CI**	**HEV**	**PHEV50**	**FCEV**	**BEV300**	**BEV200**
Vehicle	$0.1395	$0.1486	$0.1469	$0.1848	$0.1849	$0.2465	$0.2015
Financing	$0.0154	$0.0165	$0.0162	$0.0192	$0.0186	$0.0250	$0.0205
Fuel	$0.0937	$0.0854	$0.0666	$0.0627	$0.0970	$0.0496	$0.0470
Insurance	$0.0712	$0.0715	$0.0716	$0.0678	$0.0616	$0.0689	$0.0661
Maintenance	$0.0873	$0.0842	$0.0778	$0.0748	$0.0526	$0.0478	$0.0478
Repair	$0.0531	$0.0590	$0.0502	$0.0667	$0.0620	$0.1542	$0.1044
Tax & fees	$0.0281	$0.0290	$0.0292	$0.0340	$0.0362	$0.0415	$0.0374
Total	**$0.4883**	**$0.4941**	**$0.4585**	**$0.5101**	**$0.5129**	**$0.6335**	**$0.5247**

TABLE B.12 Small SUV taxicab, MY2025; Figure 4.12

Lifetime Costs	ICE-SI	ICE-CI	HEV	PHEV50	FCEV	BEV300	BEV200
Vehicle	$29,481	$31,397	$30,860	$36,631	$35,414	$47,753	$39,028
Financing	$2,884	$3,072	$3,019	$3,584	$3,465	$4,672	$3,818
Fuel	$24,067	$22,116	$17,110	$16,969	$32,755	$13,570	$12,860
Insurance	$15,361	$15,430	$15,448	$14,739	$13,567	$14,942	$14,422
Maintenance	$24,857	$23,989	$22,905	$21,672	$15,823	$14,367	$14,367
Repair	$2,087	$2,171	$1,954	$2,078	$1,579	$2,033	$1,700
Tax & fees	$5,244	$5,409	$5,460	$6,356	$6,763	$7,741	$6,991
Total	**$103,982**	**$103,584**	**$96,756**	**$102,029**	**$109,366**	**$105,078**	**$93,187**
Per-Mile Costs	**ICE-SI**	**ICE-CI**	**HEV**	**PHEV50**	**FCEV**	**BEV300**	**BEV200**
Vehicle	$0.1081	$0.1152	$0.1132	$0.1343	$0.1299	$0.1751	$0.1431
Financing	$0.0106	$0.0113	$0.0111	$0.0131	$0.0127	$0.0171	$0.0140
Fuel	$0.0883	$0.0811	$0.0628	$0.0622	$0.1201	$0.0498	$0.0472
Insurance	$0.0563	$0.0566	$0.0567	$0.0541	$0.0498	$0.0548	$0.0529
Maintenance	$0.0912	$0.0880	$0.0840	$0.0795	$0.0580	$0.0527	$0.0527
Repair	$0.0077	$0.0080	$0.0072	$0.0076	$0.0058	$0.0075	$0.0062
Tax & fees	$0.0192	$0.0198	$0.0200	$0.0233	$0.0248	$0.0284	$0.0256
Total	**$0.3814**	**$0.3799**	**$0.3549**	**$0.3742**	**$0.4011**	**$0.3854**	**$0.3418**

TABLE B.13 Class 8 sleeper cab tractor with fueling time costs, MY2025; Figure 4.13

Lifetime Costs	ICE-CI	BEV, 50 kW	BEV, 200 kW	BEV, 400 kW	BEV, 1 MW	BEV, 2 MW
Vehicle	$129,699	$341,088	$341,088	$341,088	$341,088	$341,088
Financing	$14,793	$38,903	$38,903	$38,903	$38,903	$38,903
Fuel	$318,806	$258,583	$258,583	$258,583	$258,583	$258,583
Insurance	$67,898	$96,050	$96,050	$96,050	$96,050	$96,050
M & R	$183,575	$110,145	$110,145	$110,145	$110,145	$110,145
Tax & fees	$90,484	$143,129	$143,129	$143,129	$143,129	$143,129
Payload	$0	$137,918	$92,959	$85,465	$80,970	$79,471
Labor	$619,561	$1,853,517	$927,261	$772,885	$680,259	$649,384
Total	**$1,424,817**	**$2,979,334**	**$2,008,118**	**$1,846,249**	**$1,749,128**	**$1,716,754**
Per-Mile Costs	**ICE-CI**	**BEV, 50 kW**	**BEV, 200 kW**	**BEV, 400 kW**	**BEV, 1 MW**	**BEV, 2 MW**
Vehicle	$0.1657	$0.4356	$0.4356	$0.4356	$0.4356	$0.4356
Financing	$0.0189	$0.0497	$0.0497	$0.0497	$0.0497	$0.0497
Fuel	$0.4072	$0.3303	$0.3303	$0.3303	$0.3303	$0.3303
Insurance	$0.0867	$0.1227	$0.1227	$0.1227	$0.1227	$0.1227
M & R	$0.2345	$0.1407	$0.1407	$0.1407	$0.1407	$0.1407
Tax & fees	$0.1156	$0.1828	$0.1828	$0.1828	$0.1828	$0.1828
Payload	$0.0000	$0.1762	$0.1187	$0.1092	$0.1034	$0.1015
Labor	$0.7913	$2.3673	$1.1843	$0.9871	$0.8688	$0.8294
Total	**$1.8198**	**$3.8052**	**$2.5648**	**$2.3581**	**$2.2340**	**$2.1927**

APPENDIX C: ADDITIONAL SENSITIVITY ANALYSES

This section presents additional sensitivity analyses with different baseline vehicles than those presented in Section 4.3. For LDV, the side cases are presented in Table 4.1, while side cases for MHDV are presented in Table 4.2.

Figures C.1 through C.3 show tornado charts for MY2025 small SUV, assuming a baseline vehicle ownership of five years. These are similar to those for fifteen year, though early-year costs are increased in importance. The 'residual value' term represents scrapping the vehicle at the end of the analysis window; this is an unlikely case as sale to a second owner is much more economical.

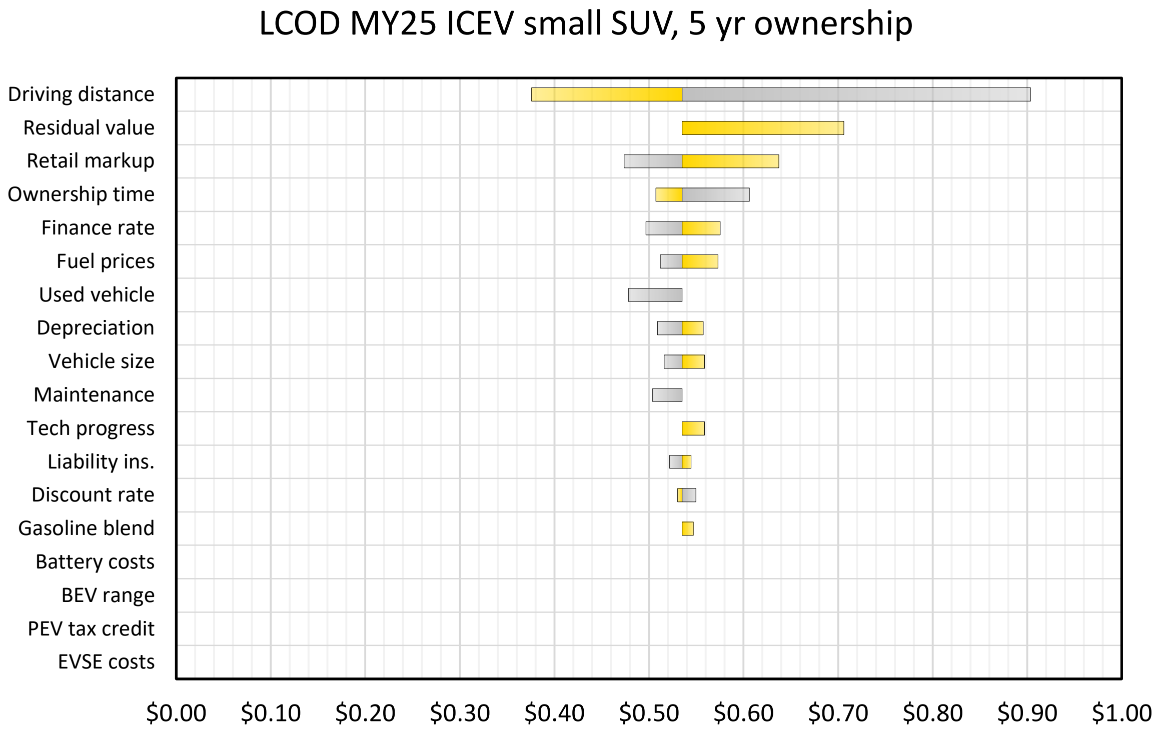


FIGURE C.1 Tornado chart for LCOD of MY2025 small SUV ICEV, 5 year analysis window

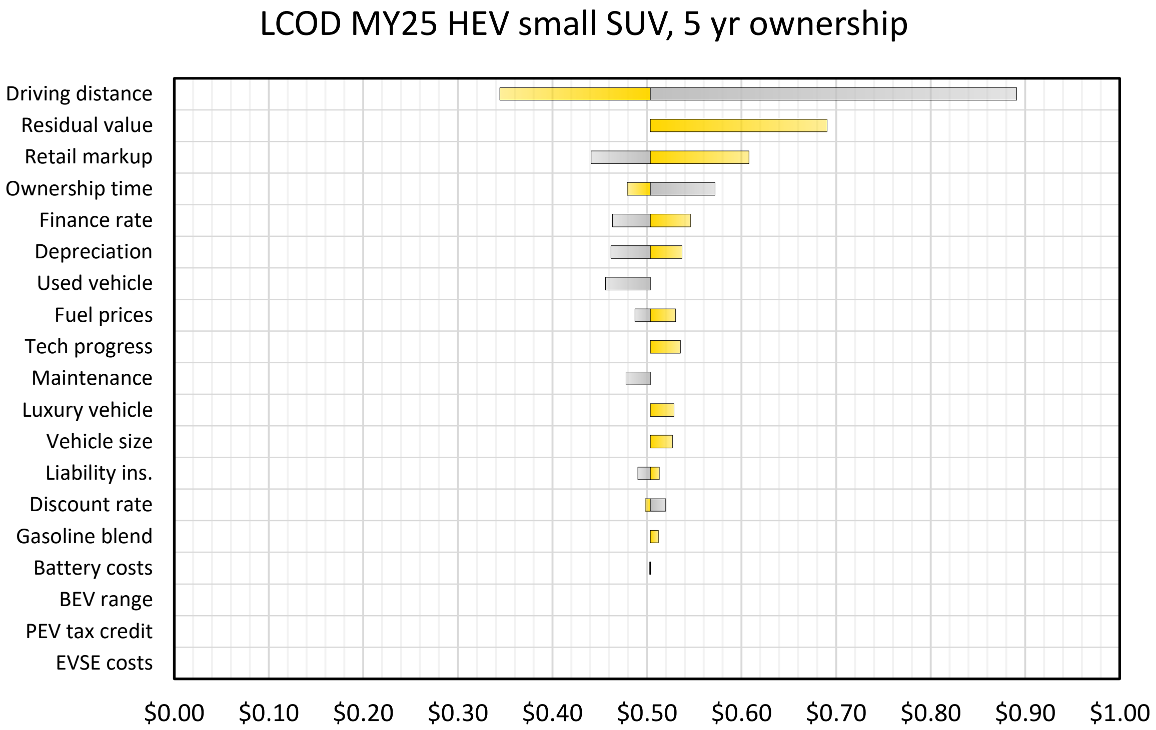


FIGURE C.2 Tornado chart for LCOD of MY2025 small SUV HEV, 5 year analysis window

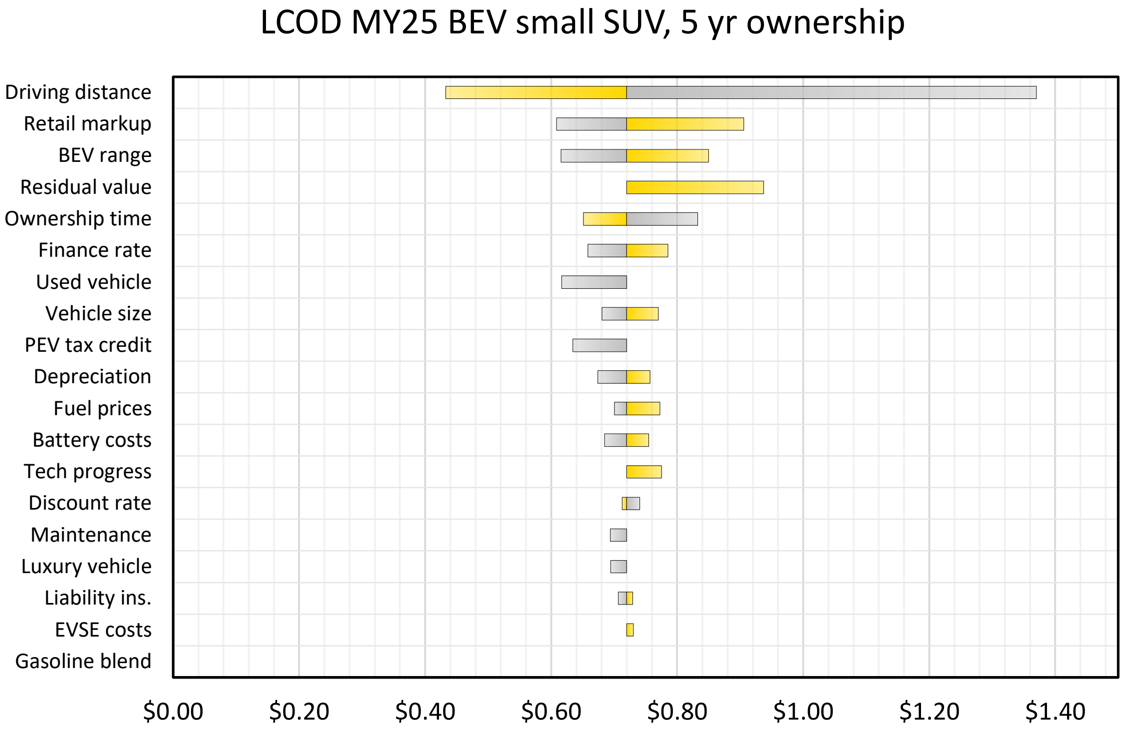


FIGURE C.3 Tornado chart for LCOD of MY2025 small SUV BEV, 5 year analysis window

Figures C.4 through C.6 show tornado charts for MY2025 small SUV, purchased used in 2030, and owned for another ten years afterwards. In these graphics, the BEV has the lowest baseline cost, at 39.4 cents/mile, followed by 41.7 cents/mile for the HEV and 44.4 cents/mile for the ICEV. For most of the side cases, this holds true, including for the low-technology progress side case. In this case, the vehicle has depreciated sufficiently that the initial extra cost for the battery is no longer burdening the second owner.

Uncertainty in maintenance costs is one of the largest factors for each of the powertrains. The results reported by Consumer Reports are lower for all powertrains than those from a typical recommended maintenance schedule, as described in Section 3.5.2. For the BEV, the PEV tax credit is included in a sensitivity case, but for this vehicle, it is a credit that accrues to the first owner, which changes the residual value of the purchase. The 'depreciation' bar is higher in these graphics than in Section 4.3 because there is more uncertainty in the residual value at year 5 than after 15 years, seen as a large difference between the 15th and 85th percentile confidence intervals in residual value. Similarly, the salvage bar is blank for each powertrain because each vehicle retains enough residual value that it would not be preferably scrapped.

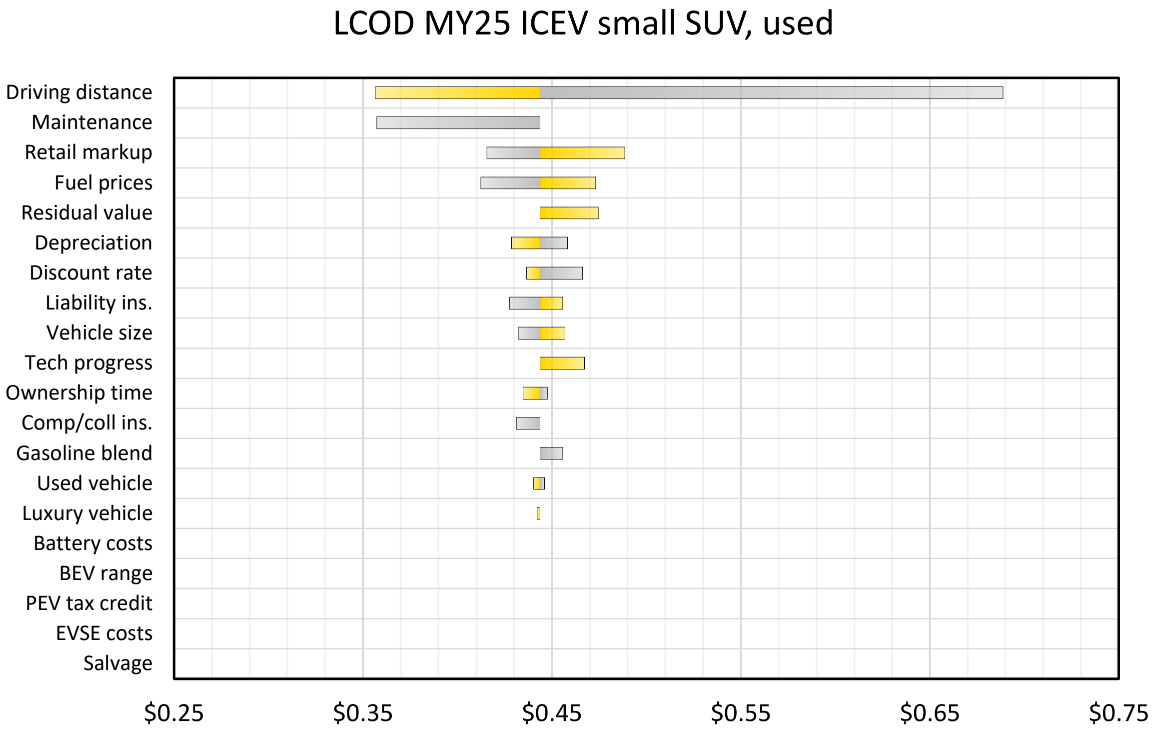


FIGURE C.4 Tornado chart for LCOD of MY2025 small SUV ICEV, purchased used

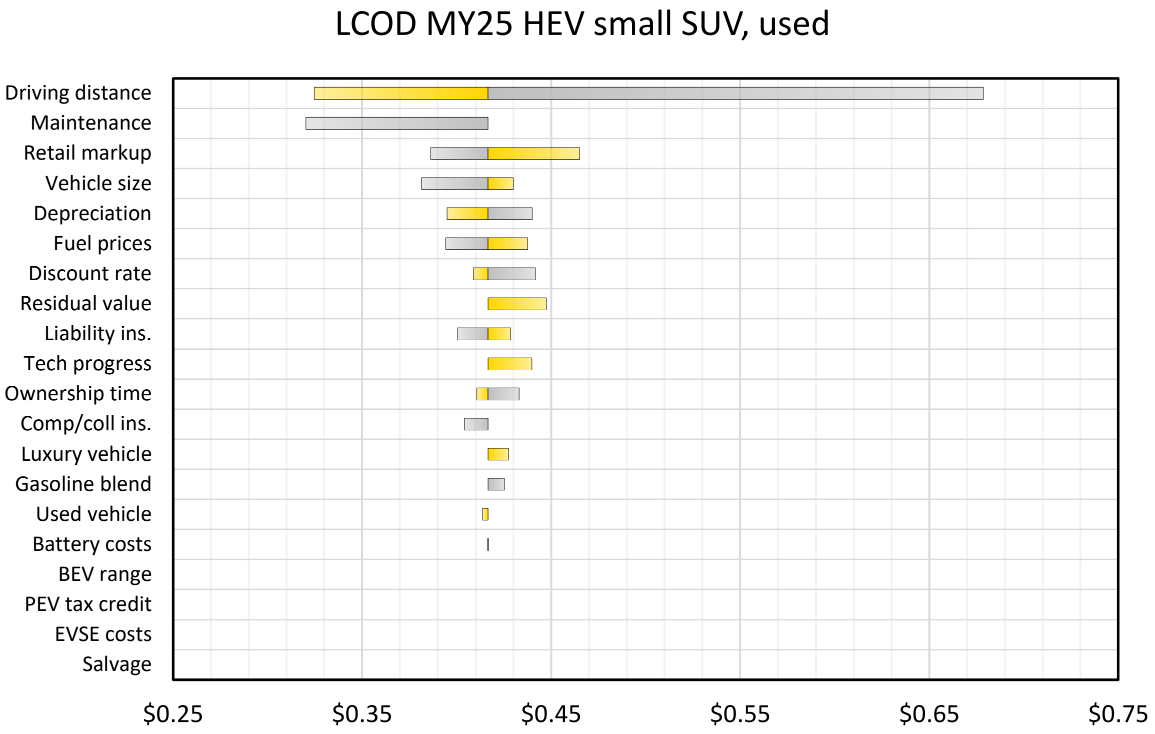


FIGURE C.5 Tornado chart for LCOD of MY2025 small SUV HEV, purchased used

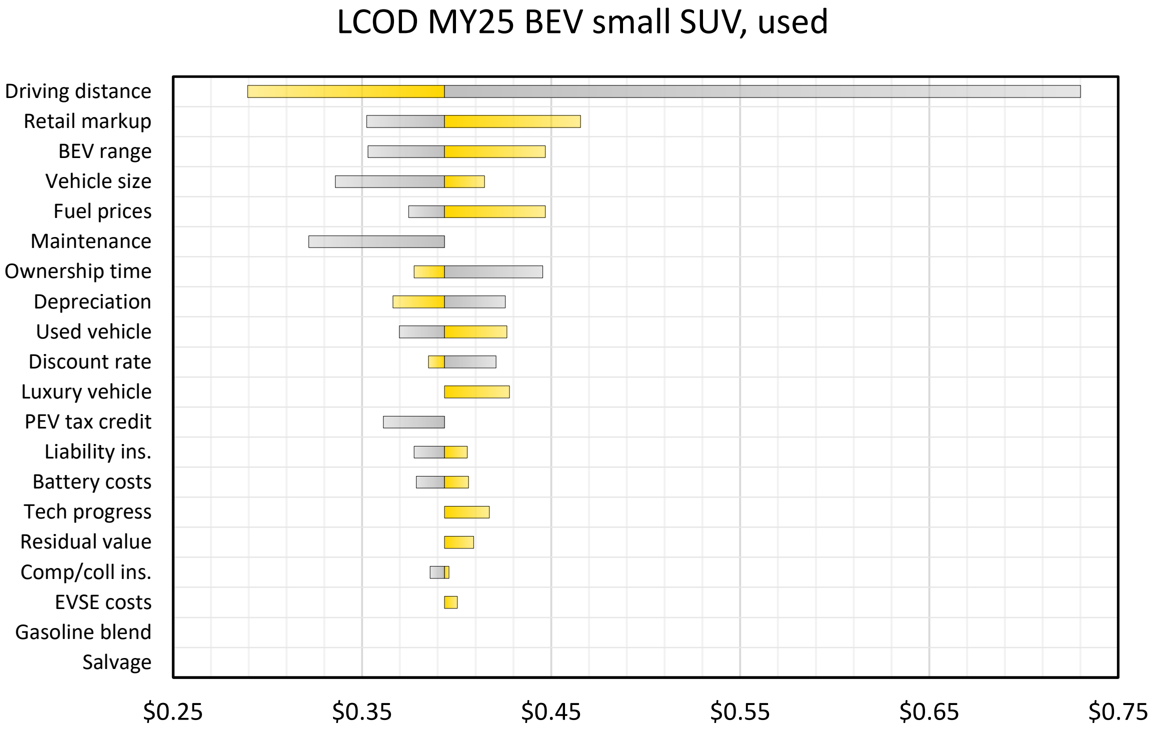


FIGURE C.6 Tornado chart for LCOD of MY2025 small SUV BEV, purchased used

Figures C.7, C.8, and C.9 show tornado charts for costs for real-world vehicles, based on a sales-weighted average of vehicles sold in 2019. The baseline cost of the HEV small SUV is the lowest at 40.6 cents/mile, followed by the BEV300 at 42.1 cents/mile and the ICEV at 44.2 cents/mile. While this analysis does not include RPE markup factors, it does show clear impacts of the vehicle market, especially looking at vehicle size and luxury designation. TCO as a function of vehicle size does not exhibit a clear monotonic trend as in the Autonomie-modeled values. For the ICEV and HEV, the small SUV is lower cost than the midsize sedan, and for the BEV300, the medium SUV has a large premium over the small SUV, at more than double the purchase price. The luxury ICEV and HEV have notable price premiums as well, while the lack of data for the BEV300 is due to the lack of available models in the market. The BEV200 only has a slight reduction in price relative to the BEV300, as opposed to the large difference in prices in the Autonomie modeling.

In most cases the HEV is the cheapest option followed by the BEV, but the BEV becomes the cheapest option when considering a midsize car rather than a small SUV, a used vehicle, long driving distances, or inclusion of the IRS tax credit. In no scenario considered here is the ICEV the lowest-cost option, though an ICEV held for only 5 years and driven lightly can be cheaper than the similarly-owned HEV. Conversely, a BEV held for only 5 years is nearly always the most expensive of the three powertrains, unless is it driven much farther than average.

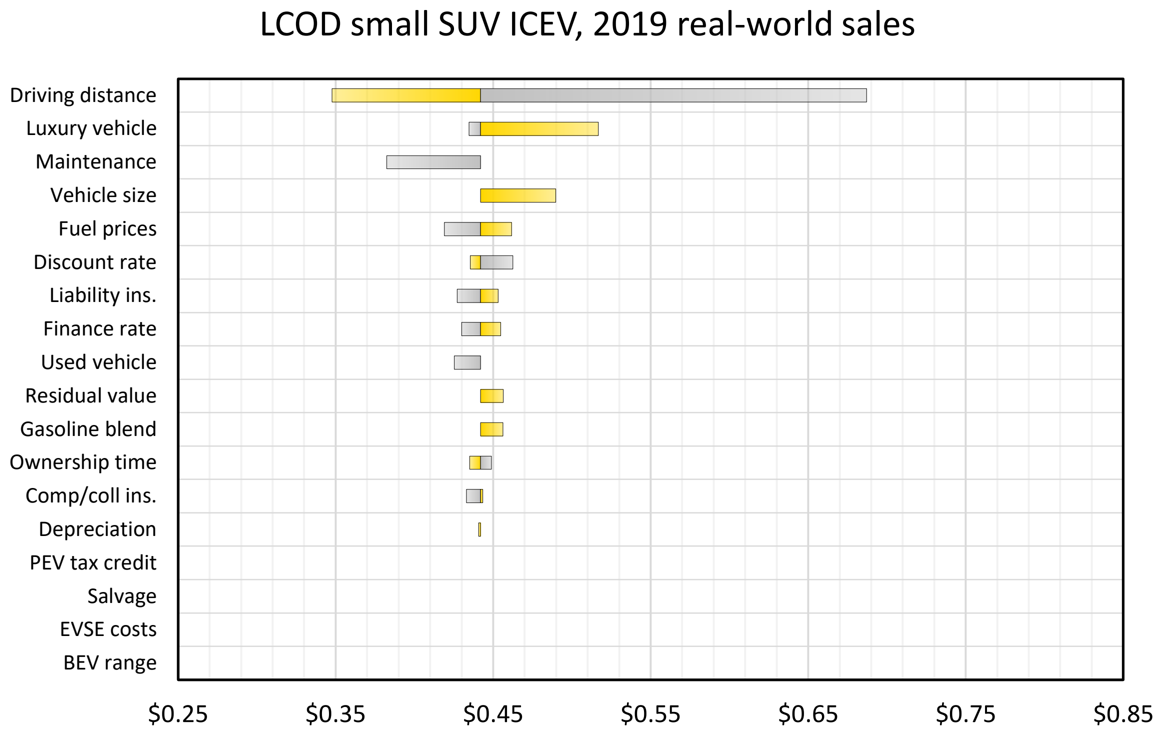


FIGURE C.7 Tornado chart for LCOD of a real-world small SUV ICEV, purchased in 2019

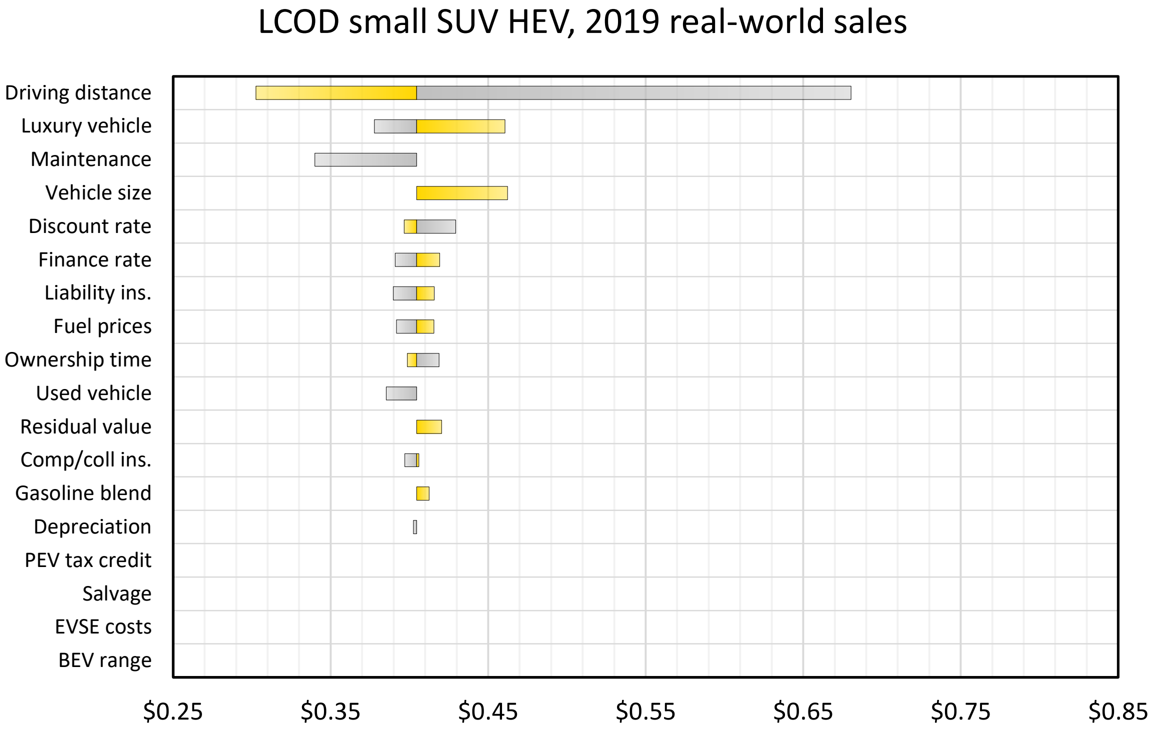


FIGURE C.8 Tornado chart for LCOD of a real-world small SUV HEV, purchased in 2019

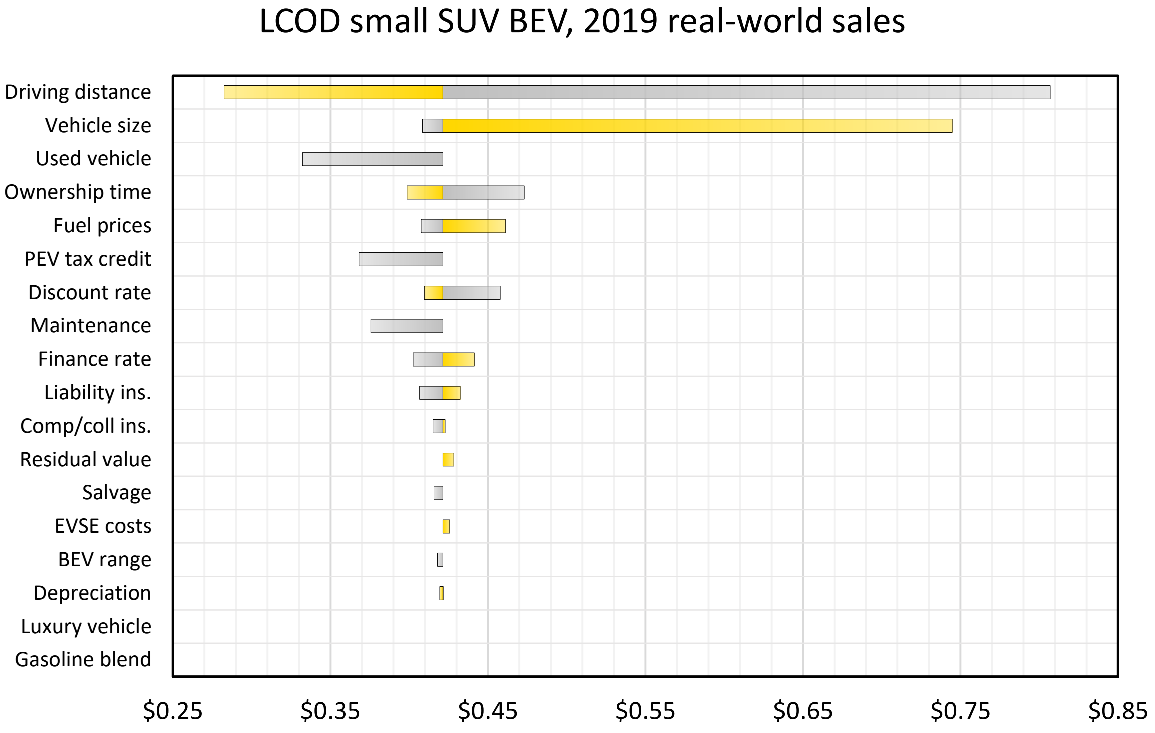


FIGURE C.9 Tornado chart for LCOD of a real-world small SUV BEV300, purchased in 2019

Figures C.10, C.11, and C.12 show tornado charts for costs for the class 4 delivery truck, with a baseline ownership period of 3 years. The baseline case has BEV as the lowest cost powertrain, which holds for many of the sensitivity cases as well. The lowest-cost powertrain is the ICEV for a two-year-old resale, and so the payback for the AFVs are between 2 and 3 years. The side case where the vehicle is scrapped at the end of its 3-year ownership is the highest cost, but this is an unlikely scenario and not plotted on this graphic.

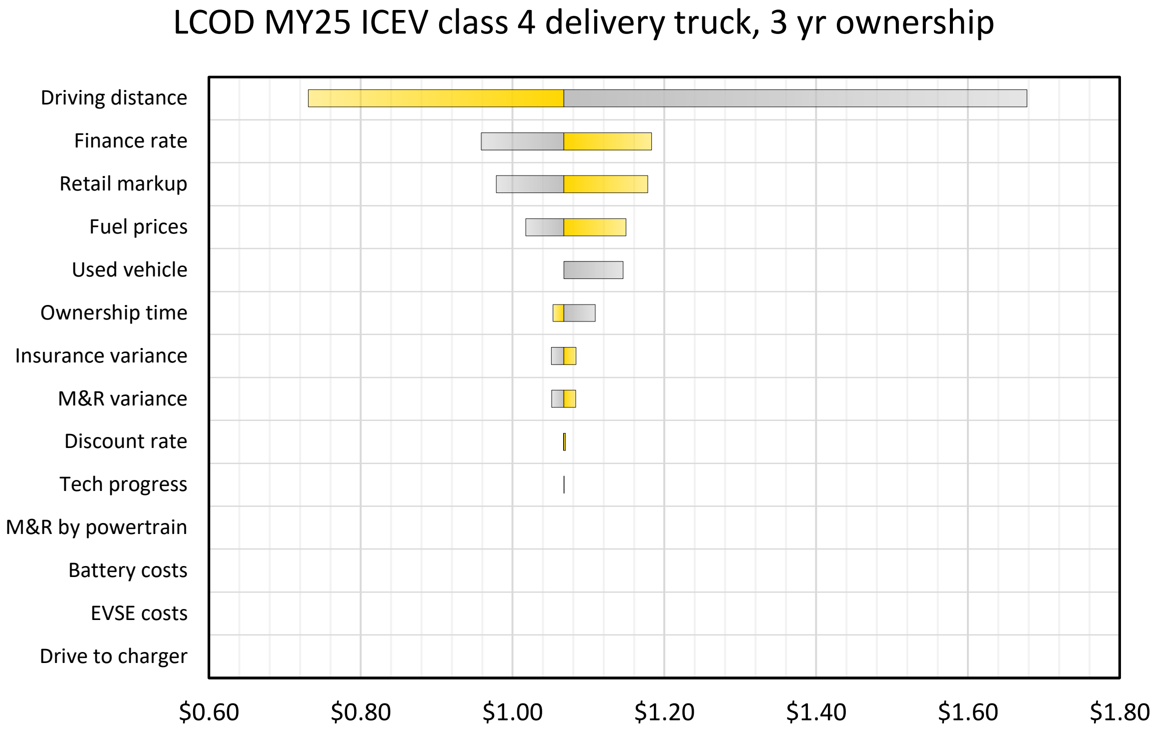


FIGURE C.10 Tornado chart for LCOD of MY2025 class 4 delivery ICEV, 3 year analysis window

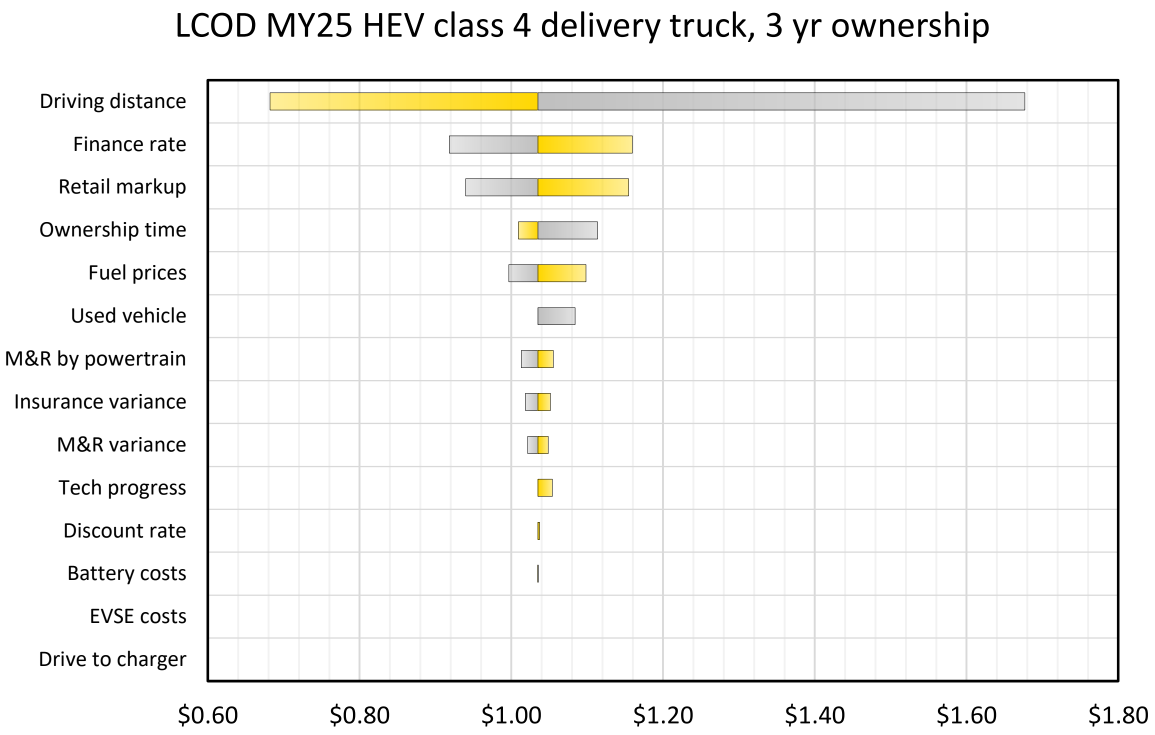


FIGURE C.11 Tornado chart for LCOD of MY2025 class 4 delivery HEV, 3 year analysis window

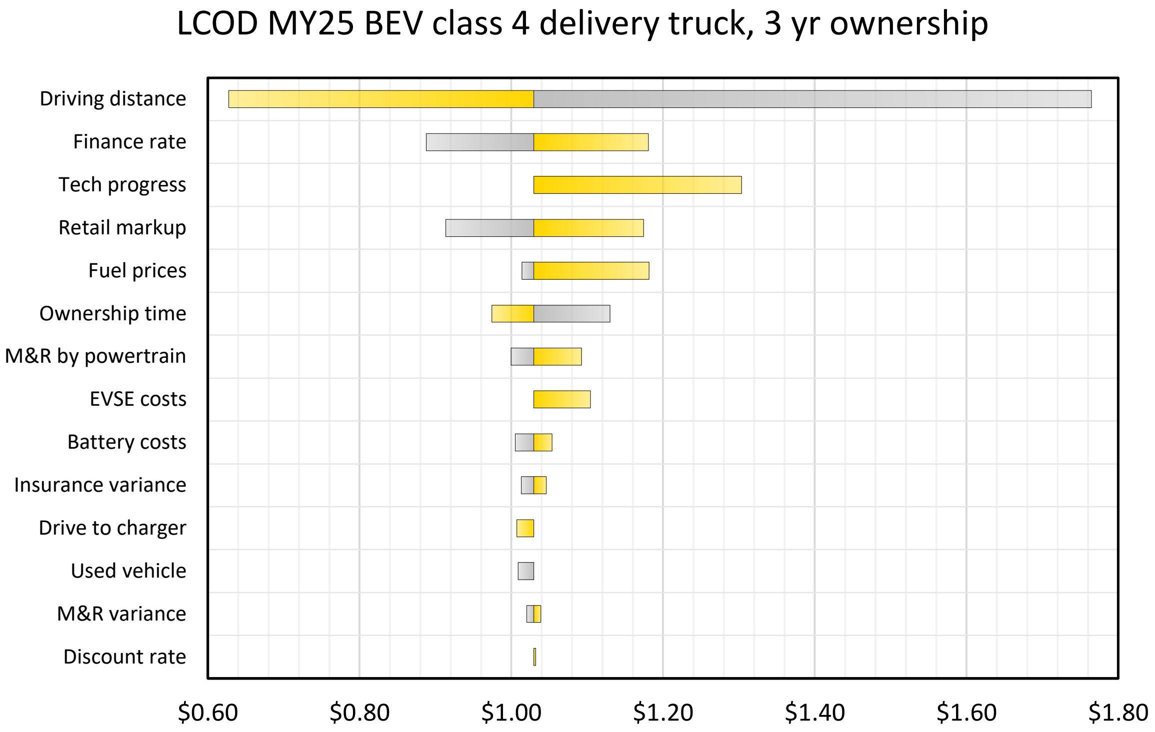


FIGURE C.12 Tornado chart for LCOD of MY2025 class 4 delivery BEV, 3 year analysis window

Figures C.13, C.14, and C.15 show tornado charts for costs for the class 8 day cab tractor trailer with a baseline ownership period of 3 years. The base case HEV is the cheapest vehicle, followed closely by the ICEV. These two vehicles exhibit very similar behavior in their tornado charts, with uncertainty in fuel costs and vehicle costs being the largest. Costs for the hybrid are more sensitive to ownership window, and accounting for reductions in M&R costs for HEV is necessary for the HEV to be the lowest cost powertrain. Each vehicle is most sensitive to variations in the operational parameters, but for the BEV, these costs are comparable to uncertainty in technology development in the next five years.

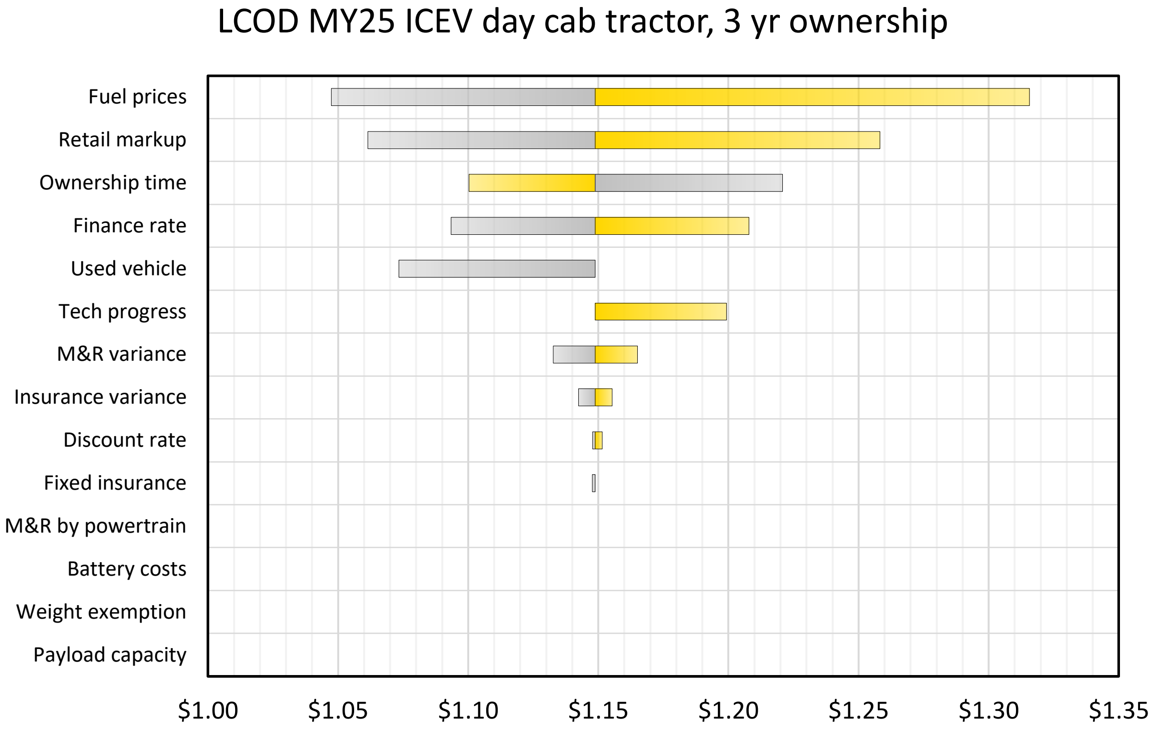


FIGURE C.13 Tornado chart for LCOD of MY2025 class 8 day cab ICEV, 3 year analysis window

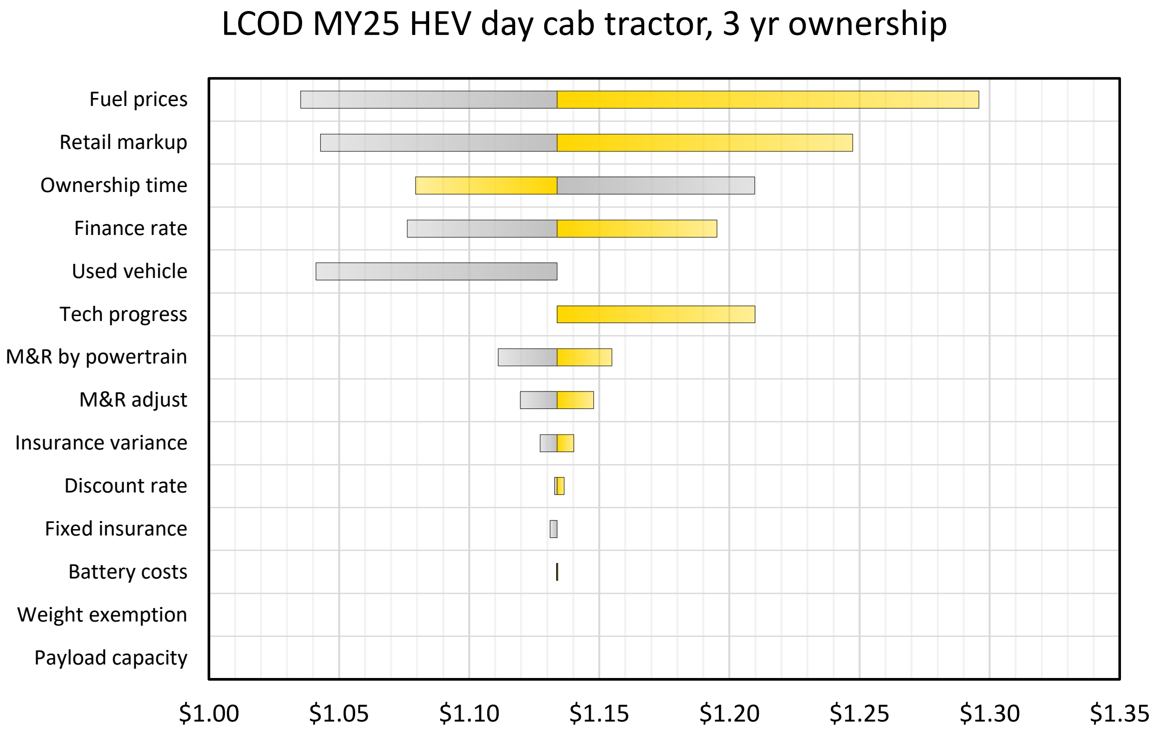


FIGURE C.14 Tornado chart for LCOD of MY2025 class 8 day cab HEV, 3 year analysis window

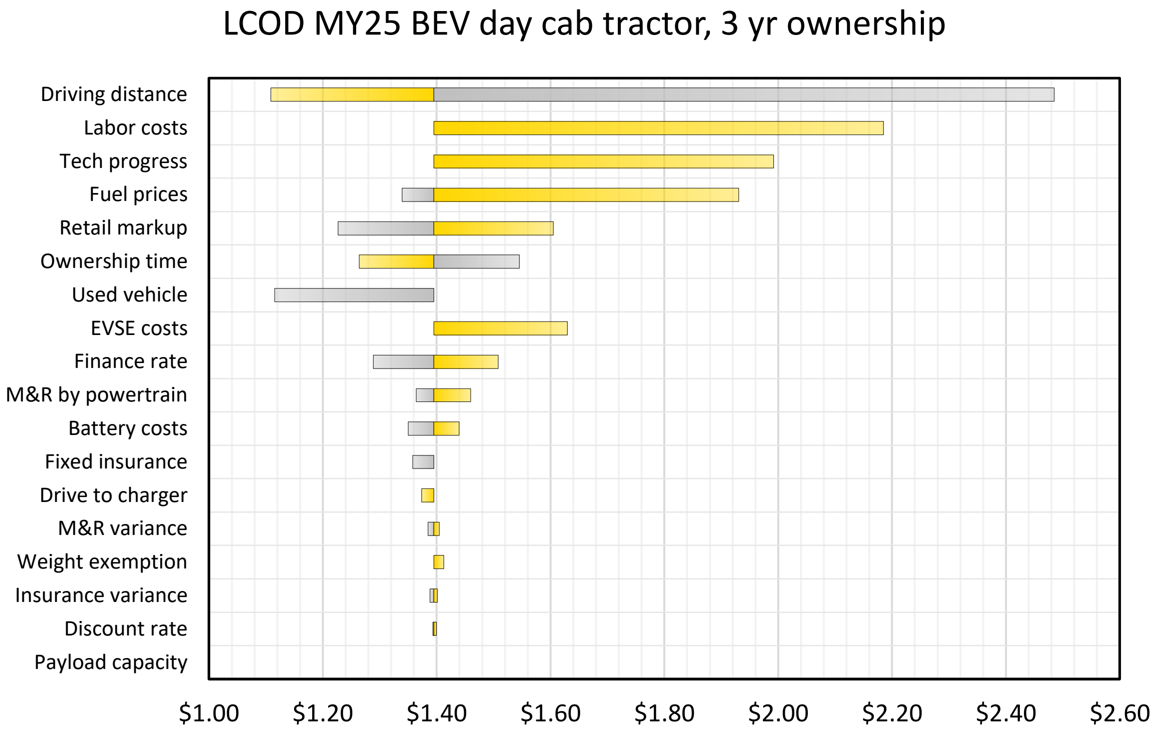


FIGURE C.15 Tornado chart for LCOD of MY2025 class 8 day cab BEV, 3 year analysis window

Figures C.16, C.17, and C.18 show tornado charts for costs for the class 8 sleeper cab tractor trailer with a baseline ownership period of 3 years. Unlike the analysis presented in Section 4.3, the Autonomie modeling shows the ICEV to be the lowest cost powertrain for this first-owner analysis, marginally cheaper than the HEV. The payback period of the HEV technology is approximately 4 years in this analysis.

For the BEV, the uncertainty in technical progress, particularly in lowering battery costs, is the single largest factor, larger even than the cost of labor. Fuel costs can also be quite impactful, particularly if high-power charging is billed at an expensive rate. Fuel costs are also the largest source of uncertainty for the ICEV and HEV sleeper cab tractors, followed by variations in the driving distance.

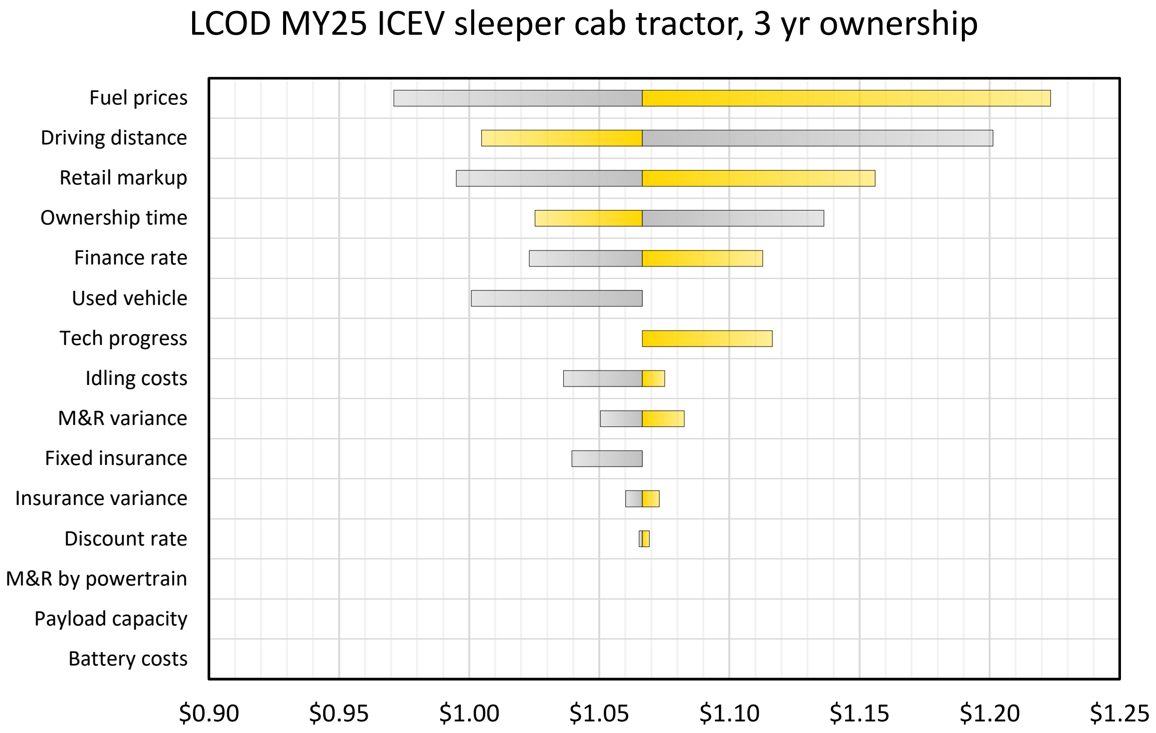


FIGURE C.16 Tornado chart for LCOD of MY2025 sleeper cab ICEV, 3 year analysis window

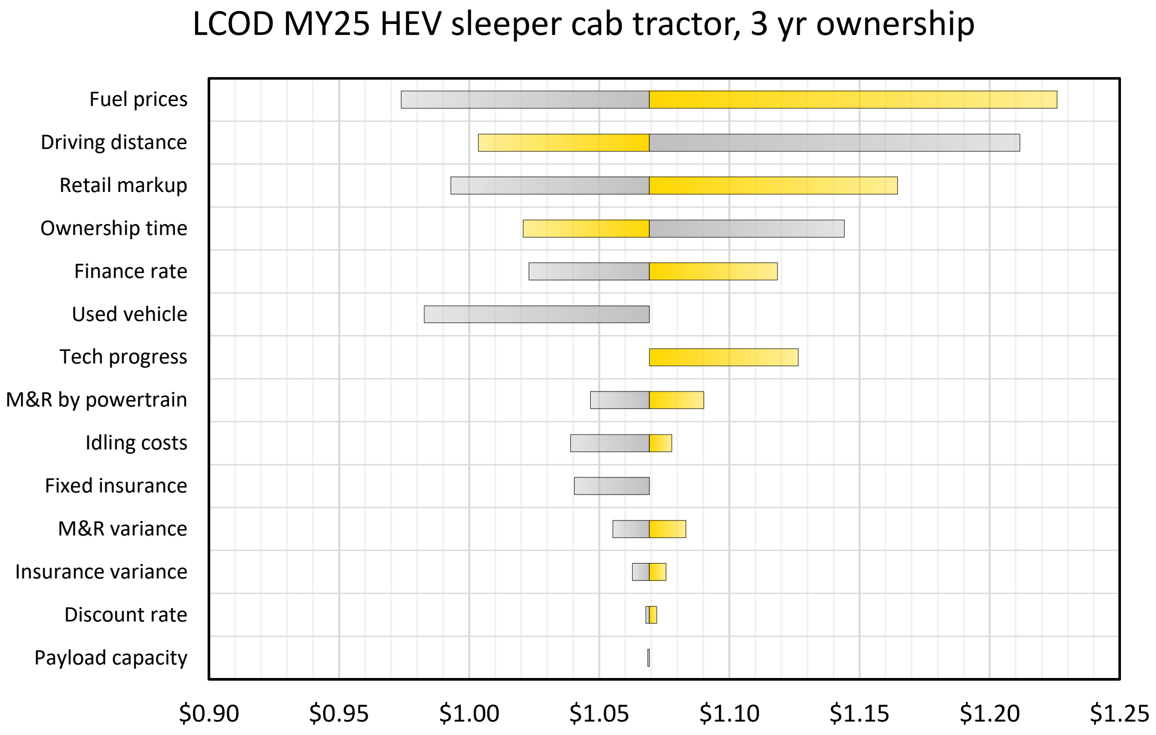


FIGURE C.17 Tornado chart for LCOD of MY2025 sleeper cab HEV, 3 year analysis window

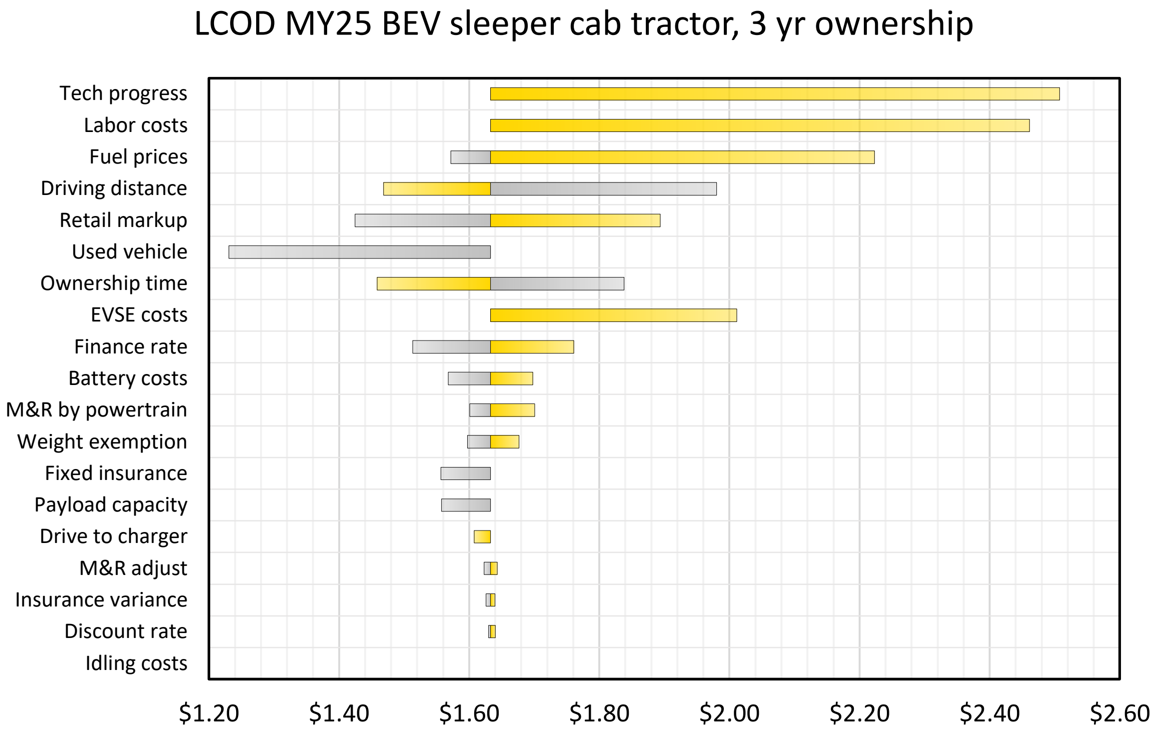


FIGURE C.18 Tornado chart for LCOD of MY2025 sleeper cab BEV, 3 year analysis window

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