Class 7 and Class 8 Tractor–Trailer Electrification for MYs 2030 and 2032

This report has been prepared for

Environmental Defense Fund

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SUGGESTED CITATION

V. Nair, H. Saxena, S. Pillai*, “Class 7 and Class 8 Tractor–Trailer Electrification for MYs 2030 and 2032,” June 2023. Roush.

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Abbreviations and Acronyms

AEO	Annual Energy Outlook
ANL	Argonne National Laboratory
BEV	Battery Electric Vehicle
CARB	California Air Resources Board
C_d	Coefficient of Drag
CMV	Commercial Motor Vehicle
DCFC	DC Fast Charger
DMC	Direct Manufacturing Costs
DRIA	Draft Regulatory Impact Analysis
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EVSE	Electric Vehicle Supply Equipment
FCEVs	Fuel Cell Electric Vehicles
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GHG	Greenhouse Gas
GCW	Gross Combination Weight
GVW	Gross Vehicle Weight
HDVs	Heavy-Duty Vehicles
HVAC	Heating, Ventilation, and Air Conditioning
ICEV	Internal Combustion Engine Vehicle
IRA	Inflation Reduction Act
kWh	Kilowatt-hour
LCVs	Longer Combination Vehicles
LDV	Light-Duty Vehicle
M&R	Maintenance and Repair
MDHD	Medium-Duty and Heavy-Duty
MY	Model Year
NOx	Nitrogen Oxides
OEMs	Original Equipment Manufacturers
RIA	Regulatory Impact Analysis
RPE	Retail Price Equivalent
TCO	Total Cost of Ownership
V2V	Vehicle-to-Vehicle
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
ZEV	Zero-Emission Vehicle

Executive Summary

The transportation industry plays a crucial role in moving 11 billion tons of freight, accounting for about 72% of the total domestic cargo shipped in the US, according to the ATA, covering a distance of about 3 trillion vehicle miles annually [1], [2]. Interestingly, a significant portion of the weight (50%) and value (37%) of goods transported are moved within a distance of less than 100 miles [1]. However, it's important to highlight that heavy-duty vehicles (HDVs) typically run on diesel engines and are responsible for almost a quarter of the emissions from the transportation sector [3].

The United States is well-positioned to transition to electric Heavy-Duty trucks thanks to supportive policies, technological advancements, and emerging business models. The Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA) provide tax incentives and other government support to electrify HDVs and build out relevant infrastructure. In addition, the newly proposed regulations, such as the EPA's Greenhouse Gas Emission Standards for Heavy-Duty Vehicles: Phase 3 [3], will further accelerate the deployment of zero-emission vehicles (ZEVs).

Study Overview

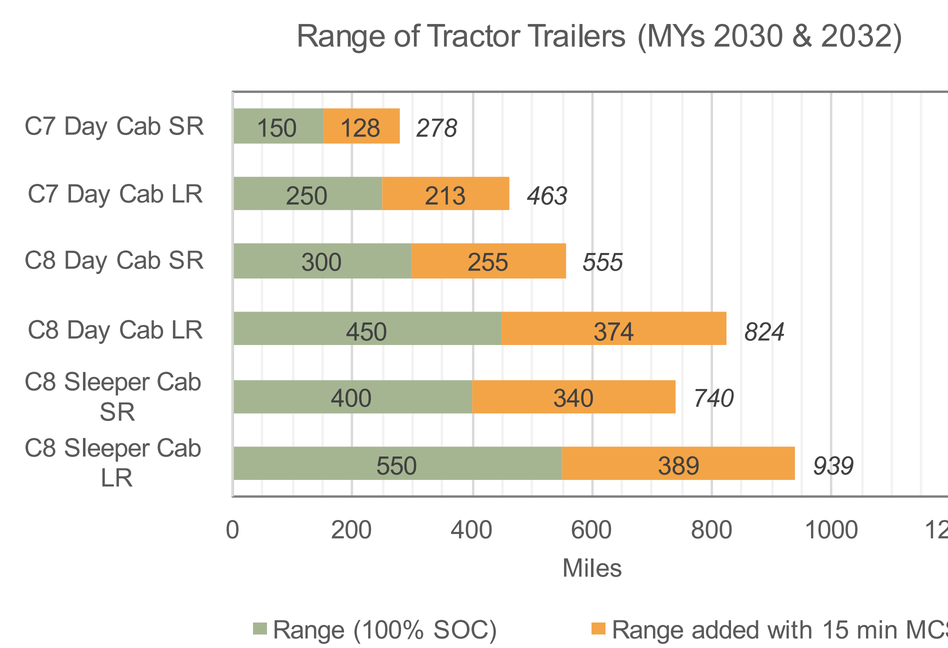
This study analyzes the potential electrification of MYs 2030 and 2032, 5-axle, single trailer Classes 7 and 8 tractors used to transport a significant fraction of road freight. It evaluates the market, vehicle usage statistics, use cases, driving patterns, and routes to select representative vehicles and ranges. We modeled the representative MY 2030-2032 vehicles in GT-Suite to estimate the energy consumption, battery capacity, and drivetrain (traction motor and inverter) power output. We assume that 90% of the battery capacity is usable with an additional 10% upsize to compensate for battery degradation over the vehicle's 10-year lifespan.

All costs are presented in 2022 dollars unless specified otherwise. The analysis assumes a 10-year vehicle life and considers vehicle powertrain, fuel, maintenance, and depot charging infrastructure costs. The TCO also factors in IRA tax credits but excludes staffing and labor costs, scrap or resale value, insurance, taxes, grants, subsidies, and intangible benefits. The results include the TCO per mile, payback period, and cumulative net savings of battery electric vehicles (BEVs) over the ownership period compared to internal combustion engine vehicles (ICEVs, or diesel vehicles).

Range of representative BEVs chosen to maximize depot charging.

The electric range of the representative Class 7/8 vehicles chosen is such that a significant portion of the trips can be completed on a single charge, ensuring that a large proportion of the charging can occur at the depot. Depot charging takes advantage of the lower energy cost ($/kWh) of captive charging infrastructure. Figure 1 shows the different BEVs, their electric range on a full charge (in green), and the gross battery capacity (kWh).

Figure 1 also shows the electric range that can be added with a 15-minute charge (in orange) on a 3,000 Amp Megawatt Charging System (MCS) and the total effective vehicle range. While depot charging can be adequate for a significant number of battery electric tractors, MCS stations along major freight corridors could be a game changer with respect to the suitability of BEVs for a broad spectrum of tractor applications–extreme weather, payloads, grades, high daily vehicle miles traveled (VMT), continuous running by swapping drivers, etc. Alternatively, with the buildout of MCS stations, electric tractors can have significantly smaller batteries, further improving the economics of BEVs compared to ICEVs.



	Battery kWh#	Test wt. lb
C7 Day Cab SR	271	44,000
C7 Day Cab LR	451	44,000
C8 Day Cab SR	688	72,000
C8 Day Cab LR	1,033	72,000
C8 Sleeper Cab SR	890	72,000
C8 Sleeper Cab LR	1,224	72,000

LR - Long range, SR - Standard range, # Gross battery capacity

Figure 1: Battery size (kWh), range (miles), test weight (lb), and the range added with a 15-minute charging session at a Megawatt Charging System (MCS) station.

The cargo capacity of most BEVs will be at par with diesel vehicles.

The advancements in battery chemistry and pack construction will significantly improve the energy density of the battery pack between 2023 and 2030. This improvement, combined with the 2,000 lb gross vehicle weight (GVW) exemption[1] for BEVs, will minimally affect the cargo capacity of BEVs. In the case of the Class 8 sleeper-cab long-range tractor, which has the largest battery pack in our study at 1,224 kWh, we estimate a small reduction in cargo capacity of approximately 1,208 lb (as illustrated in Figure 1). For other BEVs with smaller battery packs, the impact of cargo capacity will be lower. All projections assume an NMC battery chemistry.

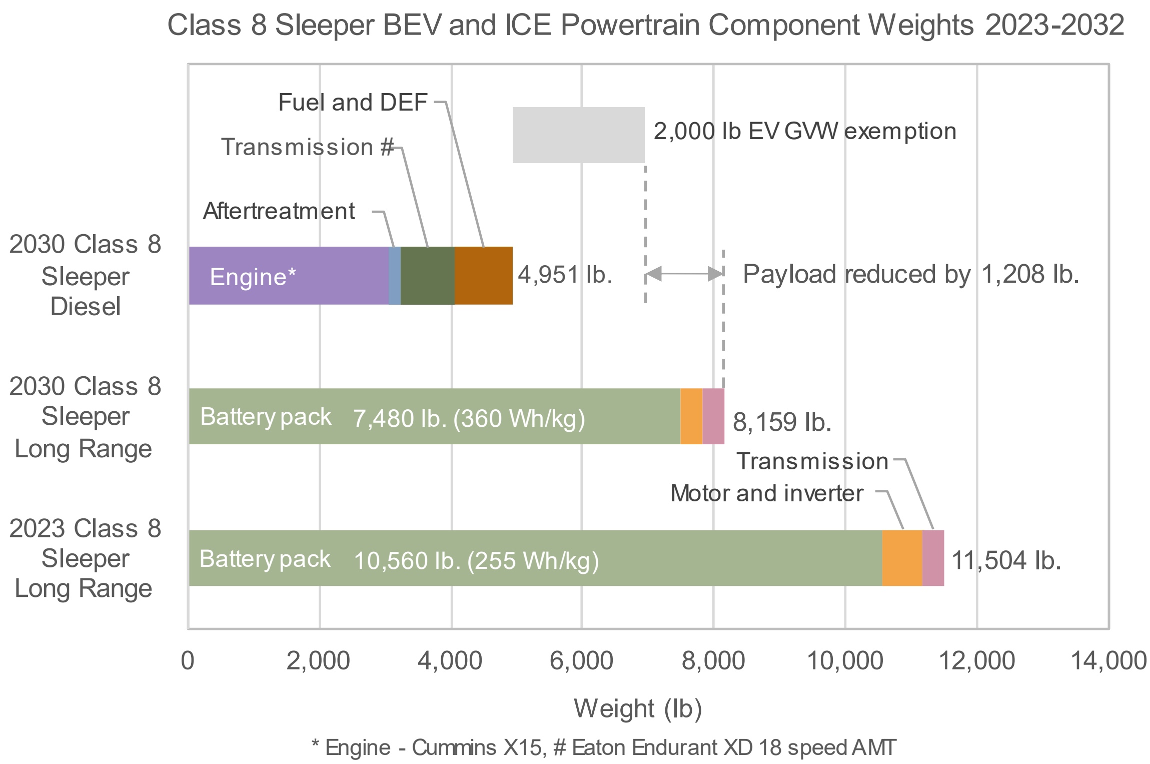


Figure 2: Comparison of the powertrain weight of Class 8 Sleeper long-range diesel and electric powertrains, respectively

With the IRA credits, most BEVs' effective powertrain retail price is at par or cheaper than diesel vehicles.

The cost estimates for diesel powertrains are based on the EPA Draft RIA's HD TRUCS technology assessment tool, adjusted to reflect in 2022 $. On the other hand, the cost estimates for BEV powertrains are sourced from teardown studies, various literature

[1] 23 U.S. Code § 127 - Vehicle weight limitations—Interstate System [59] (s) Natural Gas and Electric Battery Vehicles - A vehicle, if operated by an engine fueled primarily by natural gas or powered primarily by means of electric battery power, may exceed the weight limit on the power unit by up to 2,000 pounds (up to a maximum gross vehicle weight of 82,000 pounds) under this section.

sources, and our evaluations. To be conservative in our estimates, we assume higher direct manufacturing costs (DMCs) for domestically produced batteries compared to the global average. We anticipate a widespread availability of domestically produced batteries due to the significant onshoring of battery manufacturing facilitated by the IRA of 2022. The high lifetime VMTs of Class 7/8 tractors and fast DC (MCS) charging impose significant cycle life requirements (distinct from LDVs and MDVs) on the battery chemistry. The higher battery costs in this report consider these unique requirements. Also, the motor and power electronics costs assumed in this report are higher, factoring in the specific design and extreme durability requirements of Class 7/8 tractors.

It is important to note that the cost of battery packs for these commercial vehicles could be significantly lower, as automakers can choose cells and modules manufactured outside the United States. This would allow them to further reduce their powertrain costs. Currently the vehicle tax credits do not mandate the use of domestically produced batteries. Nonetheless, we have considered the projected cost of a battery pack produced and assembled domestically to apply battery tax credits.

Table 1 compares the effective powertrain DMC with the RPE of BEVs and diesel vehicles. The figures in Table 1 incorporate the IRA credits for domestic battery manufacturing (26 U.S.C. §45X) and vehicle tax credits (26 U.S.C. §45W). Our analysis assumes that the glider (the bare chassis without the powertrain components) remains the same for both BEVs and ICEVs. Consequently, the credits are utilized to calculate the effective powertrain DMCs with RPE.

Table 1: Comparison of effective powertrain cost with RPE of ICEVs and BEVs factoring in DMC, RPE, and IRA Credits (vehicle and battery tax credits)

Vehicle Categories	MY 2030		MY 2032	
	ICEV	BEV	ICEV	BEV
Class 8 Sleeper Long Range	$97,128	$97,128	$97,128	$105,963
Class 8 Sleeper Standard Range	$95,477	$95,477	$95,477	$95,477
Class 8 Day Cab Long Range	$96,933	$96,933	$96,933	$96,933
Class 8 Day Cab Standard Range	$90,886	$83,478	$90,886	$89,390
Class 7 Day Cab Long Range	$73,014	$55,852	$73,014	$59,536
Class 7 Day Cab Standard Range	$72,819	$39,013	$72,819	$40,930

BEV is higher than ICEV with IRA credits
BEV is equal to ICEV with IRA credits
BEV is lower than ICEV, so no IRA vehicle credits

The advanced manufacturing production credit (26 U.S.C. §45X) under the IRA of 2022 substantially reduces the effective costs of domestically produced batteries for the manufacturers. Additionally, the vehicle tax credit (26 U.S.C. §45W) reduces the price of BEVs for end consumers. Across all vehicle categories examined, these credits bring the prices of BEVs on par, or nearly on par, with those of ICEVs in MYs 2030 and 2032.

TCO of BEVs is significantly lower than ICEVs across all segments.

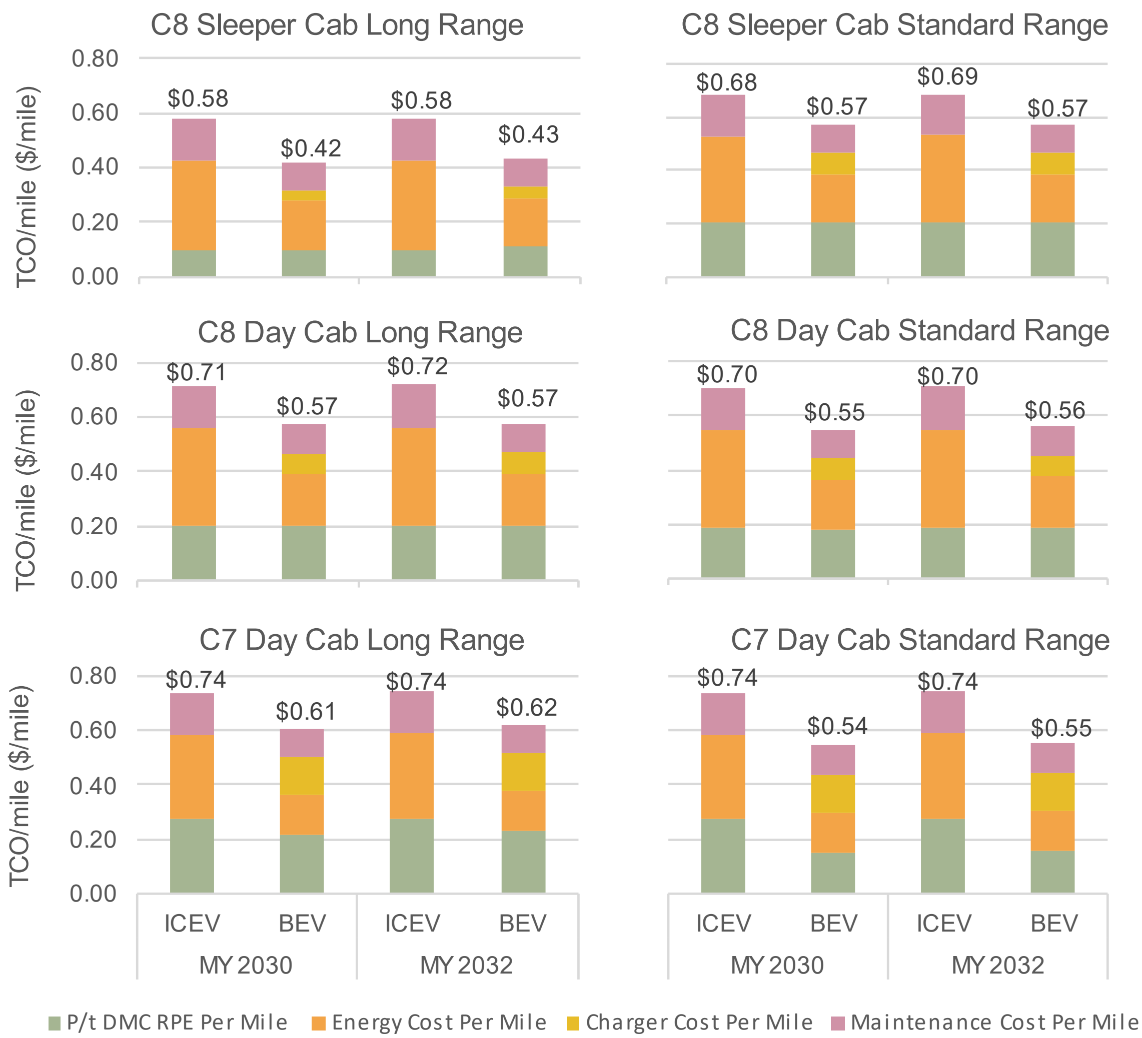


Figure 3: TCO per mile and its components for Class 7/8 vehicles in the primary analysis

BEVs offer a TCO per mile that is 17-35% lower than comparable ICEVs, depending on the vehicle category. This translates to savings of 11 cents per mile for a Class 8 sleeper cab tractor with a long-range battery pack and up to 20 cents per mile for a Class 7 day cab tractor with a standard-range battery pack (as illustrated in Figure 3). The primary factor contributing to these TCO savings is the lower energy and maintenance costs (30% lower when compared ICEVs) associated with BEVs per mile. Additionally, certain vehicles, like the Class 7 tractors, have considerably lower powertrain costs (due to smaller battery sizes), further reducing their TCO per mile.

Across all vehicles studied, BEVs reach TCO parity in less than 3 years (as indicated in Table 2). It's important to note that this study assumes the same annual VMT for a couple of sets of different vehicles (e.g., both standard- and long-range Class 8 day and sleeper cabs), as outlined in the EPA Phase 3 Draft Regulatory Impact Analysis (DRIA) [3].

Table 2: Years to reach TCO parity

Vehicle Categories	Annual VMT (miles)	Payback Period (in years)	
		MY 2030	MY 2032
C8 Sleeper Cab Long Range	97,935	1	2
C8 Sleeper Cab Standard Range	46,636	3	3
C8 Day Cab Long Range	47,634	3	3
C8 Day Cab Standard Range	47,634	2	3
C7 Day Cab Long Range	26,576	3	3
C7 Day Cab Standard Range	26,576	<1	<1

BEVs have a lower TCO per mile, even with significant en route charging.

By utilizing an assumed combination of 70% depot charging and 30% en route charging (en route charging used to charge from a SOC of 20% to 80% on 50% of the days using a 3,000 Amp Megawatt Charging System (MCS)), the TCO for BEVs remains 9% to 20% lower than that of diesel vehicles (a saving of 5 to 15 cents per mile), as depicted in Figure 4. With the inclusion of en route charging, the payback period extends slightly, but it remains less than five years for all vehicles, as indicated in Table 3.

Adequate charging infrastructure would enable electric tractors to utilize smaller battery packs, reducing powertrain costs and further enhancing the economic advantages of BEVs over ICEVs. This study did not quantify this potential. The EPA did not consider en route charging in their proposal.

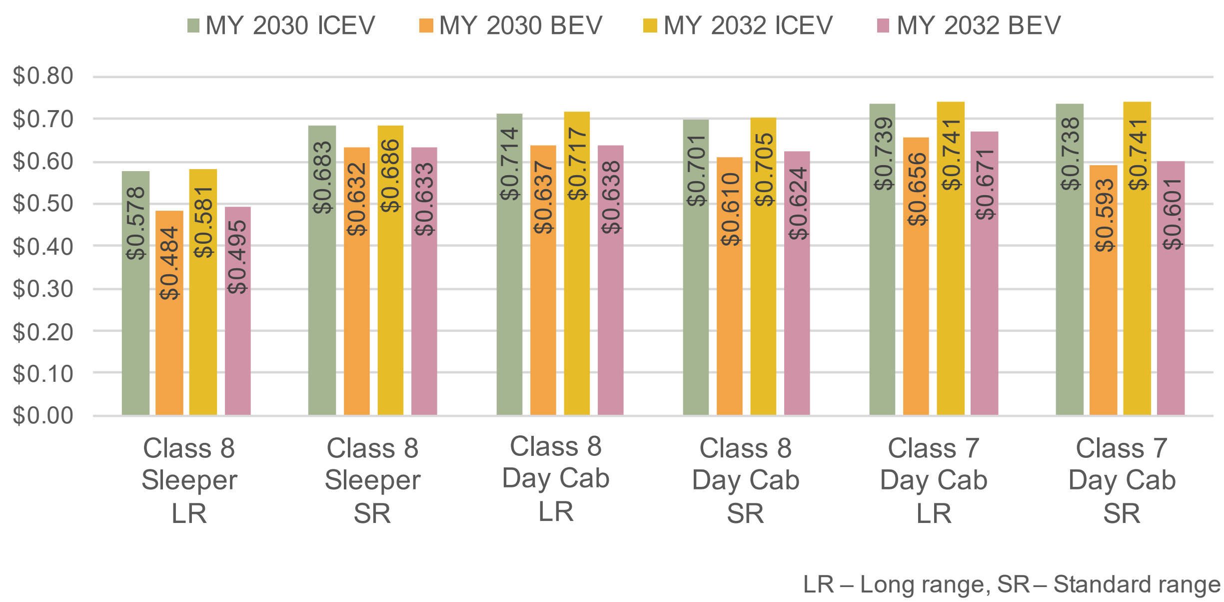


Figure 4: Comparison of the total cost of ownership (TCO) in $/mile in a mixed charging scenario (70% Depot and 30% En route MCS) across MYs 2030 and 2032

Table 3: Payback period in a mixed charging scenario (70% Depot, 30% En route MCS)

Vehicle Categories	Payback Period (in years)	
	MY 2030	MY 2032
C8_SC_Long Range	2	3
C8_SC_Standard Range	5	5
C8_DC_Long Range	4	4
C8_DC_Standard Range	3	4
C7_DC_Long Range	4	5
C7_DC_Standard Range	<1	1

Higher annual operational VMTs lead to an even shorter payback period for BEVs.

BEVs' energy (electricity) cost per mile is between 14.5 and 17.0 cents lower than the comparable ICEVs. Furthermore, BEVs have a maintenance cost advantage of approximately 5 cents per mile. Since the operating cost per mile of BEVs is significantly lower than ICEVs, the higher the annual VMT, the higher the annual savings of the BEV. Therefore, as the annual VMT increases, the annual savings of BEVs increase, and the payback period decreases, as illustrated in Figure 5.

The average operational daily VMT used to calculate TCO (in the baseline analysis 1VMT in Figure 5) represents 42% to 71% of the BEV range (as shown in Table 4). Given this battery sizing, the tractors can cover significantly higher daily VMTs without charging en route. This has the potential to reduce TCO per mile and Payback period further.

Table 4: Daily sizing VMT and operational VMT (MYs 2030 and 2032)

Vehicle	Daily Sizing VMT/Range (miles)	10 yr Average Daily Operational VMT (miles)	Operational VMT/Sizing VMT
C8 Sleeper Cab Long Range	550	392	71%
C8 Sleeper Cab Standard Range	400	187	47%
C8 Day Cab Long Range	450	191	42%
C8 Day Cab Standard Range	300	191	64%
C7 Day Cab Long Range	250	106	42%
C7 Day Cab Standard Range	150	106	71%

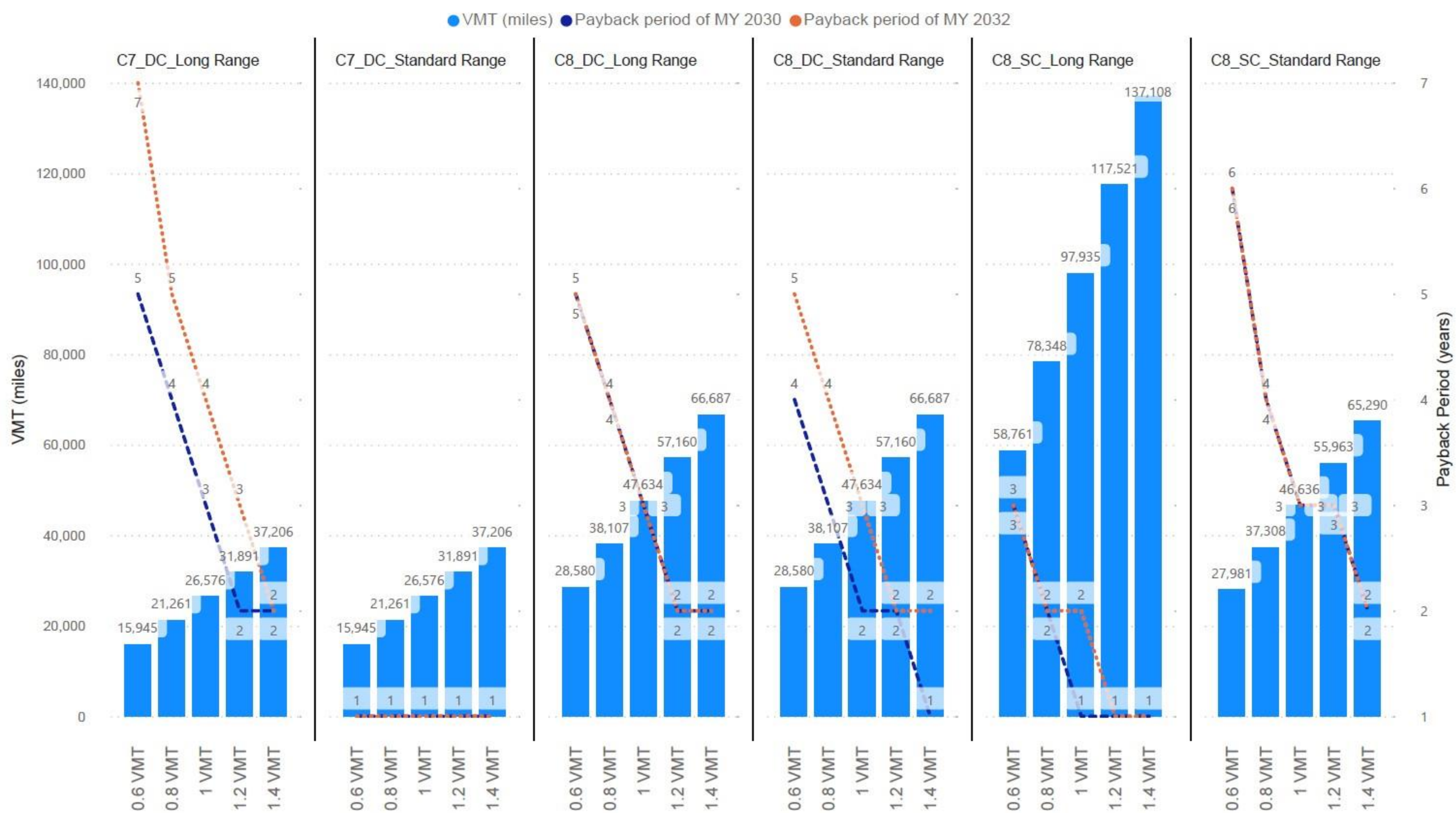


Figure 5: Effect of annual VMT on the payback period (1 VMT represents the VMT used in primary analysis)

Different GVWs do not increase the payback period of BEVs.

To ascertain the impact of GVWs on the cost of ownership (primary analysis assumed a GVW of 72,000 lb), we analyzed the Class 8 tractor-trailers for different GVWs. Based on our BEV powertrain sizing and available fuel consumption data of diesel tractors, the energy consumption of diesel vehicles increases marginally more than BEVs at high GVWs. This results in a small reduction in the BEV payback period at high GVWs (Figure 6). At 80,000 lb GVW, the time to parity of BEVs decreases by a year except for the Class 8 Day cab standard range.

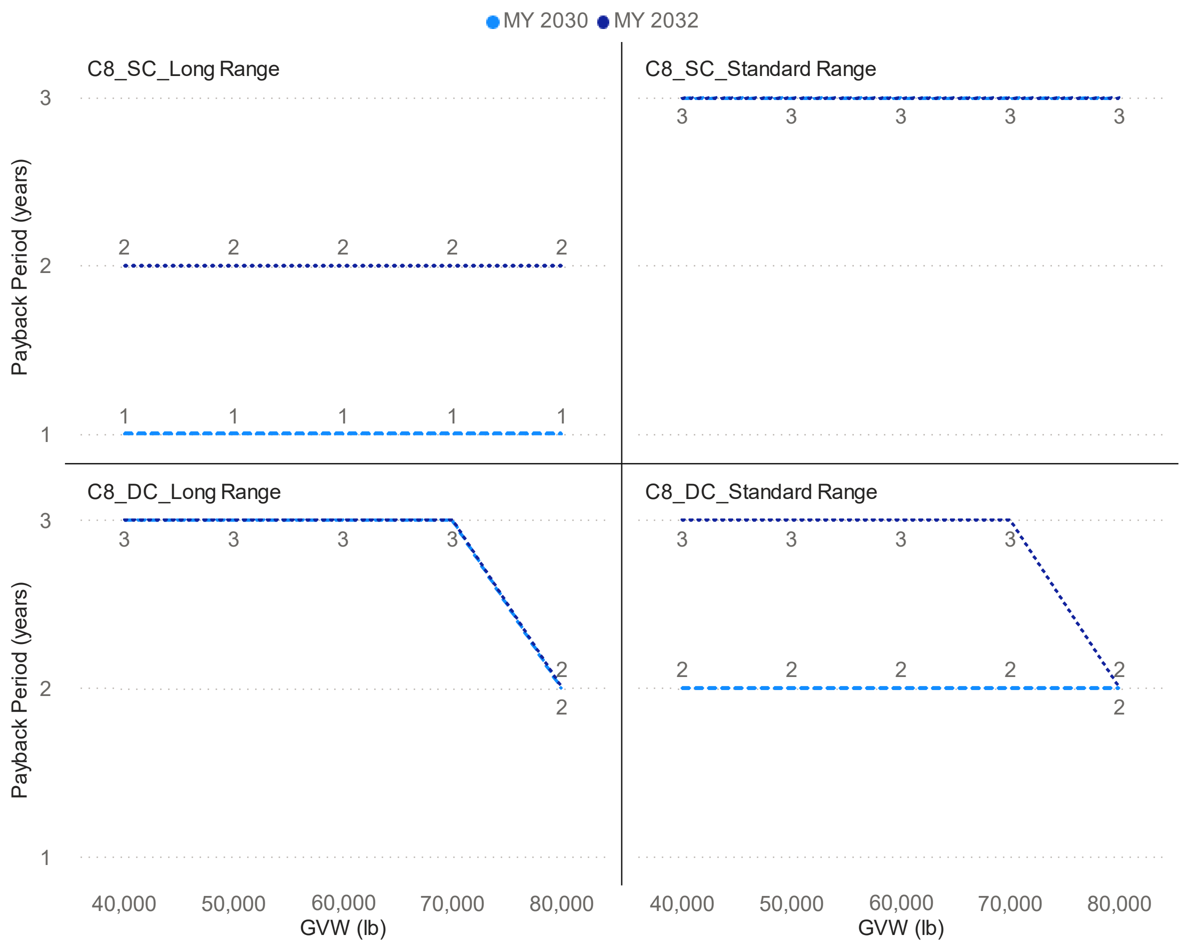


Figure 6: Effect of GVW on the payback period

An increase in diesel prices makes the economics of BEVs even more attractive.

In June 2022, the average diesel price reached a record high of $5.75 per gallon, per U.S. Energy Information Administration (EIA) data. However, our primary analysis considered a diesel price range of $3.07 to $3.23 per gallon (excluding taxes) based on the AEO 2023 reference case projection. It's important to note that using the AEO's high diesel price scenario of $5.18 per gallon (excluding taxes) significantly increases the TCO per mile of diesel tractors and leads to a shorter payback period for BEVs, as outlined in Table 5. When comparing BEVs to ICEVs, all BEVs achieve TCO parity within the first year of ownership in MY 2030 and nearly all in MY 2032, as indicated in Table 5. Additionally, it results in greater cumulative net savings for BEVs, as shown in Figure 7.

Table 5: Payback period in a high diesel price scenario

Vehicle Categories	Payback Period (in years)	
	MY 2030	MY 2032
C8_SC_Long Range	<1	1
C8_SC_Standard Range	1	1
C8_DC_Long Range	1	1
C8_DC_Standard Range	1	1
C7_DC_Long Range	1	2
C7_DC_Standard Range	<1	<1

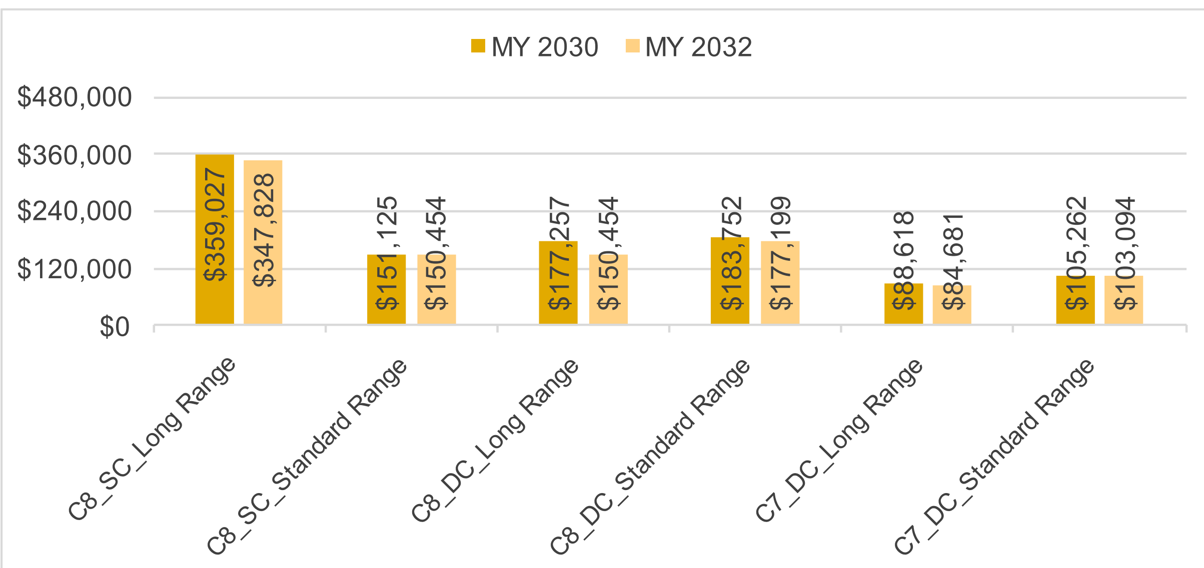


Figure 7: Cumulative Net Savings of BEVs over ICEVs in a high diesel price scenario

In Summary

The study chose representative BEVs for 2030-32 with ranges sufficient to cover a high percentile of daily VMT use cases without en route charging (to take advantage of cheaper charging from captive depot infrastructure). The study found that,

a) Powertrain costs of most BEVs will be at par or cheaper than diesel vehicles even after conservatively considering a 50% higher battery DMCs (compared to the global average) due to the battery tax credits under IRA of 2022.

b) The TCO of BEVs is significantly lower than diesel ICE across all segments. The payback period is less than 3 years for all vehicles.

c) The cargo capacity of most BEVs will be at par with ICEVs due to the increase in battery energy density.

d) 15 minutes of en route charging from an MCS charger can add more than 80% of the full range of battery electric tractors, enabling them to meet the requirements of more demanding use cases. Battery technology will enable repeated fast charging while meeting lifetime VMT requirements. The extended range provided by fast en route charging could reduce required battery capacity, with the economics being a trade-off between a cheaper, lighter BEV with more load capacity versus higher electricity cost.

e) BEVs have a lower TCO per mile, even with significant en route charging. With 30% en route charging (20-80% charge on 50% of days), the payback period of all vehicles is still less than 5 years.

f) Higher annual operational VMTs increase annual savings and reduce the payback period for BEVs due to their lower energy and maintenance cost per mile.

g) At the high GVWs, the energy consumption of an ICEV increases marginally more than a BEV leading to a slight decrease in the payback period of BEVs.

h) An increase in diesel prices makes the economics of BEVs even more attractive due to the low energy cost per mile.

The electric vehicle (EV) market has experienced substantial growth, particularly in the light-duty passenger EV segment, with US EV sales expected to exceed a million units in 2023. In addition, the uptake of EVs in the medium and heavy-duty vehicle segments, such as buses, delivery vans, school buses, and garbage trucks, with low/medium demand on daily driving distance, is also accelerating. The resulting R&D and manufacturing volumes of batteries and other powertrain components have significantly improved their performance and reduced manufacturing costs. This is poised to provide compelling BEV economics for Class 7 and Class 8 tractor-trailer segments in the near future (like the Tesla Semi-500 miles range at maximum GVW). In addition, the manufacturing credits and vehicle tax credits under the IRA will accelerate the timeline to the TCO parity of BEVs. Furthermore, the falling cost of renewable energy and the levelized cost of grid storage will provide the high-power demands of MCS charging stations without paying high demand charges to utilities. However, near-term challenges still need to be overcome for electric tractors to displace diesel vehicles across the entire tractor-trailer category. For example, MCS charging infrastructure will need to be built along freight corridors to enable electric tractors to add more than 80% of their full range in less than 15 minutes.

1. Introduction

In the United States, the trucking industry plays a critical role in the economy, transporting goods and materials across the country. However, the trucking industry is also a significant contributor to greenhouse gas (GHG) emissions, making it an important target for efforts to reduce emissions and combat climate change. Class 7 and Class 8 trucks are responsible for a substantial portion of transportation emissions in the United States per the EPA [4], and electrifying this sector could have a significant impact on mitigating climate change [4]. As more and more states adopt emissions reduction targets, the electrification of heavy-duty trucks is becoming an increasingly important strategy for meeting these goals.

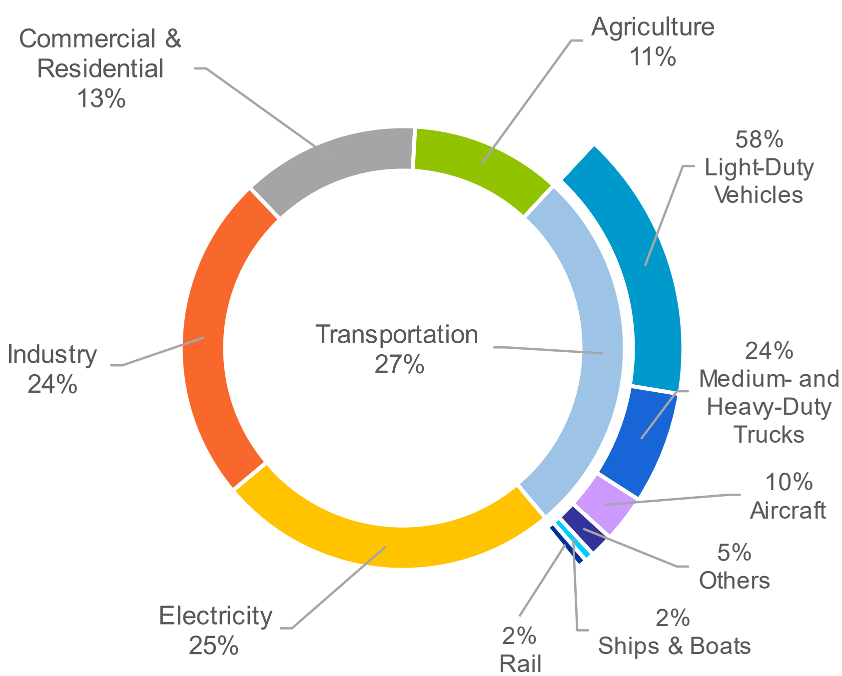


Figure 8: Distribution of U.S. greenhouse gas (GHG) emissions by sector [4]

The transportation industry moves 11 billion tons of freight and drives 3 trillion vehicle miles, with 50% of the weight and 37% of the value of goods being moved less than 100 miles. Transportation costs are high, second only to housing expenses, and there are challenges such as a shortage of drivers and traffic congestion. However, there are also opportunities for new business models, propulsion modes, and technologies such as managed lanes, fleet management, and automation. Classes 7 and 8 have the biggest potential for low-cost efficiency solutions, but all classes can benefit from these solutions.

Vehicle-to-vehicle (V2V) communication and automation are opportunities for long-haul trucks carrying larger loads [1].

Trucks account for a disproportionate amount of GHG emissions and air toxins such as NOx, volatile organic compounds (VOC), and particulates. The electrification of the trucking industry can play a crucial role in reducing GHG emissions and strengthening energy security in the United States. With the rapidly falling cost of wind and solar energy and grid storage, increasing the fraction of renewable energy powering the grid is becoming significantly cheaper. Classes 7 and 8 electric trucks running on domestically produced clean energy will reduce the country's dependence on imported oil and increase energy independence. These vehicles significantly reduce greenhouse gas emissions, lower fleet operators' costs, and strengthen energy security. As more and more states adopt emissions reduction targets, we can expect to see a growing demand for electric trucks, driving innovation and helping to build a more sustainable transportation future.

1.1 Proposed Standards to Reduce Greenhouse Gas Emissions from Heavy-Duty Vehicles for Model Year 2027 and Beyond

The U.S. Environmental Protection Agency has proposed a new set of more stringent regulations to reduce GHG emissions from HDVs for MYs 2027 through 2032. These revised guidelines built over "Phase 2" referred to as "Phase 3," will significantly reduce carbon emissions from HDVs. The goal of these guidelines is to help mitigate the issues of global climate change and air pollution, particularly in communities close to major roadways. The proposed Phase 3 rulemaking applies to heavy-duty vocational vehicles in Classes 2b–8 (such as delivery trucks, refuse haulers, public utility trucks, transit, shuttle, and school buses) and tractors in Classes 7 and 8 (such as day cabs and sleeper cabs on tractor-trailer trucks). The new Phase 3 standards for vocational vehicles and day cab tractors become increasingly more stringent each year from 2028 through 2032. For sleeper cab tractors, stricter standards will be implemented starting in the MY 2030 and will increase in stringency until the MY 2032.

The proposed standards are performance-based, allowing each manufacturer to choose what set of emissions control technologies is best suited for their vehicle fleet to meet the standards. EPA projects that one potential pathway for the industry to meet the proposed standards for MY 2032 would be through:

a) 50% ZEVs for vocational vehicles, which includes the use of battery electric and fuel cell technologies.
b) 34% ZEVs for day cab tractors, which includes the use of battery electric and fuel cell technologies.
c) 25% ZEVs for sleeper cab tractors, which primarily includes the use of fuel cell technologies.

1.2 Truck Classification

Trucks have axles, known as lift axles, drop axles, or tag axles, which can change the Classification category of the vehicle depending on its position. To be consistent, the Trucking Monitoring Guide (TMG) recommends that only axles in the dropped position be considered when classifying a vehicle, even though this may cause difficulty in interpreting summary Classification statistics in certain situations. Some States permit specific vehicle types not legal in other States, and these States require that vendors install their State-specific Classification methods in the data collection electronics or post-processing software. However, many engineering and planning analyses do not require detailed Federal Highway Administration (FHWA) 13 categories but require information on truck volumes versus car volumes. Therefore, many engineering and planning analyses use a simple car/truck split or a very simplified truck classification system based on vehicle length, number of axles, or other vehicle attributes. The length Classification systems consist of four generalized length bins that approximate cars, small trucks, large trucks, and multi-trailer trucks. One advantage of length Classification systems is that vehicle length can be easily calculated by several sensor technologies that do not require axle sensors [5].

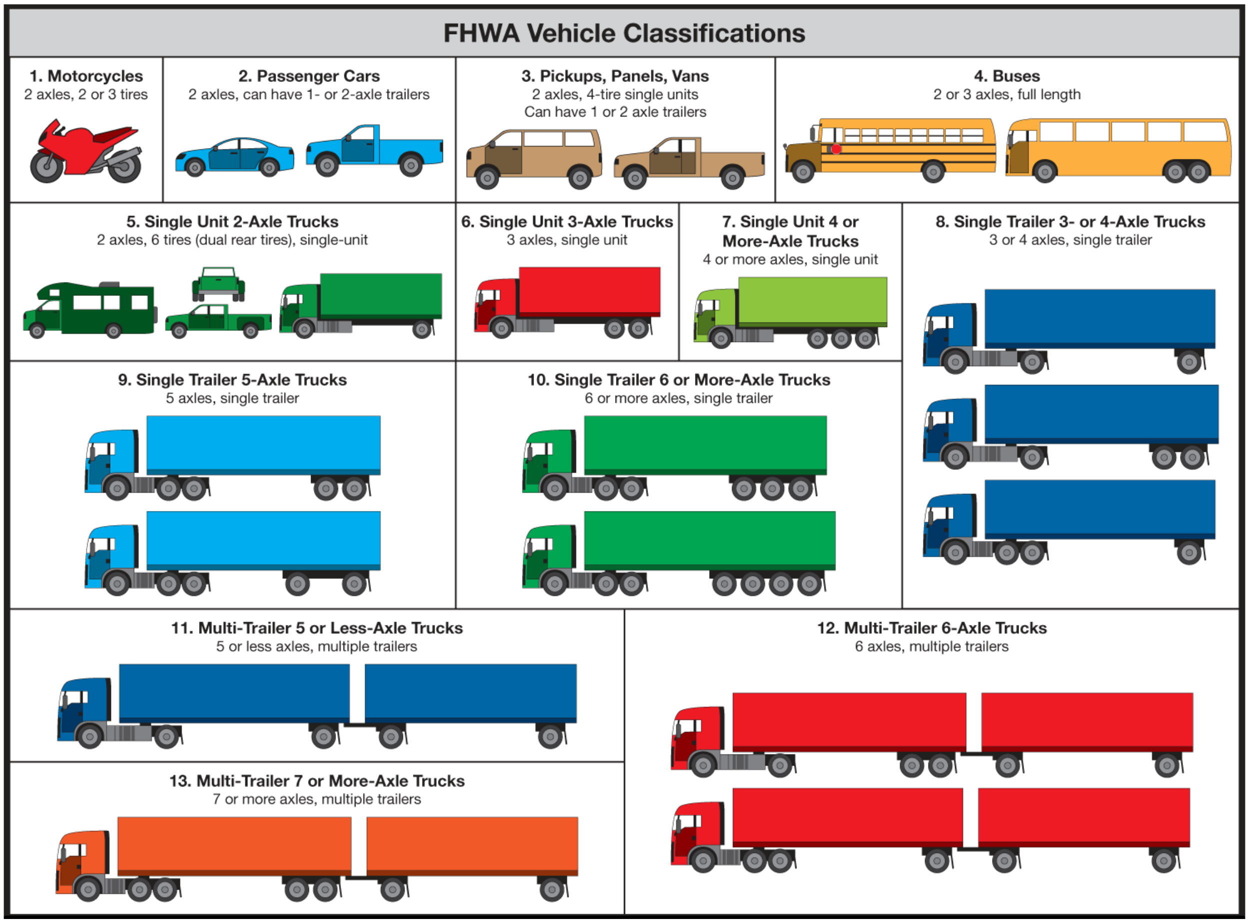


Figure 9: FHWA 13-Category Scheme for Vehicle Classifications [6]

Commercial trucks can be categorized in various ways, with the Federal Motor Carrier Safety Administration (FMCSA) defining them as vehicles carrying freight with a GVW rating of 10,001 lb or more and the FHWA defining them into nine Classes based on the number of axles and vehicle type. The report to Congress, *"Compilation of Existing State Truck Size and Weight Limit Laws,"* [7] focuses on describing the U.S. commercial truck fleet in terms of three primary configurations: Single Unit (S.U.) or Straight Trucks, Combination trucks, and Longer Combination Vehicles (LCVs), as shown in Figure 10. S.U. trucks have a permanently attached power unit and chassis and are used for delivery, construction, and utilities. Combination Trucks are the most recognized and include day cab and sleeper cab tractors pulling cargo-carrying units of varying lengths. LCVs are a subset of combination vehicles that can only operate in certain states and include Rocky Mountain Doubles, Turnpike Doubles, and Triples, which use at least one full-length or three shorter trailers [7]. This study analyzes the costs of electrification of the combination trucks only.

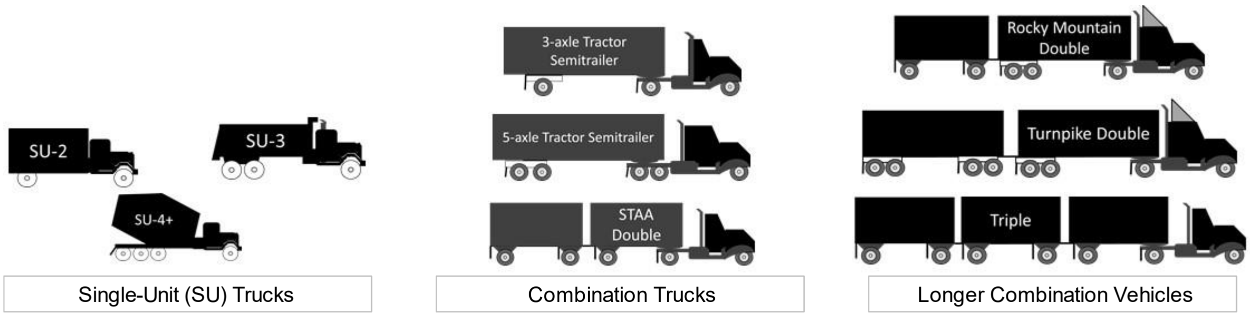


Figure 10: Common Vehicle Configurations in the U.S. Commercial Truck Fleet [7]

Only 1.1% of the on-road vehicle fleet in the United States are combination trucks. However, due to their heavy weight and high annual miles driven, combination trucks have a high fuel consumption, resulting in approximately 18% of all U.S. vehicle emissions. Therefore, it is crucial to electrify the heavy-duty truck industry to promote adopting sustainable energy and transition towards a sustainable future [8].

1.3 Types of Tractor Trailers

Figure 11 displays the primary trailer types towed by Class 8 tractors. However, we lack data regarding the representative frontal area and coefficient of drag for each specific trailer type. Therefore, all energy consumption calculations per mile are derived from published data on the most prevalent dry-van trailer.

Refrigerated (reefer) trailers consume approximately 7-8 kW of electricity. In the case of a battery-electric tractor-trailer, an electric consumption of 5 kW reduces about 2.5 miles of range for every hour of operation.

Figure 11: Major types of Class 8 tractor-trailers

1.4 Market Snapshot

According to the AEO 2023 report, out of approximately 775,000 Class 3-8 vehicle sales recorded in 2022, the total sales of Classes 7 and 8 vehicles accounted for 39.3% of that total. However, the sales of BEVs and fuel-cell electric vehicles (FCEVs) represented less than 0.05% of the sales of HDVs in 2022. However, several original equipment manufacturers (OEMs) have committed to transitioning and deploying BEVs (Figure 12) in the near future to reduce emissions [9], [10].

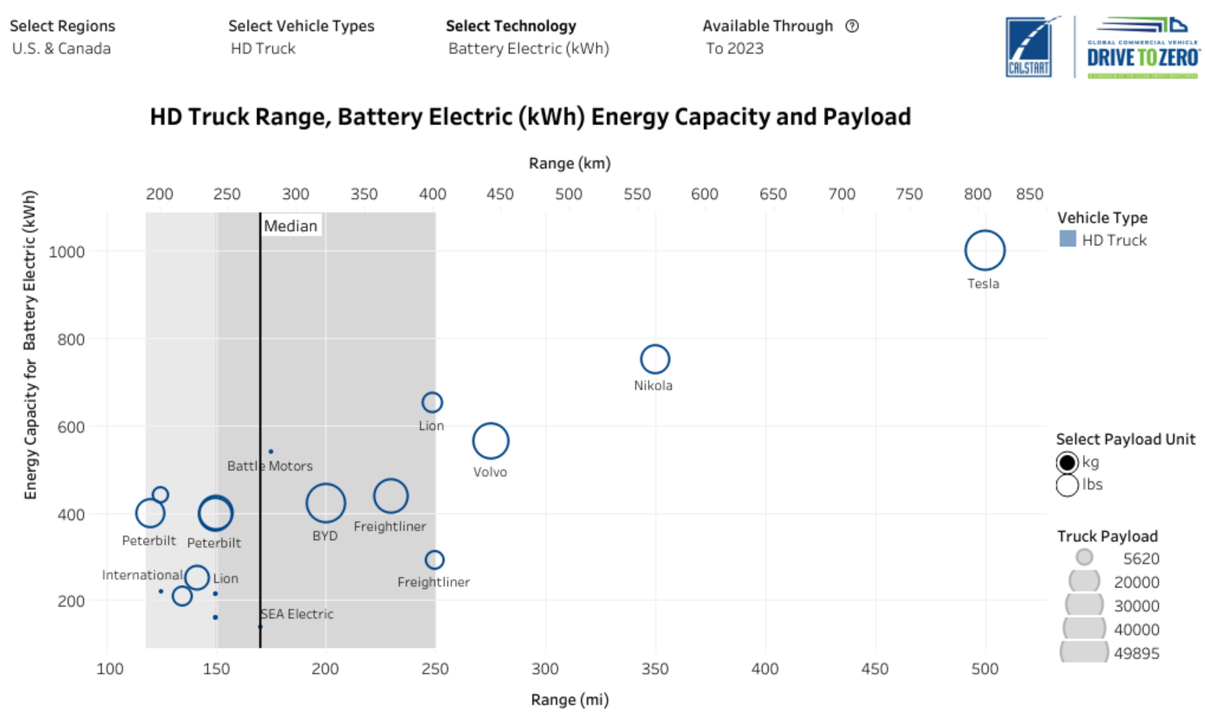


Figure 12: Summary of current market status and trends. Source: ZETI Data Explorer

Long-haul trucks make up less than 10% of the total truck population in the U.S., and characterizing vehicle weight distribution is challenging. NACFE's recent market segment report outlines the relationship between range and weight for BEVs and provides real-world data on actual operating vehicle weights. Heavy loads, such as beverage deliveries to stores, are typically handled by heavy-duty trucks that travel less than 100 miles per day, while lighter loads face no issues on routes under 100 miles a day. Longer ranges are feasible for heavy-duty BEVs with daily mileages between 100 and 200 miles. The truck range can be extended through the effective use of regenerative braking and one-pedal driving, as demonstrated in NACFE's Run on Less–Electric Depot demonstration [11]. For instance, Kenworth's T680E, equipped with a 396 kWh battery, offers an estimated operating range of 150 miles, depending on the application. It is available in 54,000 lb and 82,000 lb gross vehicle weight ratings (GVWR) [12]. Daimler's eCascadia offers multiple battery options, with a maximum capacity of nearly 440 kWh and a typical range of 230 miles, supporting up to 82,000 lb max GCW (Gross Combination Weight) [13]. Volvo's VNR Electric, featuring a 565 kWh battery capacity, provides a range of 275 miles on a single charge [11], [14].

2. Methodology

This section presents a detailed overview of the methodology employed in this report to assess and compare the total cost of ownership (TCO) between battery electric and diesel Classes 7 and 8 tractors (combination vehicles) in the years 2030 and 2032. The following list provides a concise summary of the key steps undertaken in the analysis, along with references to the corresponding sections where they are elaborated upon in detail.

a) Selecting representative vehicles - vehicle range, payload, and performance

   i) Based on published data on Class 7 and 8 usage statistics, we arrived at the GVW (Section 3.1.1.1) and range (Section 3.1.1.5) of battery electric tractors covering more than 90% of use cases for 2030-2032.

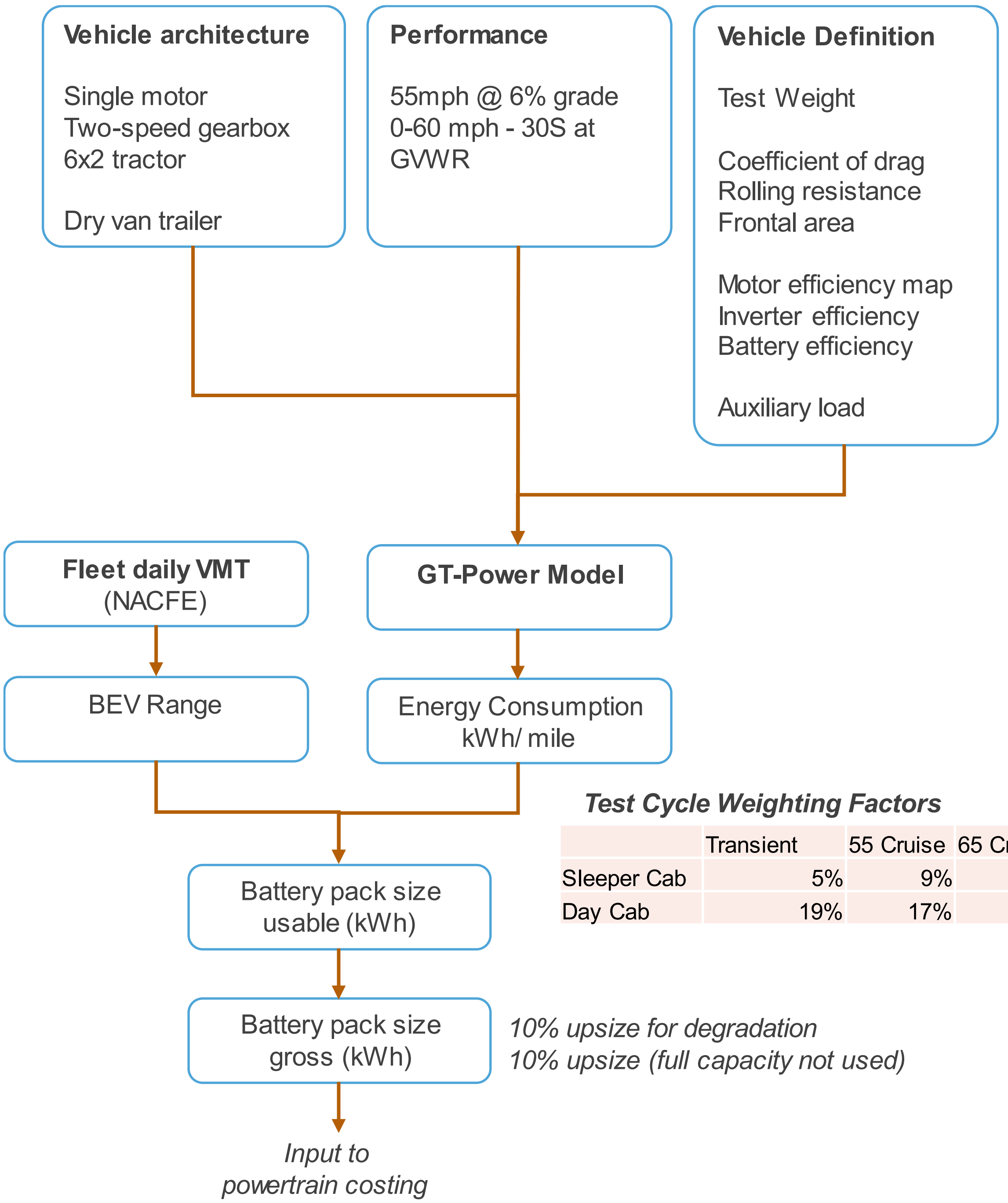
   ii) Considering vehicles on sale, technology trends, and engineering judgment, we made reasonable assumptions about performance (time for 0-60 mph, speed at max grade) and vehicle attributes (coefficient of drag, rolling resistance, auxiliary loads, etc.) for a representative tractor in 2030-2032. (Section 3.1).

b) Vehicle modeling to size battery electric tractor powertrain

   i) We modeled the vehicles in GT-suite based on the performance, GVW, and vehicle attributes from (a) and determined the size (output) of the traction motor (kW) and the energy consumption per mile (kWh/ mile). (Section 3.2)

   ii) We calculated the different vehicles' usable battery sizes (kWh) from the vehicles' energy consumption (kWh/ mile). Then, reasonable assumptions were made for reserve capacity and upsizing capacity degradation to arrive at the gross battery size (kWh). (Section 3.3.2)

Figure 13 overviews the process described above in steps (a) and (b).



Test Cycle Weighting Factors

	Transient	55 Cruise	65 Cruise
Sleeper Cab	5%	9%	86%
Day Cab	19%	17%	64%

Figure 13: Methodology for powertrain sizing (input to powertrain costing) and energy consumption (input for TCO calculation)

c) Calculating powertrain costs and the purchase price of electric and diesel tractors.

   i) We use the EPA Draft Regulatory Impact Analysis (HD TRUCS technology assessment tool) [3] for all diesel vehicle powertrain DMCs. We developed our own RPE factor for diesel tractors. Sections 3.3.1 and 3.3.3 detail the costs and the Retail Price Equivalent (RPE) used for diesel tractors.

   ii) The components factored for costing the battery-electric powertrain, costs of different components, and their RPE factors are detailed in Sections 3.3.2 and 3.3.3. In addition, we factor manufacturing credits provided by §45X of the IRA in the cost of batteries for MYs 2030 and 2032.

   iii) We assume that the price difference between a battery-electric and a diesel tractor is purely due to the difference in powertrain costs. In addition, the consumer purchase credits available under §45W of the IRA are factored in the purchase price for the electric tractor for MYs 2030 and 2032.

d) Calculating the TCO for battery electric and diesel tractors. Section 3.4 details the various inputs and their rationale for TCO calculation.

   i) We assume a 10-year life for all Classes 7 and 8 tractors and the same annual vehicle miles traveled (VMT) as that assumed by the EPA Draft Regulatory Impact Analysis [3]. We also calculate the annual effect of VMT on battery electric vehicles' payback period.

   ii) The maintenance costs of diesel and electric vehicles are addressed in Sections 3.4.1 and 3.4.2, respectively.

   iii) The Energy Information Agency's (EIA) Annual Energy Outlook (AEO) 2023 projections are used for fuel and electricity prices.

   iv) The depot charging scenario assumes a 350-kW charger shared between 3 vehicles.

All costs are calculated and presented in 2022 dollars unless explicitly stated otherwise.

3. Analysis

3.1 Representative Vehicles Selection

This section discusses the operational characteristics of Class 7 and Class 8 tractor-trailers: their gross vehicle weight (GVW) distribution, trucking route Classification, daily miles driven, and fleet composition (fleet size and ownership).

3.1.1.1 Gross Vehicle Weight Distribution

Table 6 presents the distribution of freight weights for Class 7/8 vehicles. The table reveals that depending on the type of route (city, regional, or long haul), a significant portion (40-50%) of Class 8 tractor-trailers have a GVW between 72,000 lb and 80,000 lb, the maximum allowable weight.

Table 6: Distribution of freight and GVW of Class 7/8 tractor-trailers (NACFE, 2018) [15]

Daily portion of the fleet (of max allowed GVWR)	Typical Vehicle Daily Weight Range (lb)	Daily freight (lb)	City Tractor	Regional Tractor	Long Haul
Between 90% to 100%	72,000 to 80,000	39,500 to 47,500	0.51	0.43	0.44
Between 80% to 90%	64,000 to 72,000	31,500 to 39,500	0.37	0.20	0.23
Between 70% to 80%	56,000 to 64,000	23,500 to 31,500	0.08	0.10	0.09
Between 60% to 70%	48,000 to 56,000	15,500 to 23,500	0.03	0.10	0.10
Between 50% to 60%	40,000 to 48,000	7,500 to 15,500	0.01	0.11	0.13
Less Than 50%	Less Than 40,000	0 to 7,500	0.00	0.06	0.02

In practice, tractor-trailers are rarely loaded to their full GVW for the entire route. Therefore, all range calculations and battery sizing for Class 8 tractor-trailers are based on a GVW of 72,000 lb, while for Class 7, it is based on a GVW of 44,000 lb. This aligns with the ANL TCO analysis [16] and EPA Phase 3 DRIA [3].

3.1.1.2 Classification of Trucking Routes

Trucking routes are classified into three categories based on their lengths:

a) **Local routes:** These routes are typically shorter, and trucks operate within a specific metropolitan area or a range of approximately 100 to 150 miles from their base. Local drivers often return to their base each day.

b) **Regional routes:** Regional routes cover a broader area, usually within a specific country region, such as the Southeast or the Midwest. Regional drivers might travel between 150 to 500 miles daily and may be away from home for a few days or up to a week.

c) **Over-the-road (OTR) or long-haul routes:** These are the longest routes, often spanning coast-to-coast or between distant cities. OTR drivers might travel between 500 to 3,000+ miles per trip and could be on the road for one to several weeks.

Table 7 provides the distribution of different types of trips published by the American Transport Research Institute (ATRI) [17]. The respondents of the 2022 report (2021 data) represent 173,322 truck tractors, 552,351 trailers, and over 14.6 billion vehicle miles traveled.

Table 7: Distribution of tractor-trailer trip types 2018 to 2021: Source: ATRI 2022 [17]

Type of route	2018	2019	2020	2021
Local (less than 100 miles)	26%	26%	32%	27%
Regional (100-500 miles)	37%	39%	37%	41%
Inter-regional (500-1,000 miles)	21%	22%	19%	24%
National (over 1,000 miles)	16%	13%	12%	17%

3.1.1.3 Daily Miles Driven

Table 8 presents the typical daily miles driven by Class 7/8 tractor-trailers. Considering factors such as the maximum allowed hours per day (11 hours in 24 hours [18]), rest breaks, loading and unloading times, and other delays [19], the maximum daily distance driven by a tractor is about 500 miles [19].

Table 8: Typical Daily Range Requirements by Class 7/8 Tractor (NACFE/ACT Fleet Survey, 2018) [15]

Daily range (miles)	City Tractor	Regional Tractor	Long Haul tractor
Less than 50	5%	0%	0%
50 to 100	16%	3%	1%
100 to 150	10%	3%	0%
150 to 200	6%	3%	1%
200 to 250	8%	6%	3%
250 to 300	15%	15%	10%
300 to 350	14%	8%	5%
350 to 400	2%	14%	7%
400 to 450	9%	26%	28%
450 miles per day	15%	22%	46%

3.1.1.4 Fleet Composition

Figure 14 shows the 2021 fleet ownership and fleet size distribution of the respondents (representing 138,930 truck tractors) in the 2021 American Transport Research Institute (ATRI) study [17]. In 2021, for-hire operators owned 70% of the U.S. Class 7/8 truck fleet (Figure 14). A for-hire carrier is a transportation company that provides freight transportation services to other businesses or individuals in exchange for payment. Since for-hire carriers represent a large percentage of the market, representative Class 7/8 tractors for 2030-32 must be able to handle a wide range of payloads and routes.

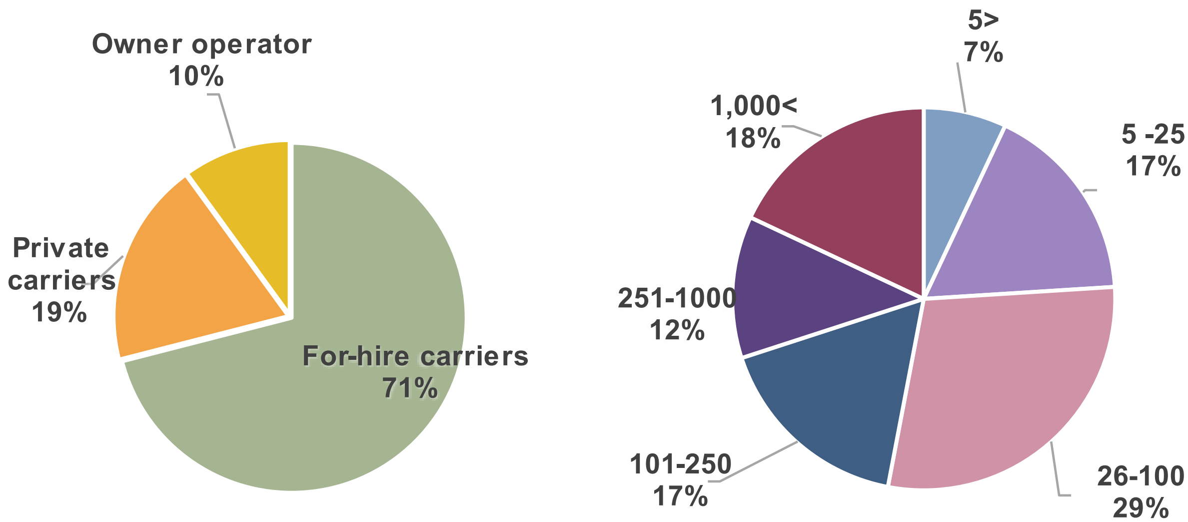


Figure 14: ATRI 2021 study Class 7/8 tractor fleet size distribution [20]. Fleet ownership (left) and tractor fleet size distribution (right)

3.1.1.5 Range Justification for MYs 2030 and 2032

Figure 15 illustrates the cumulative number of tractors driven below a certain daily mileage threshold.

Table 9 provides various BEVs chosen for this study, their range on a single charge, and the percentile of daily trips they can cover on a single charge (without stopping and charging) across city, regional, and long-haul applications. The table demonstrates the percentage of trips that the different tractor-trailers can complete without stopping and charging. While a 450-mile range only covers 85%, 78%, and 55% of the daily mileage cases for city, regional, and long-haul tractors, respectively, it's worth noting that the maximum daily distance a tractor typically drives is around 500 miles [8], [19] (as shown in Figure 16). Therefore, a 500-mile range tractor-trailer will cover nearly 100% of the daily mileage cases without requiring charging.

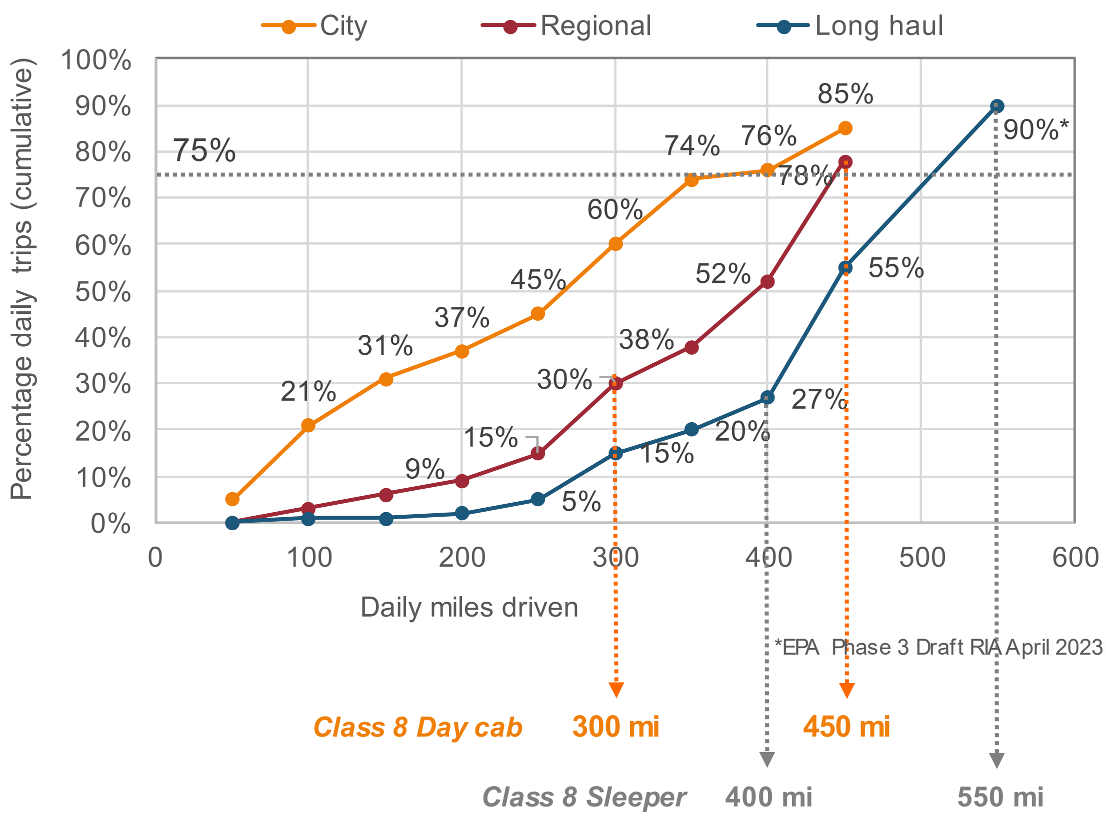


Figure 15: Typical Daily VMT by segment based on NACFE and ACT study of 2018. Cumulative percentage of tractor-trailers under a particular daily mile driven (calculated from Table 3).

Table 9: Electric range of the two representative tractor trailers chosen for 2030-2032 in the US Market

Vehicle	Identifier	BEV Range	% of Daily VMT cases that can be met without en route charging		
			City	Regional	Long haul
Class 7 Day cab	Standard Range	150	31%	9%	-
	Long Range	250	45%	15%	-
Class 8 Day cab	Standard Range	300	60%	30%	-
	Long Range	450	85%	78%	-
Class 8 Sleeper	Standard Range	400	-	52%	27%
	Long Range	550	-	~100%	90%

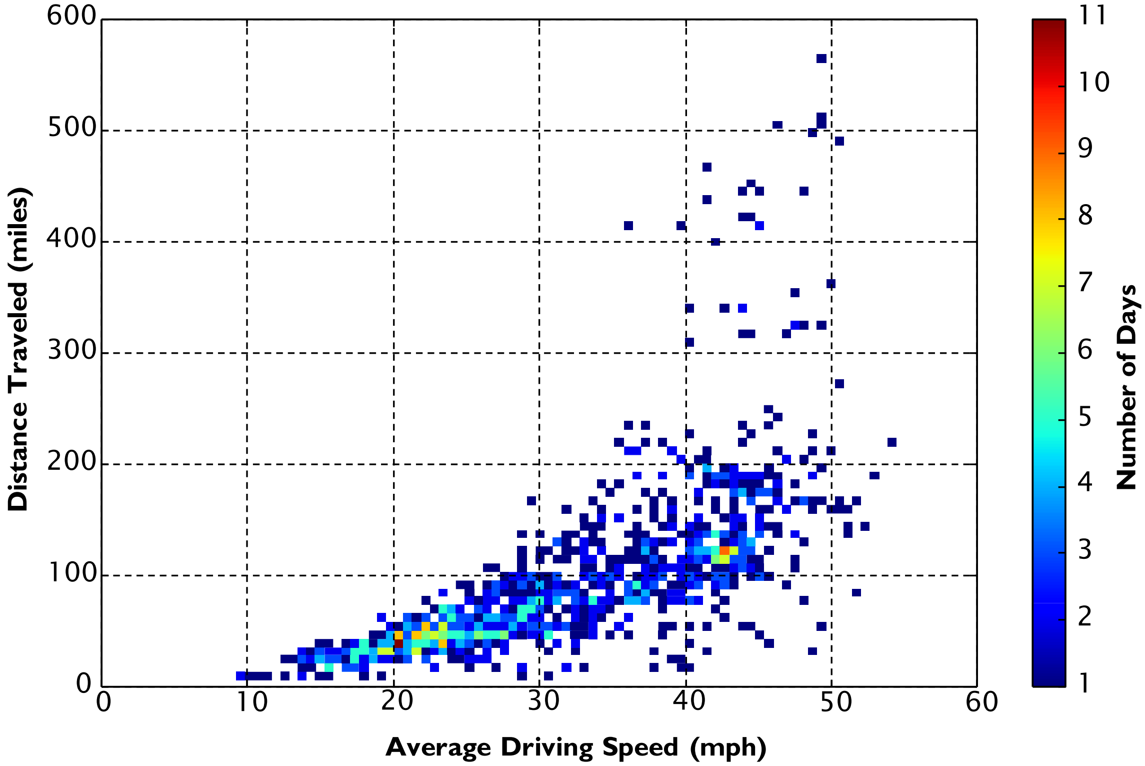


Figure 16: Daily average driving speed vs. distance traveled for Class 8 traveled for Class 8. NREL Fleet DNA, 2014 [21]

It is important to consider that extremely low temperatures, adverse weather conditions (such as rain, snow, and slush), and headwinds may reduce the range of an electric semi-truck. Nevertheless, with the proper charging infrastructure, covering the same daily distance and achieving a utilization rate comparable to a diesel-powered semi won't be an issue.

3.1.2 Vehicles Selected

Based on the proposed regulations by the EPA, we have selected the following vehicle categories, as shown in Table 10, as they represent an opportunity for electrifying large fleets and for-hire carriers that are a significant source of emissions. Used for long-haul trucking, construction, agriculture, drayage, and in various settings, these Classes 7 and 8 tractor-trailers can be charged overnight at depots or on highways or while unloading cargo at their destination.

Table 10: Specification of battery electric tractor-trailers considered in this analysis.

Vehicle	Engine (kW)	Test Weight (lb)	Standard Range (miles)	Long Range (miles)
Day Cab – Class 7	340	44,000	150	250
Day Cab – Class 8	750	72,000	300	450
Sleeper Cab – Class 8	750	72,000	400	550

3.1.3 En route Charging in 2030-2032

We selected the vehicles presented in Table 10 to cover a certain percentage of the daily VMT cases without en route charging. DC fast chargers along freight corridors can quickly add significant range to an electric tractor, significantly reducing the battery size requirements to cover a given fraction of use cases.

Figure 17 shows the breakup of the cost per mile of operating tractor-trailers in 2021. Driver Wages and benefits accounted for 43.6% of the total cost of operating a tractor-trailer. Additionally, the Federal Motor Carrier Safety Administration (FMCSA) has stringent limits on the duration a tractor-trailer driver can be on duty [18]. Furthermore, there is a severe shortage of drivers [17], a problem that cannot be solved by only increasing driver compensation [17], [22]. Hence, for favorable economics of a battery electric tractor, the vehicle downtime for charging while the driver is on duty and driving the vehicle has to be minimized. Ideally, the charging session has to last no more than the duration that a driver will stop for a restroom break and a meal, or the duration compared to a diesel fuel stop.

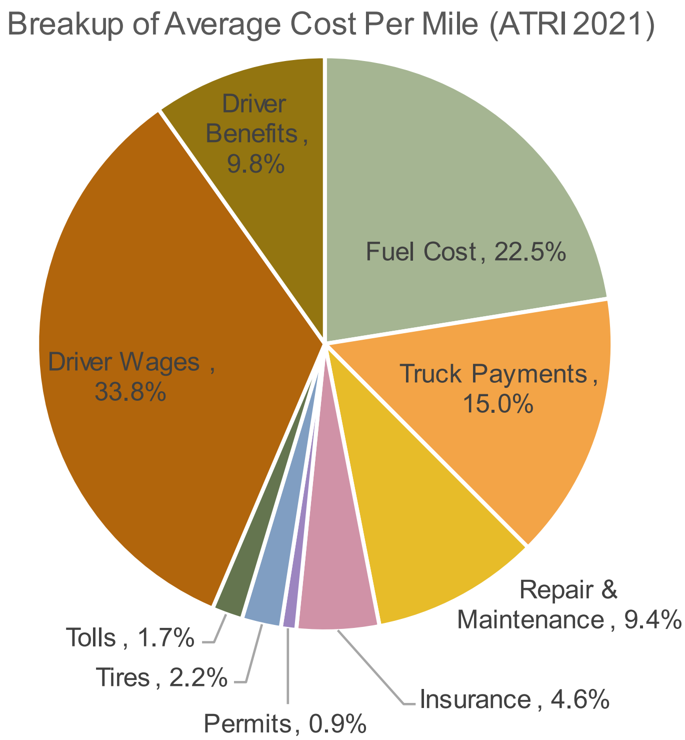


Figure 17: Breakup of the average marginal cost ($/mile) of operating tractor-trailers in 2021, ATRI [17]

CharIN [23] (Charging Interface Initiative e.V.), the global non-profit association with more than 300 members comprising OEMs, suppliers, research organizations, etc., launched the Megawatt Charging System (MCS) [24] at The Testival & Conference North America in October of 2022. Based on the CCS system, the de facto standard for charging light-duty vehicles across the globe, MCS can provide a maximum of 3,000 Amps at 1,250 Volts resulting in a charge rate exceeding 3 MW (limited by the BEV pack voltage, cell technology, etc.).

Production light-duty batteries can already add a significant percentage of battery in a very short duration. The Kia EV 6 can charge 10% to 80% in under 17 minutes on an Electrify America 350kW charger [25]. The CATL Qilin battery pack can add 10-80% SOC in 10 minutes [26] and is already in production in the Zeekr 001 [27]. Furthermore, future battery technologies like the Storedot XFC Cell, under evaluation by major automakers (30Ah automotive form factor pouch cell), can reduce the 10-80% charging time for a battery pack to under 10 minutes [28]. Storedot has achieved a cycle life of 1,000 (10-80% in 10 minutes) for their automotive cells [29] and 1,200 extreme fast charging cycles for their smaller research cells [30]. 1,200 cycles translate to a life of 660,000 miles (for the Sleeper Cab – Long Range BEV) with 100% fast charging. Under a combination of MCS and slower depot charging, the cycle life will be much higher than 1,000. Section

4.1.2 looks into how much range a 15-minute megawatt charging stop can add to a Class 8 sleeper – long range in the study (Table 10) with current and future battery chemistries.

For energy cost in 2030-32 at a 3-megawatt MCS station, we have considered a rate of $0.23/kWh based on NREL's 2022 study [31]. A PWC [32] study published in October 2022 estimated energy costs at an MCS station in Europe in 2030 at $0.24/kWh. The rapidly falling cost of renewable energy generation and grid storage technologies [33], the significantly decreasing cost of MCS hardware [34], their enabling of fast vehicle turnaround time (about 15 minutes), and the high energy throughput are all factors that will reduce the energy costs at an MCS station [35].

3.2 Modeling

We modeled the representative 2030-32 vehicles in GT-Suite to estimate the following:

a) Traction motor and inverter sizing required to meet the performance targets
b) Energy consumption (kWh/mile) of the base vehicles
c) Effect of GVW, Coefficient of Drag (C_d), and auxiliary loads (HVAC at low temperatures, reefer trailers) on the vehicle energy consumption

The energy consumption predicted by the model is used as input to battery size (kWh) calculations. We use the model to simulate the effect of GVW, C_d, and Auxiliary loads on energy consumption and the range to confirm the suitability of the representative tractors to haul different trailers (different aero characteristics) in all weather conditions. The modeling results are detailed in Section 4.1.

Table 11: GT-Suite Vehicle modeling inputs (LR – Long Range, SR – Standard Range)

Class	Units	8	8	8	8	7	7
Vehicle		Sleeper LR	Sleeper SR	Day cab LR	Day cab SR	Day cab LR	Day cab SR
GVWR		82,000	82,000	82,000	82,000	-	-
Test Weight	lb	72,000	72,000	72,000	72,000	44,000	44,000
Drive configuration		6x2	6x2	6x2	6x2	4x2	4x2
Frontal area	sq. m	10.2	10.2	10.2	10.2	10.2	10.2
Coefficient of Drag (C_d)		0.35	0.35	0.39	0.39	0.39	0.39
Rolling resistance		0.00475	0.00475	0.00475	0.00475	0.00475	0.00475
Aux Load	kW	2.5	2.5	2.0	2.0	1.80	1.80
0-60 mph at GVWR rated	sec	30	30	30	30	30	30
Max speed at 6% grade	mph	55	55	55	55	55	55
Max motor efficiency	%	96.5	96.5	96.5	96.5	96.5	96.5
Max inverter efficiency	%	97.0	97.0	97.0	97.0	97.0	97.0

Table 11 gives the various inputs for vehicle modeling in GT-Suite. We assume Classes 7 and 8 vehicles to have a 4x2 and 6x2 configuration, respectively, with one drive axle. In addition, we assume all vehicles to have a single traction motor and a two-speed transmission. We have assumed a 0-60 time of 30 seconds and a max speed of 55 mph at 6% grade for sizing the traction motor. The peak motor and inverter efficiency of 96.5% and 97%, respectively, are very conservative (i.e., low).

We assume an auxiliary load of 2.5 kW, 2.0 kW, and 1.8 kW for Class 8 sleeper cabs, Class 8 day cabs, and Class 7 day cabs, respectively. NREL's analysis of cabin heating requirements for a sleeper cab for the SuperTruck II program [36] found that 1.59 kW of heating was sufficient for 95% of ambient temperature cases (over the whole US). Factoring in the Coefficient of Performance (COP) of the heat pump (heating output/ power input >1.5 even at temperatures less than -20°C), battery insulation, and harvesting of heat from powertrain components (motors and inverters), the actual electric power requirements for heating will be lower. Hence 2.5 kW of auxiliary load is sufficient to account for HVAC and other auxiliary loads under most circumstances.

Table 12 shows the test cycles and weighting factors used to calculate the energy efficiency of sleeper and day cab tractor-trailers.

Table 12: GEM test cycles and weighting factors

Cycle	Sleeper Cab	Day Cab
Transient	5%	19%
55 Cruise	9%	17%
65 Cruise	86%	64%

Figure 18 shows the screenshot of the GT suite of the electric tractor-trailer. When benchmarking the model against the ANL study [16] with the same inputs, the model outputs were within 5%.

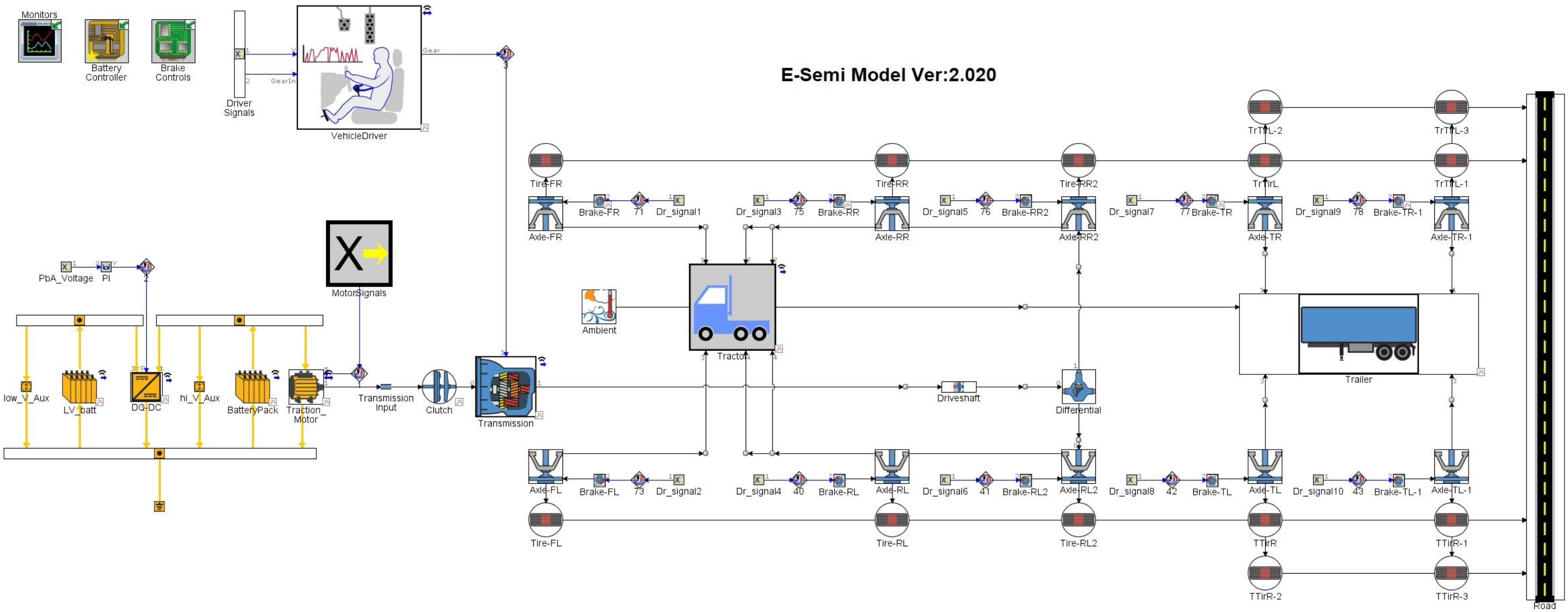


Figure 18: GT Suite model of the electric tractor-trailer

3.3 Powertrain Costs

This section outlines the methodology used to determine the direct manufacturing costs (DMCs) of the ICEV and BEV powertrains. Additionally, it explains the approach taken to ascertain the retail price of the ICEV and BEV powertrains, which serve as inputs for the TCO analysis in MYs 2030 and 2032, respectively.

3.3.1 ICEV

The ICEV powertrain costs are taken from the EPA Draft RIA's HD TRUCS resource sheet [3]. This is because the ICEV technology is pretty mature in this market segment and the individual technology piece costs are not expected to vary a lot in the 2030-2032 timeframe. EPA estimations for the ICEV costs are accurate and concisely capture the market and the prevalent technology. However, the EPA estimated costs are in 2021 $ and we have adjusted them by 8% to represent it in 2022 $. The ICEV powertrain DMCs include the following components [3]:

a) Engine and Aftertreatment DMC ($)
b) Gearbox DMC ($)
c) Final Drive DMC ($)
d) Engine Accessory DMC ($)
e) 2027 Low NOx Rule Additional DMC ($)
f) Torque Converter/Clutch DMC ($)
g) Engine Starter DMC ($)
h) Generator DMC ($)

To establish the ICEV Powertrain RPE, we have utilized an RPE factor of 1.5 based on our previous analyses of the ICEV segment [37], [38]. Considering the stringent requirements mandated by the EPA, we anticipate a further increase in the cost of ICEV technology in MYs 2030 and 2032. However, we have not modified the cost of the aftertreatment system required by the recent NOx rule. Instead, we utilize a slightly higher RPE factor (1.5) than the RPE factor of 1.42 employed by the EPA. This ICEV Powertrain RPE factor of 1.5 is the same that we have utilized in our previous analyses of the ICEV segment [37], [38]. Considering the stringent requirements mandated by the EPA, we anticipate a further increase in the cost of ICEV technology in MYs 2030 and 2032.

3.3.2 BEV

In this section, we outline our methodology for calculating the powertrain cost of a representative battery electric tractor-trailer used in this study for MYs 2030 and 2032. Following a similar breakdown to the EPA's analysis of battery electric vehicles (BEVs), the BEV powertrain DMCs encompass the following components:

a) Battery DMC with a battery tax credit ($)

b) Motor + Inverter DMC ($)
c) Gearbox DMC ($)
d) Electric Accessories ($)
e) Final Drive DMC ($)
f) On-board Charger + DC-DC Converter DMC ($)

Table 13 provides a list of battery tax credits available under §45X for domestically manufactured battery packs. These credits can be claimed by either the battery producer or the automaker and are applied to the DMC of the battery pack.

Table 13: IRA credits assumed for the battery pack

Description of Credit	Unit	2030	2032
IRA Cell Credit	$/kWh	$26.25	$8.75
IRA Module Credit	$/kWh	$7.5	$2.5
IRA Total Battery Credit	*$/kWh*	*$33.75*	*$11.25*

We have used our own estimated DMCs for the battery pack, motor and inverter, onboard charger, and DC-DC converter. However, for the gearbox, electric accessories, and final drive, we have utilized the DMCs assumed by the EPA and adjusted them to represent the costs in 2022 $.

3.3.3 Retail Price Equivalent (RPE)

The DMCs do not take into account the indirect costs associated with tools, capital equipment, financing, engineering, sales, administrative support, or return on investment. Regulatory agencies address these indirect costs by incorporating a scalar markup of DMCs known as the retail price equivalent (RPE). The RPE represents the ratio of the vehicle's retail price to its manufacturing cost [39]. It serves as a multiplier used by original equipment manufacturers (OEMs) to ensure a competitive rate of return on their production investment [40].

The RPE multiplier is applied to the direct manufacturing costs to capture the disparity between the cost of producing vehicle components and the price typically charged by manufacturers when selling a vehicle.

This disparity accounts for the indirect costs, which include factors such as production overhead, corporate overhead, selling costs, dealer costs, and net income before taxes, as presented in Table 14. The specific breakdown of these indirect costs may vary among manufacturers, but their overall proportion to revenues tends to be similar. These indirect costs contribute to the final price paid by consumers when purchasing a vehicle.

Table 14: Retail Price Components as considered by DOT [41]

Direct Costs	
Manufacturing Cost	Cost of materials, labor, and variable energy needed for production
Indirect Costs	
Production Overhead	
Warranty	Cost of providing product warranty
Research and Development	Cost of developing and engineering the product
Depreciation and amortization	Depreciation and amortization of manufacturing facilities and equipment
Maintenance, repair, operations	Cost of maintaining and operating manufacturing facilities and equipment
Corporate Overhead	
General and Administrative	Salaries of nonmanufacturing labor, operations of corporate offices, etc.
Retirement	Cost of pensions for manufacturing labor
Health Care	Cost of health care for nonmanufacturing labor
Selling Costs	
Transportation	Cost of transporting manufactured goods
Marketing	Manufacturer costs of advertising manufactured goods
Dealer Costs	
Dealer selling expense	Dealer selling and advertising expense
Dealer profit	Net Income to dealers from sales of new vehicles
Net income	Net Income to manufacturers from production and sales of new vehicles

The EPA's analysis to determine the powertrain RPEs ($) utilized an RPE factor of 1.42 for both ICEVs and BEVs. However, in our previous reports [37], [38], we employed an RPE factor of 1.5 for ICEVs and 1.2 for BEVs. We chose a higher RPE factor for ICEVs compared to the EPA's analysis because the cost of ICEV technology is expected to rise due to increasingly stringent emission standards. Nonetheless, we maintained parity with the RPE factors used in our previous studies for the light-duty vehicle (LDV) and medium-duty heavy-duty (MDHD) segments. This decision was based on the expectation that OEMs such as Tesla, BYD, Volvo, and Daimler would leverage technological advancements from those two segments to produce cost-competitive trucks.

3.4 Total Cost of Ownership (TCO)

The methodology to analyze TCO is similar to Roush's previous works [42]–[44]. Only tangible financial aspects of ownership related to the vehicle are considered for the TCO analysis, as shown in Table 15. They include:

a) Powertrain cost (as described in the above sections)
b) Fossil fuel price for ICEVs
c) Electricity price for BEVs
d) Maintenance and repair (M&R) costs
e) Combined Hardware and Installation Electric Vehicle Supply Equipment (EVSE) Costs per vehicle (for BEVs only, including available tax credits)

Factors such as staffing and labor costs, scrap or resale value, insurance, taxes, grants, subsidies, and intangible benefits like reduced healthcare expenses or environmental costs associated with emission reductions or fuel economy improvements, are not taken into account. We expect that staffing and labor costs, scrappage, and resale values will not significantly differ between the two vehicle types.

Table 15: Summary of inputs used for Total Cost of Ownership (TCO) analysis

Inputs	ICEV	BEV
Powertrain (p/t) cost	ICE p/t	BEV p/t
Retail Price Equivalent (RPE)	1.5	1.2
Vehicle Purchase Price	VGP + (1.5 × ICE p/t)	VGP + (1.2 × BEV p/t)
Maintenance and Repair (M&R)	$0.17 per mile	30% less than the comparable ICEVs i.e., $0.119 per mile
Fuel Efficiency (mpg or kWh/mile)	Depending on Class	Depending on Class
Annual VMT (miles/annum)	Same for both depending on vehicle class	
Combined Hardware and Installation EVSE Costs, per vehicle	–	DCFC 350 kW
Lifetime	10 years	
Annual Discount Rate	3%	
Model Years	2030 and 2032	

3.4.1 ICEV

Table 16 presents the fuel economy inputs utilized for the selected vehicle types in MYs 2030 and 2032. We have adopted the same fuel economy figures as assumed by the EPA in their analysis. The resulting fuel costs are discounted annually by 3% to determine the cumulative cost of operating the vehicle. This discount rate considers the opportunity cost associated with the financial return that would be foregone by investing capital in vehicle ownership.

Table 16: Fuel economy and VMT inputs considered for TCO analysis

Model Year	EPA Vehicle ID	Roush Equivalent ID	Class	Fuel Efficiency (mpg)	Daily Sizing VMT/Range (miles)	10 yr Average Daily Operational VMT (miles)	Annual VMT (miles/annum)	Lifetime Miles (miles)
2030	79Tractor_SC_Cl8_R	C8_SC_Long Range	8	8.52	550	392	97,935	979,346
2030	78Tractor_SC_Cl8_MP	C8_SC_Standard Range	8	8.52	400	187	46,636	466,355
2030	82Tractor_DC_Cl8_R	C8_DC_Long Range	8	7.77	450	191	47,634	476,336
2030	84Tractor_DC_Cl8_U	C8_DC_Standard Range	8	7.77	300	191	47,634	476,336
2030	81Tractor_DC_Cl7_R	C7_DC_Long Range	7	8.92	250	106	26,576	265,758
2030	83Tractor_DC_Cl7_U	C7_DC_Standard Range	7	8.92	150	106	26,576	265,758
2032	79Tractor_SC_Cl8_R	C8_SC_Long Range	8	8.52	550	392	97,935	979,346
2032	78Tractor_SC_Cl8_MP	C8_SC_Standard Range	8	8.52	400	187	46,636	466,355
2032	82Tractor_DC_Cl8_R	C8_DC_Long Range	8	7.77	450	191	47,634	476,336
2032	84Tractor_DC_Cl8_U	C8_DC_Standard Range	8	7.77	300	191	47,634	476,336
2032	81Tractor_DC_Cl7_R	C7_DC_Long Range	7	8.92	250	106	26,576	265,758
2032	83Tractor_DC_Cl7_U	C7_DC_Standard Range	7	8.92	150	106	26,576	265,758

Figure 19 displays the retail prices of diesel fuel based on data from the EIA AEO 2023 [45]. It's important to note that the electricity prices mentioned below do not incorporate any taxes intended to support road construction or maintenance, unlike the retail diesel prices that do. To facilitate a fair comparison of energy costs, we have subtracted the federal and state tax components totaling $0.58 from the retail prices of diesel. This adjustment is made on the assumption that a comparable road tax will eventually be imposed on automotive electricity charging costs.

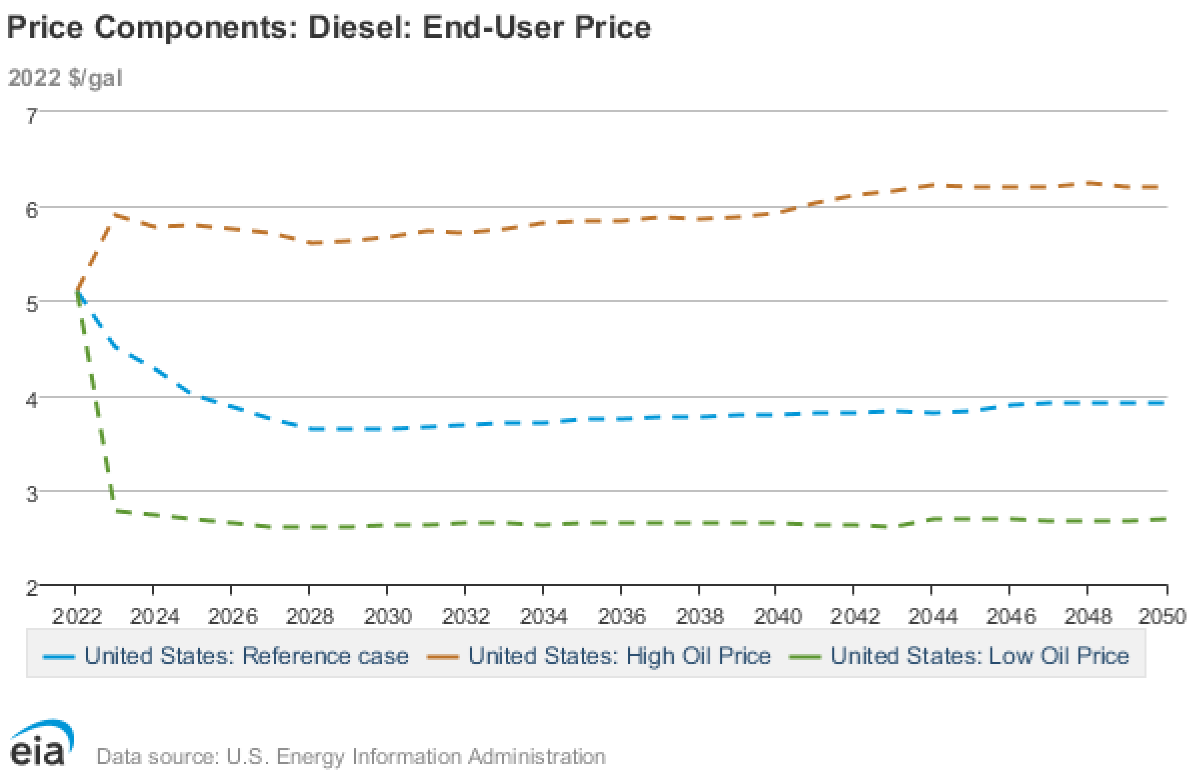


Figure 19: AEO 2023 projected retail prices of diesel in 2023 U.S. dollars per gallon [46]**.**

We have assumed M&R costs of $0.17 per mile for ICEVs, similar to the inputs specified by CARB for the Advanced Clean Fleets (ACF) regulation [31], [47]. A fuel price sensitivity analysis has been conducted to provide insights into TCO and its timeline for achieving parity with real-world fuel prices. More details on this analysis can be found in Section 5.4 below.

3.4.2 BEV

There is a lack of data regarding the maintenance and repair (M&R) costs of Classes 7 and 8 ICEVs and BEVs. However, BEVs generally have lower maintenance costs compared to ICEVs due to fewer moving parts, reduced consumption of consumables (such as lubrication oil and gaskets), and the utilization of unique components. For example, Tesla claims that its drivetrain has only 17 moving parts, including two in the motor, whereas a conventional ICEV has hundreds of moving parts. Numerous total cost of ownership (TCO) studies [39], [42], [48]–[51] indicate that the maintenance cost of BEVs is 30%–40% cheaper than that of ICEVs, due to the reduction in moving parts and the absence of engine oil, automatic transmission fluid, spark plugs, and timing belts. Therefore, in the analysis, a conservative assumption is made that the M&R cost of BEVs is 30% lower than that of comparable ICEVs [23], [33]. The assumed M&R cost for BEVs is $0.119 per mile.

3.4.2.1 Depot Charging

To ensure safety and prevent driver fatigue, the U.S. Federal Motor Carrier Safety Administration (FMCSA) imposes regulations on the number of hours a driver of a property-carrying commercial motor vehicle (CMV), such as a Class 8 tractor-trailer, can drive. According to FMCSA guidelines, a Class 8 tractor-trailer is allowed a maximum of 11 hours of driving within 24 hours [18]. Additionally, the driver must take a mandatory 30-minute break after 8 hours of continuous driving. However, in practice, most drivers drive for fewer hours per day due to rest breaks, loading and unloading times, and other delays [19].

Table 17: Vehicle Time Parked Per Day by Segment (NACFE/ACT Survey), 2018 [15]

Time parked for (in 24 hour day)	City Tractor	Regional Tractor	Long Haul tractor
less than 1 hour	0%	1%	0%
from 1 to 2 hours	2%	4%	13%
from 3 to 4 hours	18%	15%	9%
from 5 to 6 hours	12%	10%	10%
from 7 to 8 hours	3%	14%	15%
Greater than 9 hours	65%	56%	54%

To include the costs associated with charging BEVs, a depot charging scenario has been developed. Depot charging involves installing chargers in parking depots, warehouses, and other private locations where vehicles are parked during off-shift periods, as defined by the EPA in the draft Regulatory Impact Analysis (RIA) [3]. Commercial end-use electricity retail price projections from the Energy Information Administration's Annual Energy Outlook (AEO) 2023, as shown in Figure 20, are utilized, and the charger costs are considered as inputs for calculating BEV energy costs.

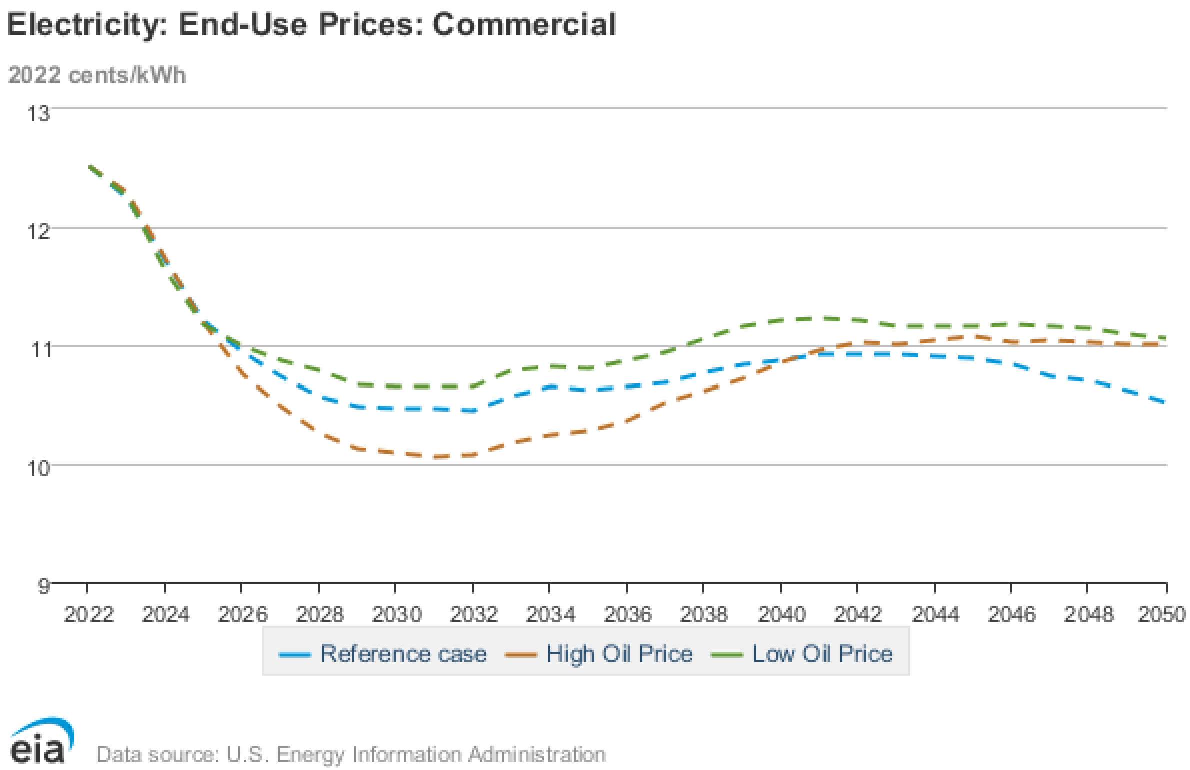


Figure 20: AEO 2023 projected commercial electricity prices in 2022 cents/kWh [46]**.**

For this analysis, it is assumed that a typical Class 7/8 vehicle will have a dwell time (the time a vehicle is off-shift and parked at a depot or warehouse) of 12 hours while operating for 8 hours per day, considering 250 operational days in a year, as assumed by the EPA. The EPA also assumes that the combined hardware and installation costs of Electric Vehicle Supply Equipment (EVSE) per vehicle, for two vehicles per port with a DC Fast Charger (DCFC) rated at 350 kW, is $81,166. However, based on our previous studies, it is assumed that a single 350 kW DCFC charger would be sufficient to serve three vehicles in a fleet [42], [52], which apportions the charger cost to $54,110 per vehicle. The vehicle with the largest battery pack i.e., a Class 8 sleeper cab long range takes about 3 hours for a full charge. Hence, this results in a less than 40% charger utilization rate (3 vehicles charging for 3 hours so 9 hours of charging over 24 hours so roughly 40%). Furthermore, considering the availability of a 30% incentive under 26 U.S.C. §30C on the apportioned charger cost of $54,110, the combined hardware and installation costs of EVSE reduce to $37,877 per vehicle.

4. Results

This section presents the overall results of the primary vehicle modeling, analysis of the ICEV powertrain DMCs and DMCs with RPE, and BEV inputs to determine the powertrain DMCs and DMCs with RPE, payback period, TCO per mile, and cumulative net savings of BEVs over ICEVs during the period of ownership.

4.1 Modeling Results and Powertrain Sizing

Table 18 presents the outputs of the GT-Suite modeling. In our analysis, we made several assumptions. Firstly, we assumed that 90% of the battery's energy storage capacity is usable. Additionally, we upsized the battery by 10% to compensate for battery degradation over the vehicle's lifespan.

To calculate the energy cost for TCO, we divided the "Weighted energy consumption" by 0.95 to obtain the "DC consumption" (kWh/mi). This adjustment accounts for the assumption that the vehicle effectively utilizes 95% of the energy dispensed by the DC fast charger.

Table 18: Modeling Results from GT-Suite and battery size calculations. LR and SR stand for long range and standard range, respectively.

Class		8	8	8	8	7	7
Vehicle		Sleeper LR	Sleeper SR	Day cab LR	Day cab SR	Day cab LR	Day cab SR
Range	miles	550	400	450	300	250	150
Motor size	kW	750	750	750	750	340	340
Consumption - transient cycle	kWh/mi	1.90	1.90	1.89	1.89	1.28	1.28
Consumption - 55 Cruise	kWh/mi	1.60	1.60	1.66	1.66	1.31	1.31
Consumption - 65 Cruise	kWh/mi	1.84	1.84	1.93	1.93	1.58	1.58
Weighted energy consumption	kWh/mi	1.82	1.82	1.88	1.88	1.48	1.48
Battery usable capacity	kWh	1,001	728	845	563	369	222
Usable/ gross batt capacity	%	90%	90%	90%	90%	90%	90%
% batt upsizing degradation	%	10%	10%	10%	10%	10%	10%
Battery gross capacity	kWh	1,224	890	1,033	688	451	271

Class		8	8	8	8	7	7
Vehicle		Sleeper LR	Sleeper SR	Day cab LR	Day cab SR	Day cab LR	Day cab SR
DC Consumption (/0.95%)	kWh/mi	1.92	1.92	1.98	1.98	1.55	1.55

The range of vehicles (battery sizes and range) presented in Table 18 covers 90% of Classes 7 and 8 use cases up to a GVW of 80,000 lb. We assume the vehicles cover the daily VMT requirements on a single charge without en route charging. Section 4.1.1 presents the effect of the GVW, Coefficient of drag, and auxiliary loads on the range of a Class 8 Sleeper Cab Long range tractor trailer. Section 4.1.2 presents the effect of a 15-minute charging session at a megawatt charging (MCS) station in significantly increasing the effective range of a vehicle.

4.1.1 Effect of Vehicle Parameters on Energy Efficiency

Figure 21 shows the effect of the coefficient of drag on the energy efficiency of a Class 8 sleeper cab with a 1001 kWh usable battery capacity (Roush sizing – Class 8 sleeper cab long range). The C_d has a significant effect on energy efficiency. An increase of C_d from 0.35 to 0.65 results in a 27% decrease in range. The impact of C_d on range shows the importance of a dedicated clean sheet for electric tractors to minimize aero drag and maximize energy efficiency (kWh/mile).

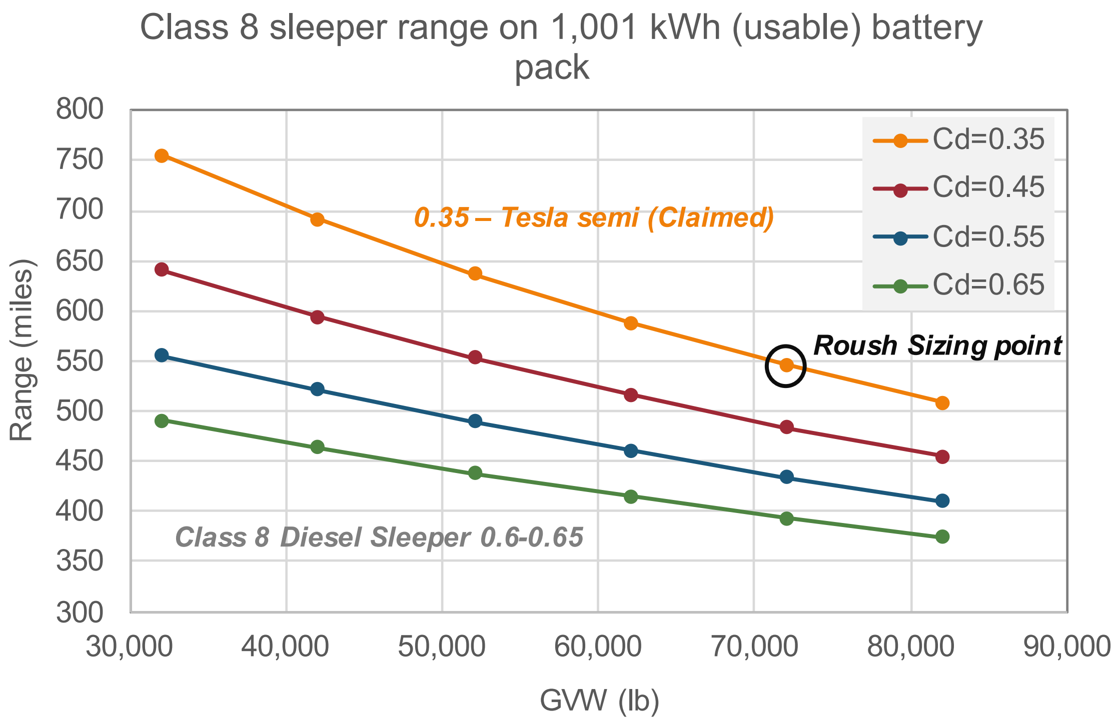


Figure 21: Effect of coefficient of drag on energy efficiency

Figure 22 illustrates the effect of auxiliary loads on the energy consumption (kWh/mile) of a Class 8 sleeper cab. Even with an electric reefer trailer's high energy consumption, the tractor-trailer loses less than 10% of its electric range.

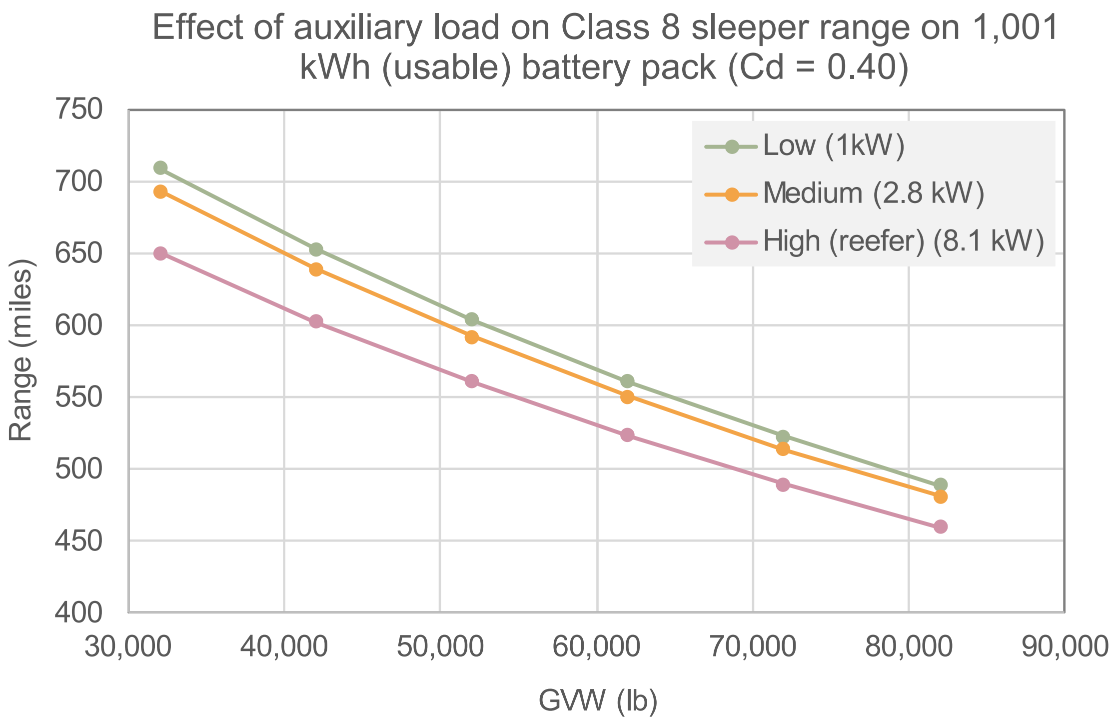


Figure 22: Effect of auxiliary loads on energy efficiency

4.1.2 Effect of En Route Megawatt Charging of Effective Range of Electric Tractors

The Megawatt Charging System (MCS) [24] can provide a maximum of 3,000 Amps at 1,250 Volts resulting in a charge rate exceeding 3 MW (limited by the BEV pack voltage, cell technology, etc.). A network of MCS chargers along major freight corridors can significantly increase the daily driving range of electric tractor-trailers and expand their use for heavy payloads (80,000+ lb) and extreme weather conditions.

Figure 23 shows the charging characteristics of a 2022 KIA EV6 when charging at a 350kW Electrify America charger. The Kia EV 6 can charge 10 to 80% in under 17 minutes [53]. It also shows the charging curve for an equivalent Storedot XFC Cell-based battery pack [54] that can reduce the 10-80% charging time to under 10 minutes. The Storedot 30 Ah automotive form factor pouch XFC Cell is currently under evaluation by major automakers and is in this report as a representative of future fast-charging battery chemistry.

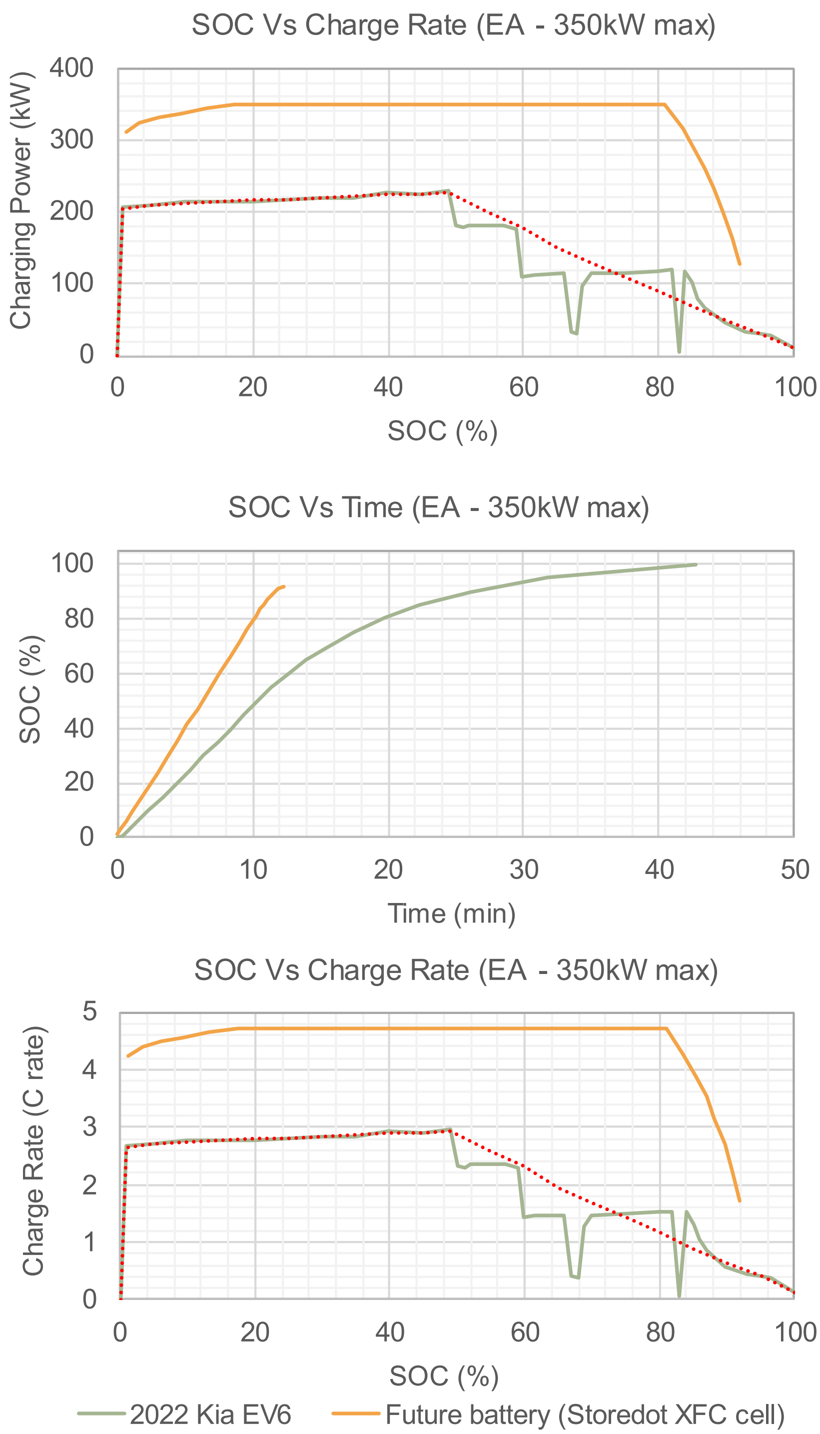


Figure 23: Charging a 2022 Kia EV6 [53]**, and an equivalent StoreDot XFC cell-based battery pack** [54] **(calculated based on cell performance) on an EA 350kW charger**

We assume that the Kia EV6 battery represents the current state-of-the-art and the StoreDot XFC represents a possible future fast-charging battery in 2030-32. Figure 24 shows an en route charging scenario for a Class 8 long range sleeper cab with today's state-of-the-art batteries (Figure 24 middle) and possible future battery technology (Figure 24 bottom). Both vehicles begin the drive at 80% battery pack SOC and are driven at a constant speed of 65 Mph. After 6 hours covering 374 miles (11% SOC remaining), they are charged for 15 minutes at a 3,000 A MCS dispenser. Today's state-of-the-art production battery will add 60% SOC (324 miles of range). Future battery technologies, such as the StoreDot XFC, can add an estimated 70.8% SOC (385 miles of range). After starting at 80% SOC and covering about 700 miles with only a 15-minute charging stop, the "today's state-of-the-art" battery has 11.2% SOC remaining while the representative "future battery" has 22.4% battery left, enough for an additional 122 miles. The difference between the present and future fast-charging battery technologies for tractors with smaller battery packs will be higher. The above example illustrates the ability of the MCS to expand the capabilities of a battery-electric tractor-trailer significantly.

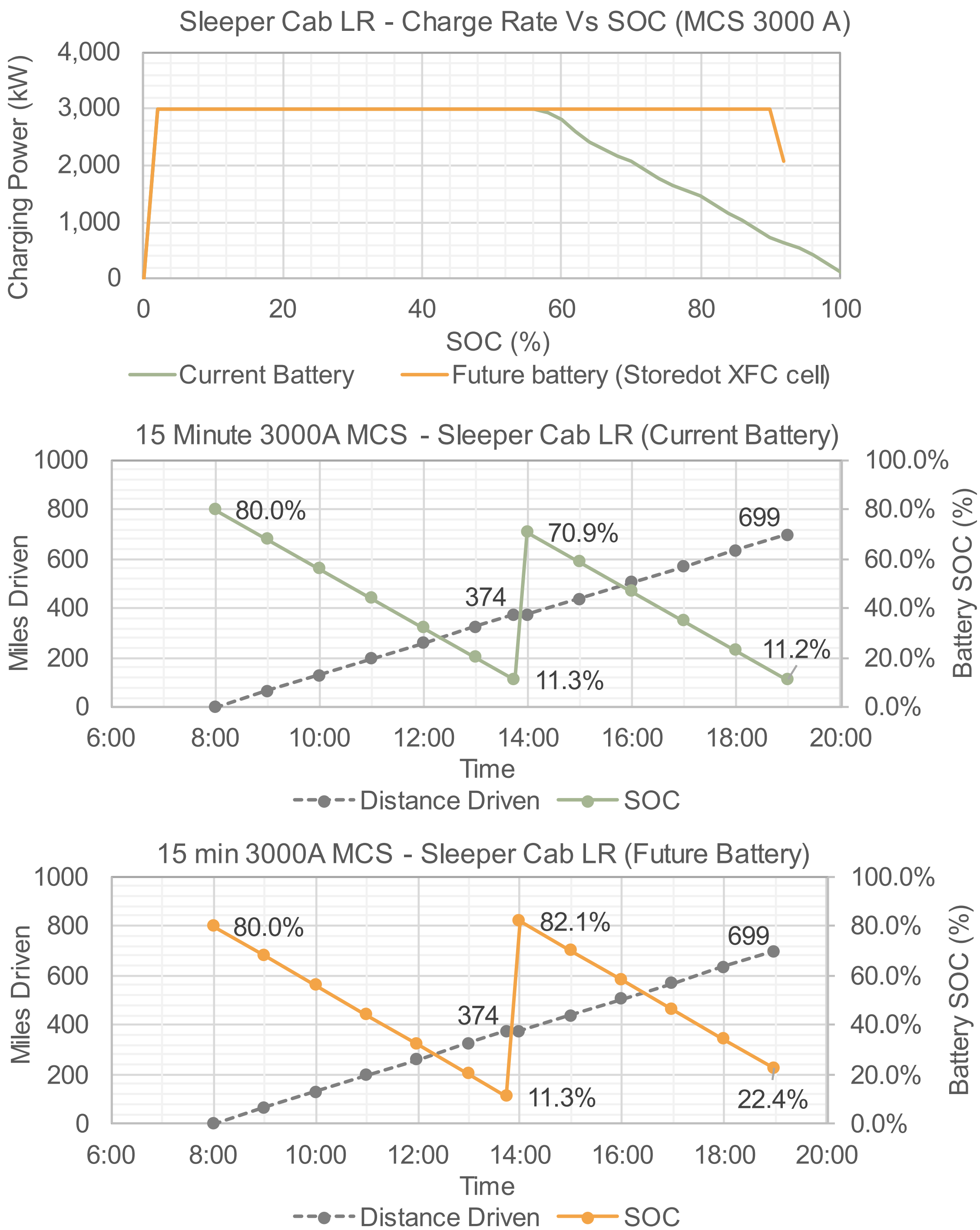
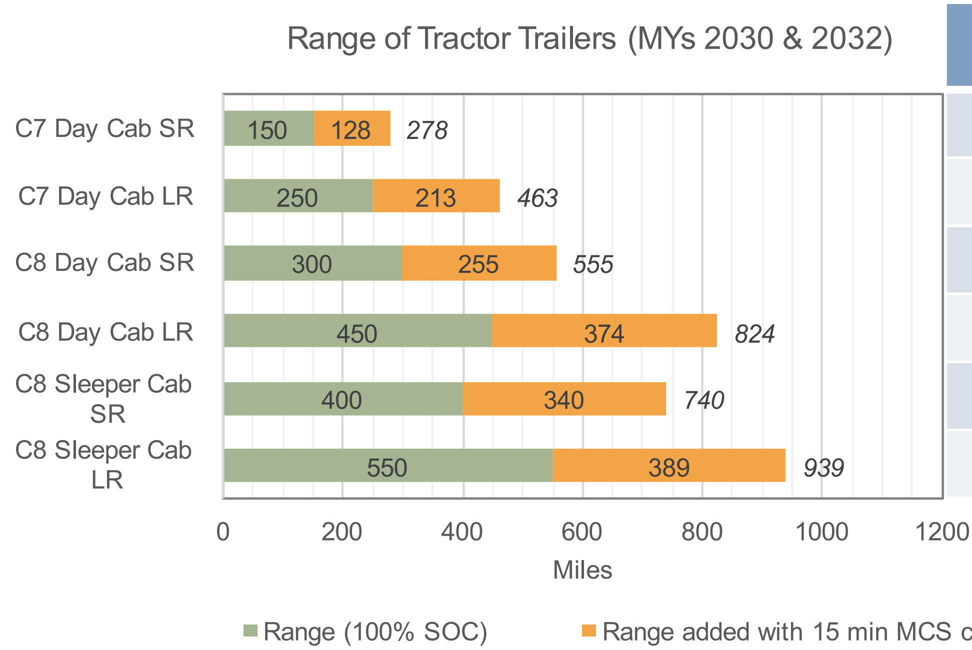


Figure 24: (Top) Estimated peak charging rate for a Sleeper Cab LR (1224 kWh battery pack) with present and future battery technologies. (Middle and bottom) Driving a Sleeper Cab LR at 65 miles an hour, starting at 80% SOC. The vehicle is charged for 15 minutes at a 3000A MCS Dispenser starting at 11.3% SOC. The pack nominal voltage is 1000V.

Figure 25 shows the different BEVs, their electric range on a full charge (green portion of the bar), and their gross battery capacity (kWh). Figure 25 also shows the electric range that can be added with a 15-minute charge on a 3,000 Amp MCS and representative fast-charging battery technology (the orange portion of the bar). (The charging session is assumed to start at 10% SOC and terminated at 15 minutes or maximum SOC of 95%, whichever is earlier). MCS stations along major freight corridors can significantly expand the capabilities of electric tractors. An MCS can increase the maximum distance covered in a day for a given battery size and compensate for any loss of range in extreme weather conditions, trailers with high drag coefficients, and auxiliary loads like a reefer trailer with high electric power consumption.



Battery kWh#	Test wt. lb
271	44,000
451	44,000
688	72,000
1,033	72,000
890	72,000
1,224	72,000

LR - Long range, SR - Standard range, # Gross battery capacity

Figure 25: Battery size (kWh), range (miles), Test weight (lb), and the range added with a 15-minute charging session at a 3,000 Amp Megawatt Charging System (MCS) station

4.2 Powertrain DMCs without RPE

4.2.1 ICEVs

Table 19 lists the ICEV powertrain costs used by the EPA in their analysis. It is important to note that the DMCs do not change between MYs 2030 and 2032.

Table 19: ICEV Powertrain DMC breakup for MYs 2030 and 2032 [3]

EPA Vehicle ID	Roush Equivalent ID	Total ICE Powertrain DMC ($) in 2021 $ *(EPA original)*	Total ICE Powertrain DMC ($) in 2022 $
79Tractor_SC_Cl8_R	C8_SC_Long Range	$59,955	$64,752
78Tractor_SC_Cl8_MP	C8_SC_Standard Range	$58,936	$63,651
82Tractor_DC_Cl8_R	C8_DC_Long Range	$59,835	$64,622
84Tractor_DC_Cl8_U	C8_DC_Standard Range	$56,102	$60,591
81Tractor_DC_Cl7_R	C7_DC_Long Range	$45,070	$48,676
83Tractor_DC_Cl7_U	C7_DC_Standard Range	$44,950	$48,546

4.2.2 BEVs

Battery costs for MYs 2027, 2030, and 2035 in our previous studies [37], [38], [42], were based on projections from the global segment before the introduction of IRA. Table 20 presents a list of battery component costs (in 2022 $) utilized in this study. A conservative approach was considered for this study by applying an adjustment multiplier of 1.5 to the high-cost case from our previous studies [37], [38]. The different factors that justified the correction are listed below:

a) There is a potential shift in reshoring/onshoring of battery manufacturing activities, leading to increased production of domestically produced battery packs. The previously considered prices were global and may not accurately reflect the cost of production in the U.S. Additionally, the vertical integration of the battery supply chain may result in the sharing of components between LDV and MD/HDV segments. Since the LD vehicle credit is partially reliant on North American-produced batteries, the sharing of components might result in a preference for domestically made batteries in the MD/HD sector.

b) Batteries with a high cycle life requirement were taken into account due to the very high lifetime mileage of tractors.

c) The battery should be able to fast charge using a megawatt charging system.

d) Regulations aimed at establishing a sustainable battery supply chain and complying with ESG (environmental, social, and governance) mandates could increase the price.

Taking all these factors into consideration, a multiplier of 1.5 was used relative to battery costs projected previously for vehicles with much lower lifetime mileages. As a result, the projected cost of a domestically produced battery pack without the IRA credits is expected to be $106/kWh and $95/kWh in 2030 and 2032, respectively. With the introduction of §45X as a result of the IRA of 2022, the battery pack costs could become competitive with the global market. Therefore, we project the costs of a domestically produced battery pack to be $78/kWh and $86/kWh in 2030 and 2032, respectively.

It is important to note that the cost of battery packs for these commercial vehicles could be lower as automakers have the option to choose cells and modules produced outside the United States, which helps reduce their powertrain costs. The vehicle tax credits do not require the usage of domestically produced batteries. However, for the purpose of applying the battery tax credits, we have considered the projected cost of a battery pack produced and assembled domestically.

Similarly, we applied the same adjustment multiplier of 1.5 to our previous motor and inverter costs. This resulted in a cost of $9/kW compared to the $6/kW used in previous studies [37], [38]. There were several reasons for this adjustment specific to Class 7/8 tractor-trailers:

a) Operational differences and higher durability requirements for the HD vehicle segment result in different design parameters and overall requirements for this segment:
    i) Lower speed and higher torque motors are required, which would increase the amount of rare earth materials and copper (windings) used per kW of output. This contrasts with the motors used in LDVs, which typically utilize high-speed, low-torque motors.
    ii) Motors need to have a longer lifespan and greater durability. Therefore, a higher factor of safety components such as bearings, stator coil insulation, and liquid cooling seals are included, which could result in higher costs.
b) Production volumes of such motors would be lower compared to LDVs and MDVs. This estimate takes into account the conservative approach, but there is potential to leverage motor architecture for multiple vehicle segments and categories.
c) Inverters need to have a longer lifespan, requiring more thermal headroom while sizing components.
d) Power devices and DC–link capacitors account for 50% of the inverter costs:
    i) Recent advances in SiC and GaN devices promise significant power density and efficiency, but their potential usage in this vehicle segment could lead to increased costs.

ii) Tightly integrated packaging with thermal management systems and high-efficiency materials are considered.

Table 20: BEV component costs used in this study (in 2022 $)

Component	Unit	2030	2032
Battery Pack Cost (no credit)	$/kWh	$106	$95
Battery Pack Cost with IRA Total Battery Credit	$/kWh	$78	$86
Motor + Inverter DMC	$/kW	$9	$9
On-board Charger + DC-DC DMC	$/kW	$5	$5
Gearbox DMC	same as EPA for MYs 2030 and 2032 for each vehicle category, respectively		
Final Drive DMC			
Electric Accessories			

Table 21 lists the BEV powertrain specification used in this study to determine their powertrain DMCs.

Table 21: BEV Powertrain Specifications for MYs 2030 and 2032

EPA Vehicle ID	Roush Equivalent ID	DC Consumption (kWh/mile)	Gross Battery Capacity (kWh)	Motor size (kW)	Onboard Converter (kW)	DC-DC Converter (kW)
79Tractor_SC_Cl8_R	C8_SC_Long Range	1.92	1224	750	22	6
78Tractor_SC_Cl8_MP	C8_SC_Standard Range	1.92	890	750		
82Tractor_DC_Cl8_R	C8_DC_Long Range	1.98	1033	750		
84Tractor_DC_Cl8_U	C8_DC_Standard Range	1.98	688	750		
81Tractor_DC_Cl7_R	C7_DC_Long Range	1.56	451	340		
83Tractor_DC_Cl7_U	C7_DC_Standard Range	1.56	271	340		

Table 22 provides a summary of the comparison between the assumed BEV parameters by the EPA and our study. Consequently, it is evident that the significant disparity in battery sizing would have an impact on the powertrain DMCs of BEVs.

Table 22: Comparison of BEV parameters

Vehicle	Roush			EPA		
	Range (miles)	Gross Battery Capacity (kWh)	DC Consumpt -ion (kWh/mile)	Range (miles)	Gross Battery Capacity (kWh)	Operating Energy Consumpt -ion (kWh/mile)
C8_SC_Long Range	550	1224	1.92	550	2015	2.75
C8_SC_Standard Range	400	890	1.92	400	1468	2.76
C8_DC_Long Range	450	1033	1.98	349	1261	2.71
C8_DC_Standard Range	300	688	1.98	349	1261	2.71
C7_DC_Long Range	250	451	1.56	214	637	2.23
C7_DC_Standard Range	150	271	1.56	214	637	2.23

Table 23 lists the BEV powertrain DMCs in 2022 $ based on the powertrain specifications listed in Table 21.

Table 23: BEV Powertrain DMC breakup (in 2022 $)

Model Year	EPA Vehicle ID	Roush Equivalent ID	Battery DMC (without IRA Battery Tax Credit) ($)	Effective Battery DMC (with IRA Battery Tax Credit) ($)	Motor + Inverter DMC ($)	On-board Charger + DC-DC Converter DMC ($)	Gearbox DMC ($)	Final Drive DMC ($)	Electric Accessor -ies ($)	BEV Powertrain DMC ($)
2030	79Tractor_SC_Cl8_R	C8_SC_Long Range	$129,562	$95,141	$6,401	$137	$4,572	$2,814	$4,221	$113,287
2030	78Tractor_SC_Cl8_MP	C8_SC_Standard Range	$94,227	$69,194	$6,401	$137	$4,572	$2,814	$4,221	$87,340
2030	82Tractor_DC_Cl8_R	C8_DC_Long Range	$109,315	$80,273	$6,401	$137	$4,580	$2,814	$4,221	$98,427
2030	84Tractor_DC_Cl8_U	C8_DC_Standard Range	$72,876	$53,515	$6,401	$137	$3,237	$2,814	$4,221	$70,326
2030	81Tractor_DC_Cl7_R	C7_DC_Long Range	$47,772	$35,080	$2,902	$137	$2,063	$2,814	$4,221	$47,217
2030	83Tractor_DC_Cl7_U	C7_DC_Standard Range	$28,663	$21,048	$2,902	$137	$2,063	$2,814	$4,221	$33,185
2032	79Tractor_SC_Cl8_R	C8_SC_Long Range	$116,606	$105,132	$6,401	$137	$4,239	$2,609	$3,914	$122,433
2032	78Tractor_SC_Cl8_MP	C8_SC_Standard Range	$84,804	$76,460	$6,401	$137	$4,239	$2,609	$3,914	$93,760
2032	82Tractor_DC_Cl8_R	C8_DC_Long Range	$98,383	$88,703	$6,401	$137	$4,247	$2,609	$3,914	$106,011
2032	84Tractor_DC_Cl8_U	C8_DC_Standard Range	$65,589	$59,135	$6,401	$137	$3,001	$2,609	$3,914	$75,197
2032	81Tractor_DC_Cl7_R	C7_DC_Long Range	$42,995	$38,764	$2,902	$137	$1,913	$2,609	$3,914	$50,239
2032	83Tractor_DC_Cl7_U	C7_DC_Standard Range	$25,797	$23,259	$2,902	$137	$1,913	$2,609	$3,914	$34,733

4.2.3 Comparison of Diesel and BEV Powertrain DMCs without RPE

Figure 26 displays the incremental DMCs (without RPE) of a BEV with battery tax credits compared to a comparable ICEV. Put simply, it shows the difference in powertrain DMCs between a BEV with battery tax credits and an ICEV. The data reveals that all Class 8 battery-electric trucks are more expensive than their ICEV counterparts in model years 2030 and 2032. However, for Class 7 trucks, except for the long-range day cab in MY 2032, all other categories are cheaper than their ICEV counterparts. The main conclusion is that despite the application of battery tax credits, the direct manufacturing costs of BEVs are significantly higher than those of ICEVs. However, subsequent sections demonstrate that when indirect cost multipliers and vehicle tax credits are taken into account, the prices shift dramatically, underscoring the importance of the IRA.

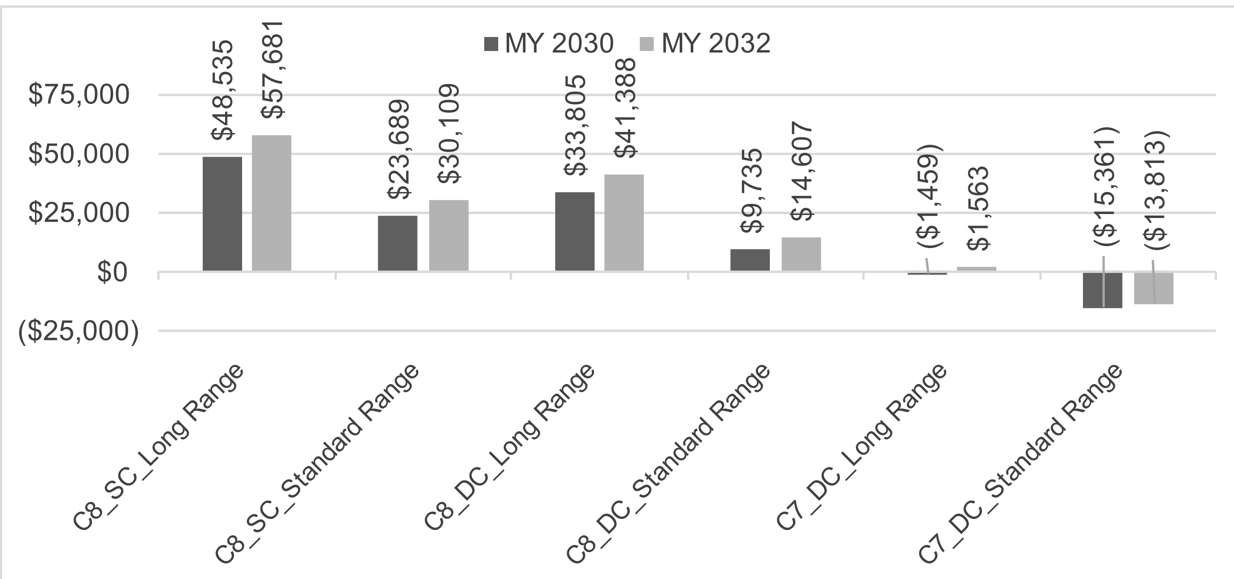


Figure 26: Incremental DMCs without RPE of a BEV with battery tax credits over a comparable ICEV. Values in parentheses indicate that the BEV is cheaper than the comparable ICEV.

4.3 Powertrain DMCs with RPE (or Purchase Price)

Figure 27 shows the RPEs of the powertrains of ICEVs and BEVs in the 2030-2032 timeframe. It can be observed that the ICEV price does not change across the MYs while the BEVs price increases (as assumed by the EPA). However, for BEVs, the gradual reduction in battery manufacturing tax credits from 2030 onwards (as outlined in Table 20) leads to an increase in net battery pack costs, subsequently impacting powertrain costs. However, in situations where the RPE of the BEV exceeds that of the ICEV, the IRA vehicle tax credits effectively bring down the RPE of the BEV to match that of the ICEV in all but one case.

a) Bringing them at par with the MYs 2030 and 2032 ICEVs as seen in the case of Class 8 sleeper cab standard range, Class 8 day cab long range, and MY 2030 Class 8 sleeper cab long range.
b) Reducing the incremental RPE by $40,000 to $9,792 in MY 2032 Class 8 sleep cab long-range vehicles.

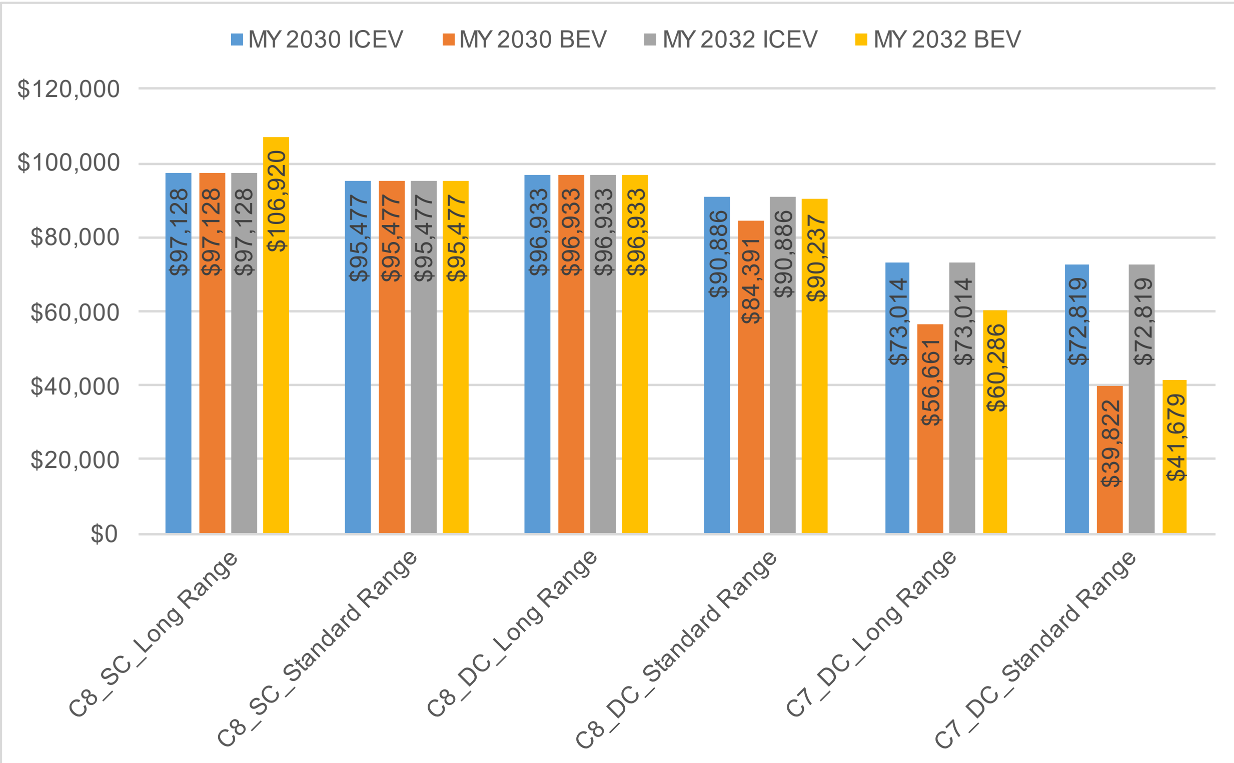


Figure 27: Powertrain DMC with RPE of ICEVs and BEVs in MYs 2030 and 2032

4.4 Total Cost of Ownership (TCO) Per Mile

In addition to their different powertrain RPEs, BEVs and ICEVs also vary in their operating expenses incurred throughout the lifetime of ownership. The TCO accounts for the vehicle retail price and factors in the charger cost, energy or fuel cost, and M&R cost over the assumed life of 10 years for vehicles purchased in 2030 (and operated through 2039) and 2032 (and operated through 2041). With a 350 kW depot charging, the TCO per mile of a BEV is lower than a comparable ICEV. It can be observed that,

a) In MY 2030, the TCO for an ICEV varies between $0.578 per mile and $0.739 per mile, whereas the TCO for a comparable BEV range from $0.421 per mile to $0.605 per mile.
b) In MY 2032, the TCO for an ICEV varies between $0.581 per mile and $0.741 per mile, whereas the TCO for a comparable BEV range from $0.431 per mile to $0.620 per mile.

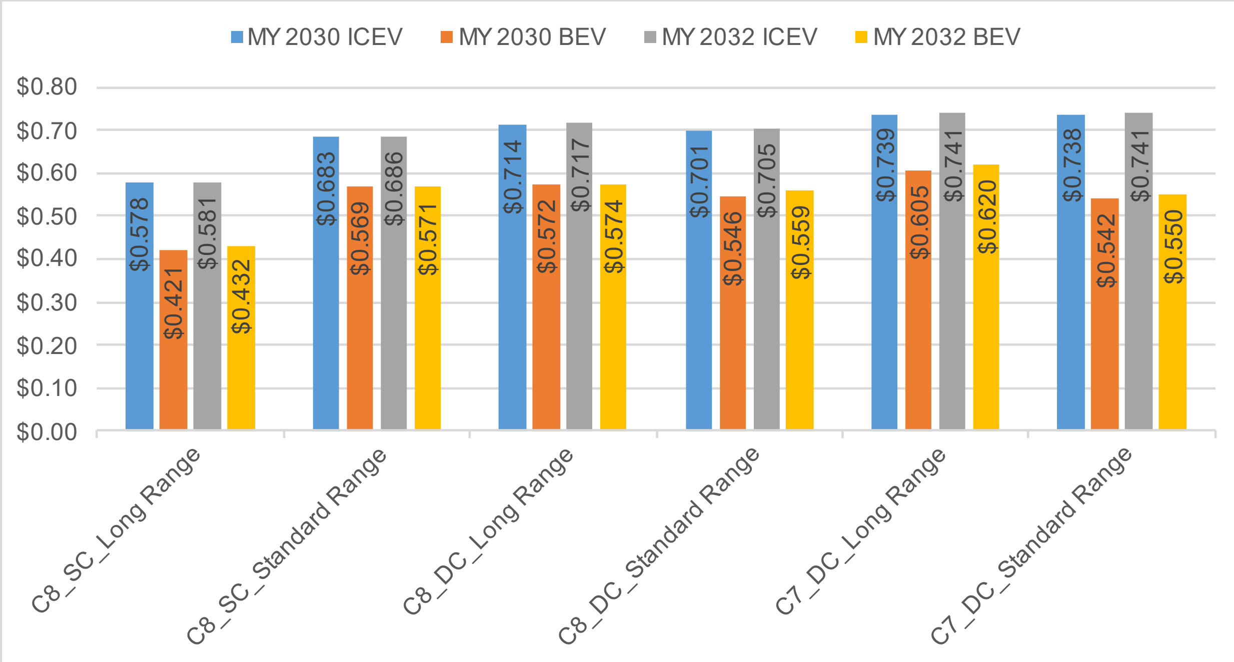


Figure 28: TCO per mile of ICEVs and BEVs in MYs 2030 and 2032.

The higher the VMT, as seen in the case of Class 8 sleeper cab long-range (refer to Table 16 for annual VMTs), the lower the TCO of a BEV against a comparable ICEV. The slight increase in TCO per mile of an MY 2032 BEV against an MY 2030 BEV is due to the higher powertrain retail price (which is due to the lower battery tax credits).

The contributions of the powertrain retail price (or purchase price) and operating expenses of a vehicle to the TCO have been depicted using donut charts for vehicles purchased in MYs 2030 and 2032, respectively. The non-purchase costs are discounted to “purchase year” equivalents. Also, in each chart, BEV is the inner ring and ICEV is the outer ring. The energy and maintenance costs of BEVs are lower than their ICEV counterparts across all vehicle types in MYs 2027 and 2030. For most fleet owners that have vehicles with longer fleet lives, energy and maintenance costs are critical decision-making metrics. They would find BEVs attractive due to lower energy and maintenance costs.

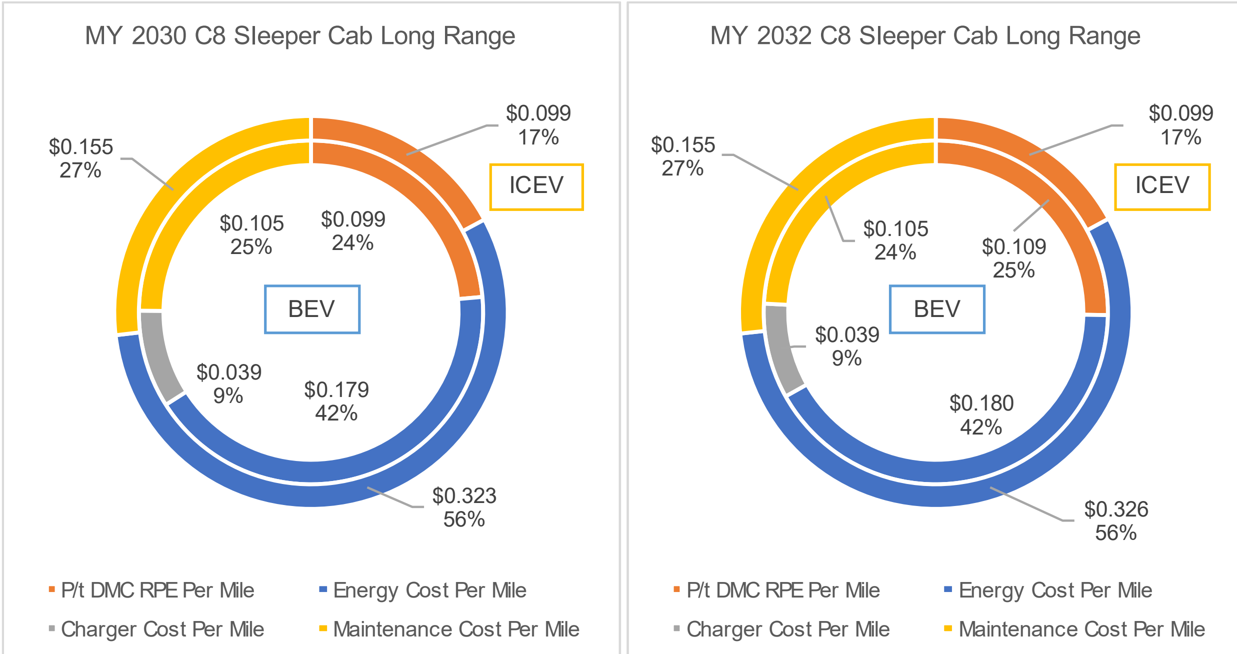


Figure 29: MYs 2030 and 2032 Class 8 Sleeper Cab Long Range ICEV and BEV contributions to TCO. P/t stands for Powertrain.

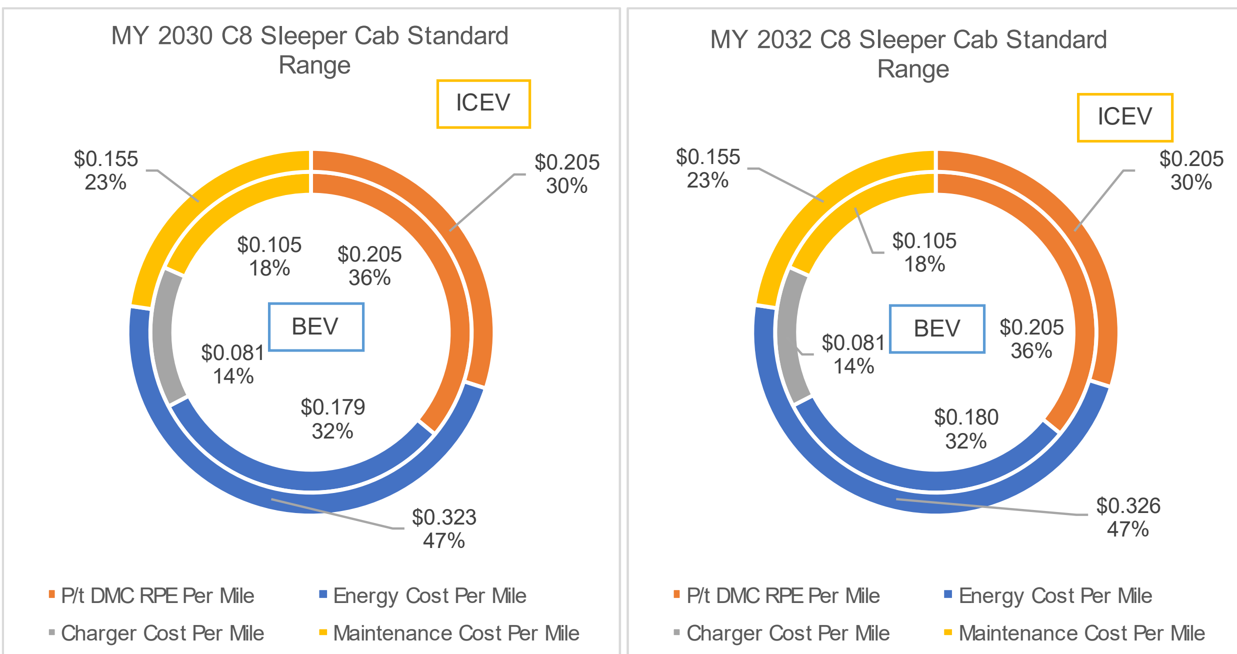


Figure 30: MYs 2030 and 2032 Class 8 Sleeper Cab Standard Range ICEV and BEV contributions to TCO. P/t stands for Powertrain.

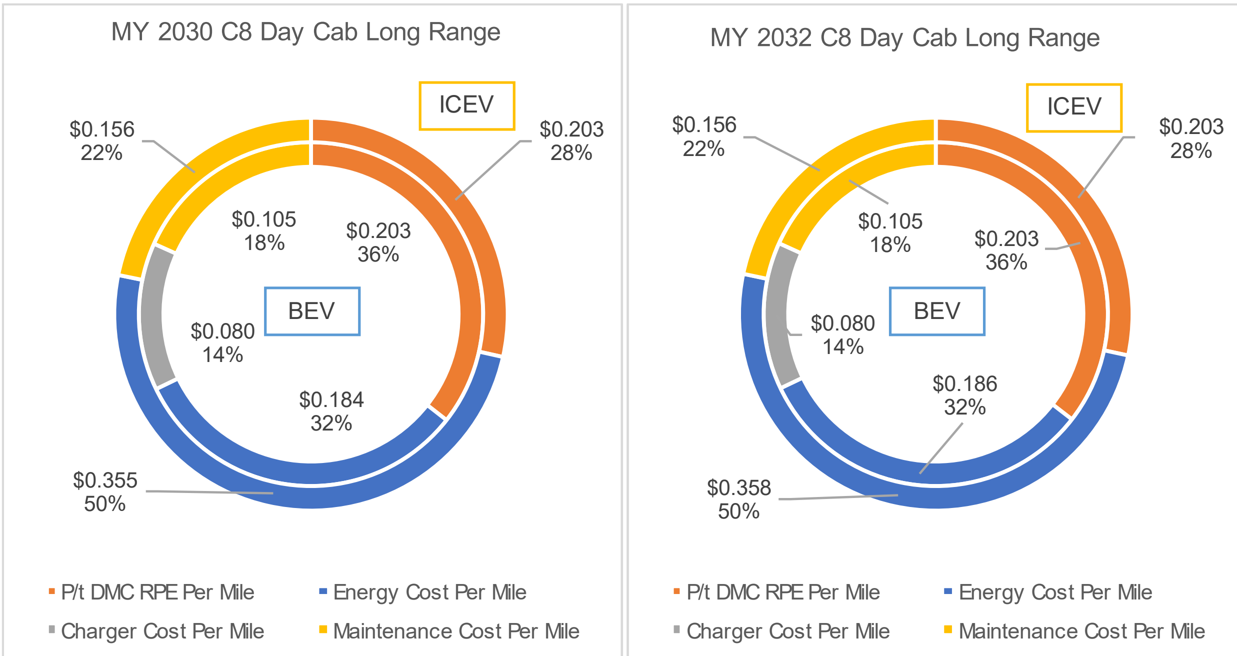


Figure 31: MYs 2030 and 2032 Class 8 Day Cab Long Range ICEV and BEV contributions to TCO. P/t stands for Powertrain.

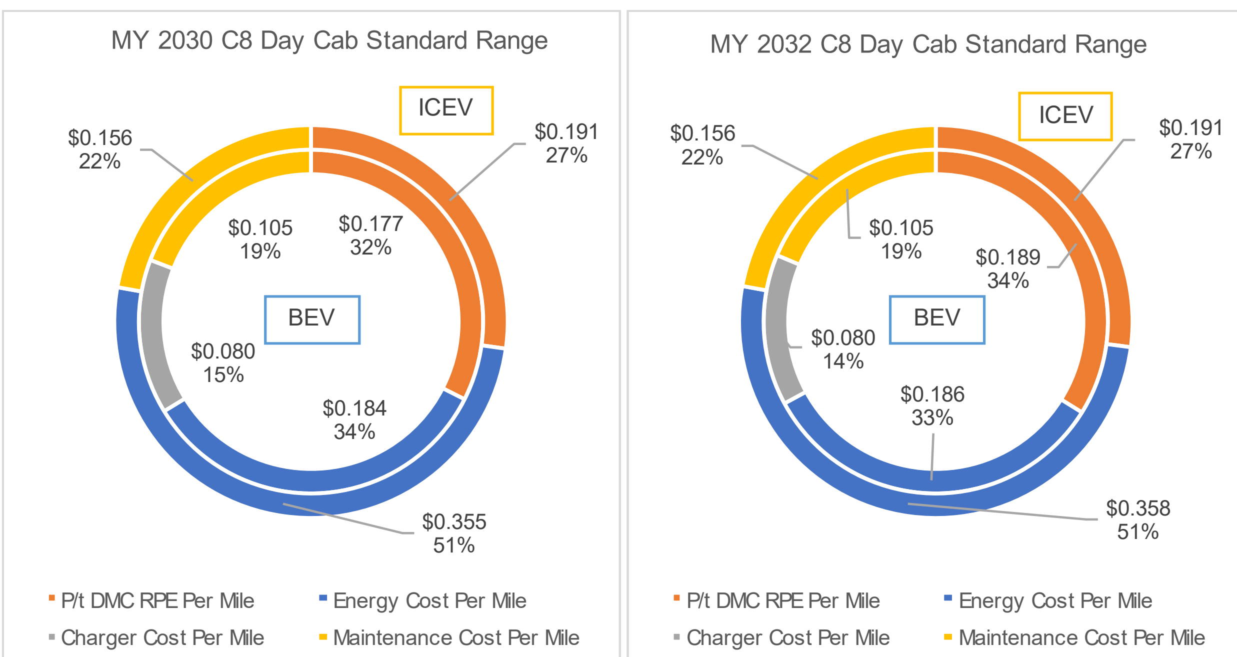


Figure 32: MYs 2030 and 2032 Class 8 Day Cab Standard Range ICEV and BEV contributions to TCO. P/t stands for Powertrain.

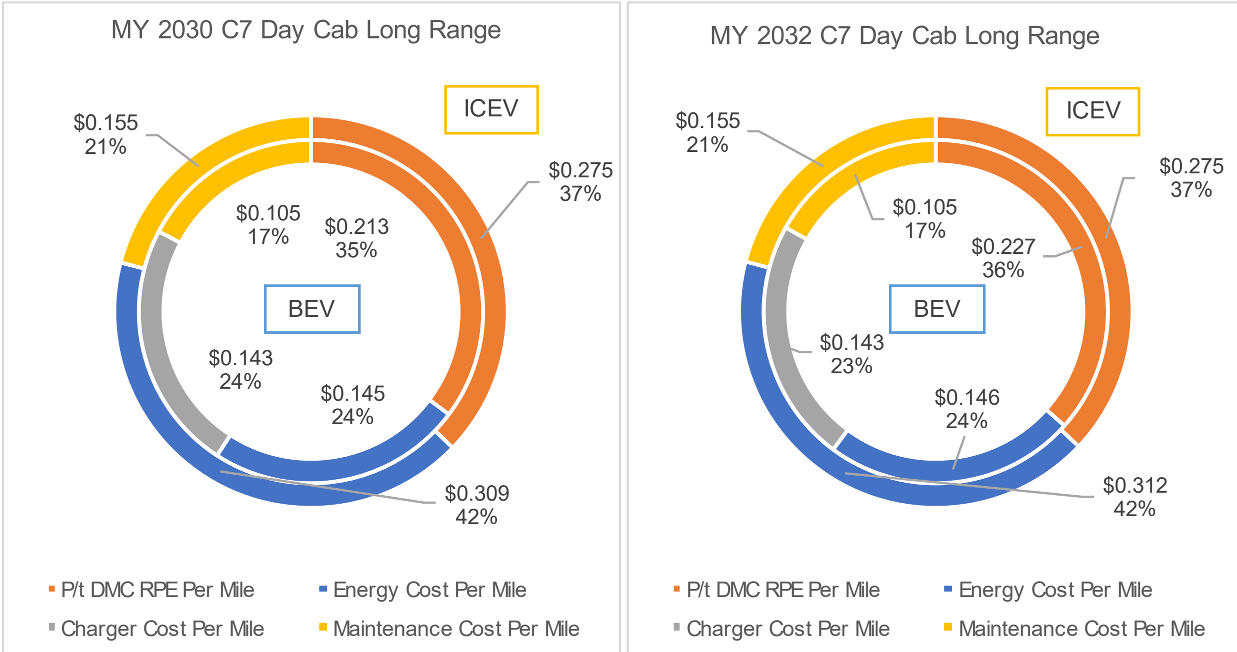


Figure 33: MYs 2030 and 2032 Class 7 Day Cab Long Range ICEV and BEV contributions to TCO. P/t stands for Powertrain.

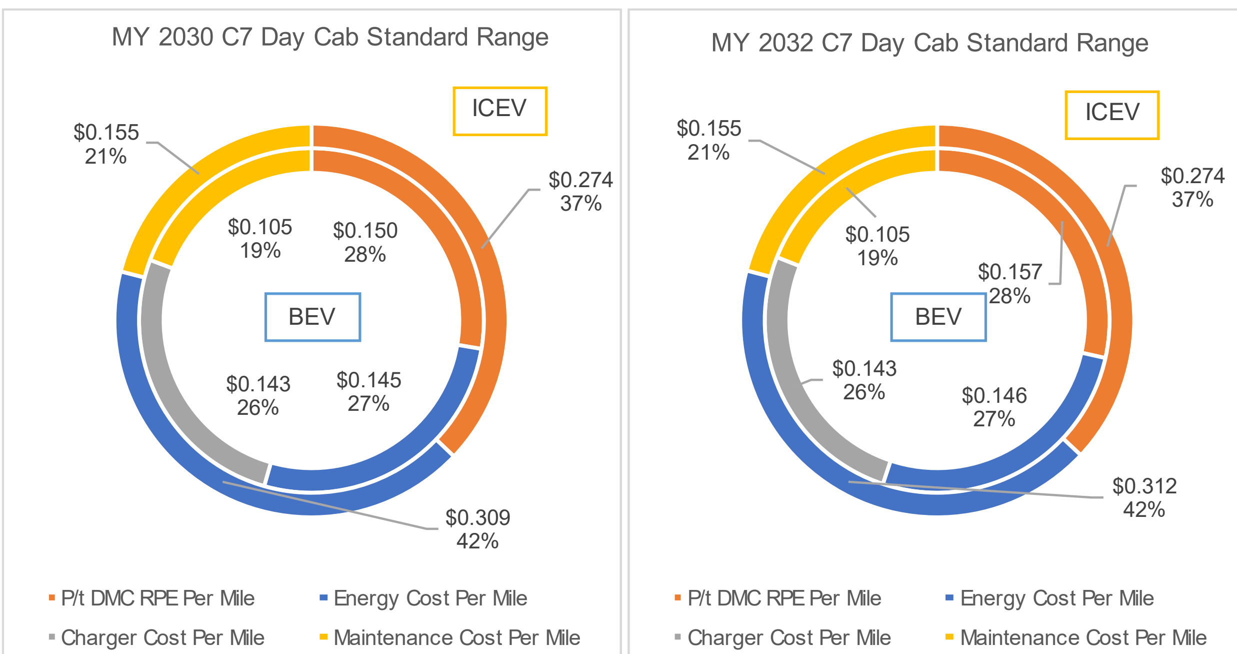


Figure 34: MYs 2030 and 2032 Class 7 Day Cab Standard Range ICEV and BEV contributions to TCO. P/t stands for Powertrain.

4.5 Payback period and Cumulative Net Savings

Table 24 provides a summary of the payback period, which represents the time required for the TCO of a BEV to equal or fall below that of an ICEV across different vehicle categories in MYs 2030 and 2032. The table reveals that the maximum period to achieve TCO parity is 3 years, which is consistently observed for both MYs. This finding is highly compelling, indicating the favorable economics of BEV ownership. Projected TCO parity timeline plots across all vehicle categories can be found in Appendix 7.1.

Table 24: Years to reach TCO parity

Vehicle Categories	Payback Period (in years)	
	MY 2030	MY 2032
C8_SC_Long Range	1	2
C8_SC_Standard Range	3	3
C8_DC_Long Range	3	3
C8_DC_Standard Range	2	3
C7_DC_Long Range	3	4
C7_DC_Standard Range	<1	1

Figure 35 illustrates the cumulative net savings of BEVs compared to ICEVs over a 10-year lifespan. These net savings are influenced by the annual VMT. The graph clearly shows that the Class 8 sleeper cab long-range BEV achieves the highest cumulative net savings of up to $153,000, while the Class 7 day cab long-range BEV exhibits the lowest cumulative net savings of up to $32,000.

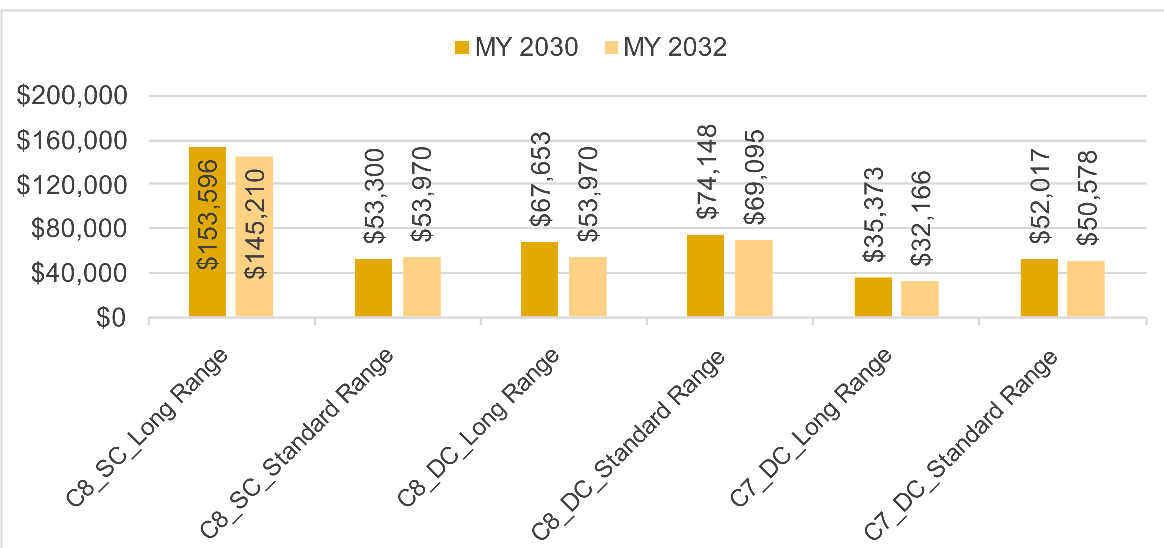


Figure 35: Cumulative Net Savings of BEVs over ICEVs in MYs 2030 and 2032

It is important to note that the VMT plays a significant role in determining the TCO per mile of a truck. The more miles a truck covers, the quicker it can break even, making it an attractive economic proposition for fleet owners. In the category of ICEVs, the engine and transmission technology are mature and well-established, and the only design changes would typically occur in the engine aftertreatment systems to comply with the 2027 NOx limits and warranty requirements.

However, with the emergence of ZEVs, manufacturers are starting with a “clean sheet” design, resulting in a significantly more efficient aerodynamic tractor. Charging costs represent a significant portion of the TCO, and improvements in the energy efficiency of these vehicles through aerodynamic enhancements would positively impact energy costs by increasing operational efficiencies. Consequently, with increased energy efficiency, electric tractor-trailers can travel longer distances compared to ICEVs. Moreover, due to their fewer moving parts, reduced maintenance downtime, and lower maintenance requirements, it is reasonable to assume that BEVs will be utilized more extensively, resulting in far greater annual VMT compared to comparable ICEVs.

For example, if we assume that BEVs travel 20% more than the assumed annual VMT in the primary analysis, the payback period would be as shown in Table 25 (refer to Section 5.1 for details).

Table 25: Comparison of Payback periods with 20% more VMT than assumed in the primary analysis

Vehicle Categories	Payback Period (in years)		VMT	Payback Period (in years)		1.2*VMT (20% more)
	MY 2030	MY 2032		MY 2030	MY 2032	
C8_SC_Long Range	1	2	97,935	1	1	117,521
C8_SC_Standard Range	3	3	46,636	3	3	55,963
C8_DC_Long Range	3	3	47,634	2	2	57,160
C8_DC_Standard Range	2	3	47,634	2	2	57,160
C7_DC_Long Range	3	4	26,576	2	3	31,891
C7_DC_Standard Range	<1	1	26,576	<1	<1	31,891

5. Sensitivity Analysis

The following sections will utilize different sensitivities to examine the potential impacts on total costs of ownership per mile. By exploring these sensitivities, we can gain an understanding of the range of options and circumstances that may arise, and how they can influence the economics of vehicle ownership.

5.1 Effect of Annual VMT

To examine the impact of annual VMT on the payback period, we conducted an analysis considering five different VMT scenarios for each vehicle category. The primary analysis used an annual VMT denoted as 1VMT (shown in the figure below), and we scaled this value by 20% and 40% on either side. Thus, we considered VMT values of 0.6*VMT, 0.8*VMT, 1.2*VMT, and 1.4*VMT.

The scaling factor chosen is an arbitrary scalar intended to demonstrate the influence of total VMT on the economics of vehicle ownership. Figure 36 illustrates the impact of varying VMTs on the payback period, highlighting the relationship between higher annual VMT and shorter payback periods. This relationship demonstrates an almost linear correlation between the annual VMT and payback period, indicating that higher VMT leads to earlier payback periods.

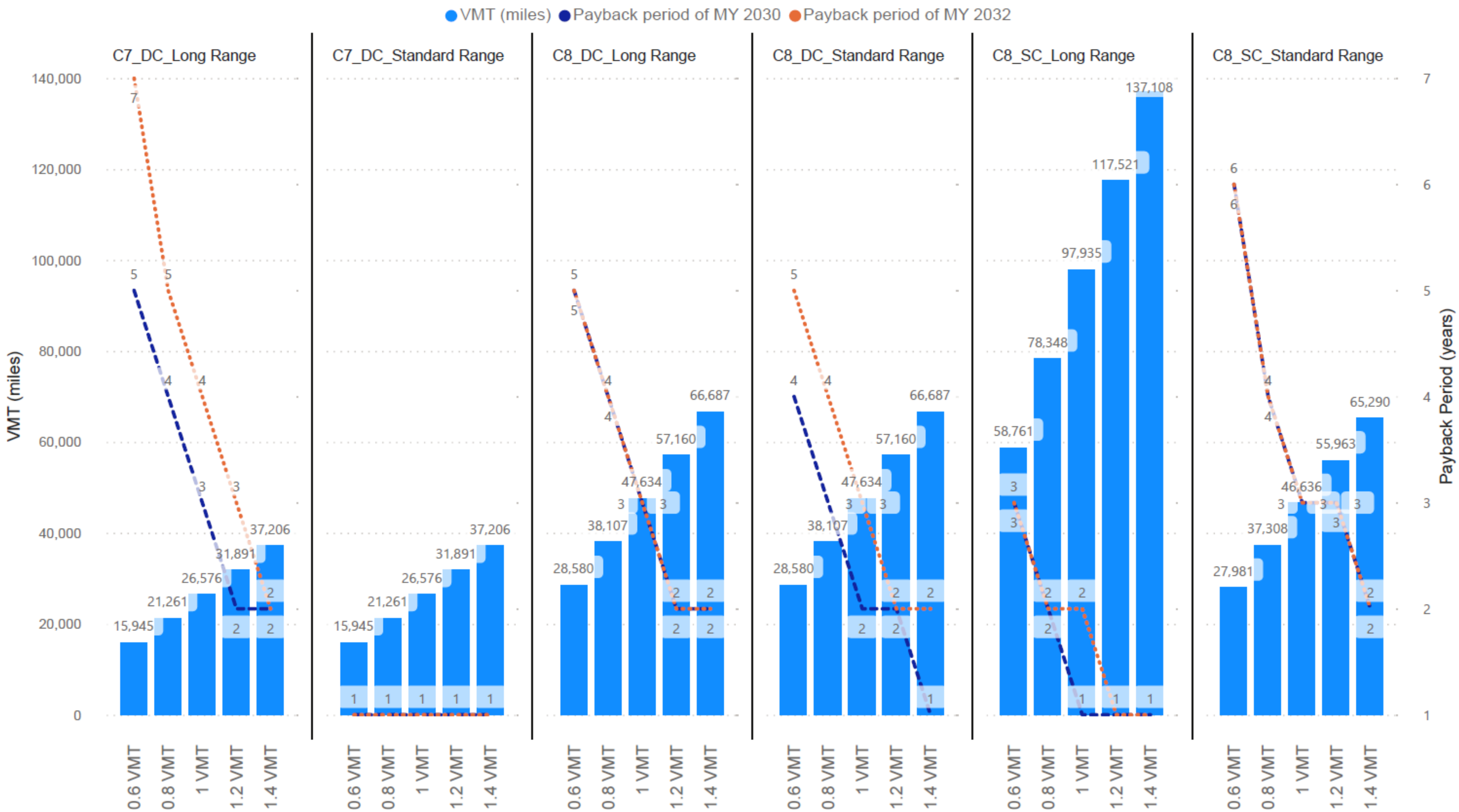


Figure 36: Effect of annual VMT on the payback period (1 VMT represents the VMT used in primary analysis)

5.2 Effect of GVW

GVWR is the maximum weight rating set by the chassis manufacturer, while GVW is the total weight of the truck and payload at a specific point in time. Truck classes are categorized based on their maximum loaded weight, including both the truck itself and its cargo. Heavy-duty trucks provide value to owners and carriers by transporting goods from one place to another. When the weight of a truck increases, the allowable payload decreases, which can result in a potential loss for the owner or carrier. However, in this analysis, we have assumed a change in payload and its effect on the payback period on the Class 8 vehicles only.

Different trucks may reach their capacity limits in terms of weight or volume. The effect of GVW on the diesel fuel economy of the tractor-trailer highlights the potential significance of payload capacity on the economics of ownership. Figure 37 provides the average MPG for each average operating weight class based on the survey conducted by ATRI [55]. It can be seen that as the GVW increases the fuel efficiency decreases.

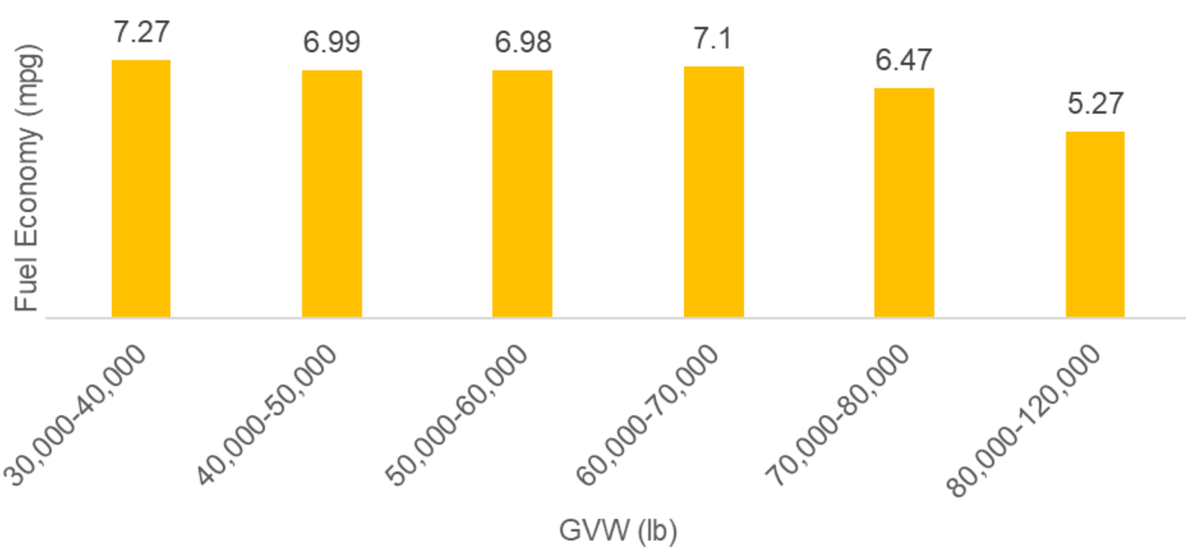


Figure 37: ATRI-Operational-Cost-of-Trucking 2022

Using the EPA's fuel economy data, which served as the basis for the primary analysis, we scaled the fuel economy numbers for the ICEV using NREL's test data [56] for lower and higher GVWs. With the scaled ICEV fuel economy numbers, we then modeled the energy consumption of the BEV using GT-Suite, which is fairly conservative. Table 26 lists the estimated fuel economy and modeled energy consumption of ICEVs and BEVs, respectively.

Table 26: ICEV fuel economy is estimated based on NREL test data [57] and BEV energy consumption is modeled using GT-Suite

Vehicle Categories	ICEV: GVW (lb)-mpg					BEV: GVW (lb)-kWh/mile				
	40,000	50,000	60,000	70,000	80,000	42,000	52,000	62,000	72,000	82,000
C8_SC_Long Range	9.66	9.31	8.87	8.33	7.70	1.51	1.64	1.78	1.92	2.06
C8_SC_Standard Range	9.66	9.31	8.87	8.33	7.70	1.51	1.64	1.78	1.92	2.06
C8_DC_Long Range	8.82	8.47	8.03	7.49	6.86	1.54	1.69	1.84	1.99	2.15
C8_DC_Standard Range	8.82	8.47	8.03	7.49	6.86	1.54	1.69	1.84	1.99	2.15

Figure 38 illustrates the impact of GVW on the payback period of Class 8 trucks. The overall change in the breakeven period remains relatively consistent from a lightly loaded to a heavily-loaded tractor-trailer. Both ICEVs and BEVs exhibit higher fuel efficiency at lighter loads.

It is worth noting that as the payload increases, the TCO per mile of a BEV improves in comparison to an ICEV, leading to greater cumulative net savings.

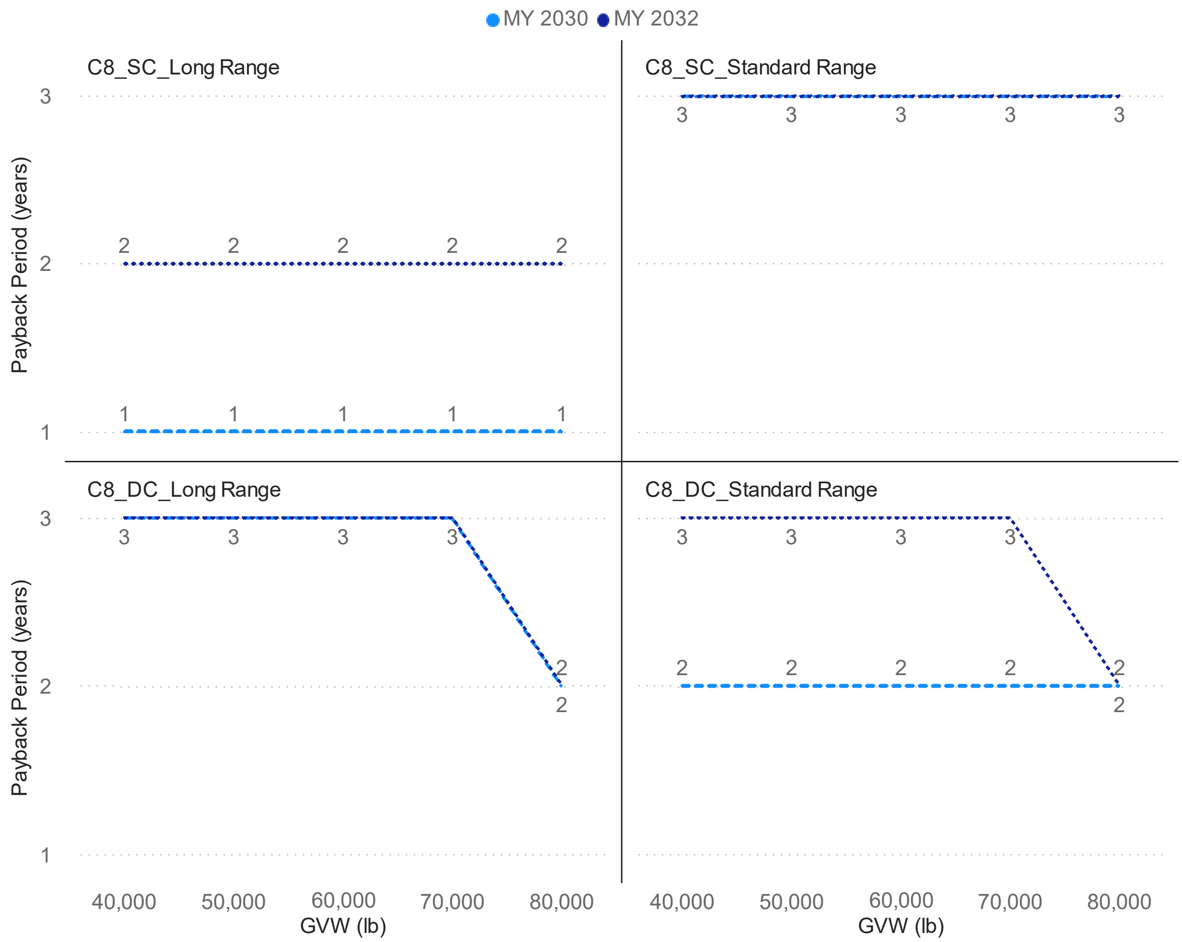


Figure 38: Effect of GVW on the payback period

5.3 Mixed charging scenario

In our analysis, we have defined a mixed charging scenario for trucks, which involves a combination of depot charging and en route charging. Specifically, we consider a usage mix of 70% depot charging and 30% en route charging. Depot charging takes place at a depot or warehouse, utilizing a 350 kW DCFC (Direct Current Fast Charger), while en route charging occurs along an express corridor or at a facility equipped with a 3 MW charging station.

A megawatt charging system (MCS), a very fast charging system for trucks, is still under development and testing but is expected to become available in the next few years. Based on the combined charging system (CCS), which is used for LDVs, MCS would be the worldwide standard for HD trucks. Some companies have already demonstrated or announced plans for using this technology. CharIN has launched a new DC fast-charging connector for HDVs that can deliver up to 3.75 MW of power [58].

The rationale behind selecting 30% of charging events for en route charging assumes that trucks would be charging every other day at a megawatt charging station. On 50% of the days, they would require a charging stop to meet their daily VMT and top up their charge from 20% to 80%. These stops would be quick, take less than 15 minutes (short dwell periods), and would not be an extended layover.

In this scenario, we have considered only the combined hardware and installation costs for the 350 kW charger and applied the charger credits of 30% available under the IRA of 2022, which amounts to $37,877. As for the 3 MW charging station, since it will be located en route, we have focused solely on the charging rate. For the charging rates at a 3 MW station, we have adopted a rate of $0.23/kWh based on NREL's scenario under Rate 2 of EHL-MW (En Route High Utilization Rate and Low Install Cost) [31].

Figure 39 illustrates the TCO per mile comparison between an ICEV and a comparable BEV in a mixed charging scenario. The figure demonstrates that, despite a lower utilization of depot charging and higher charging costs associated with en route charging at a megawatt charging station, the TCO per mile for a BEV remains lower and still compelling for all vehicle categories.

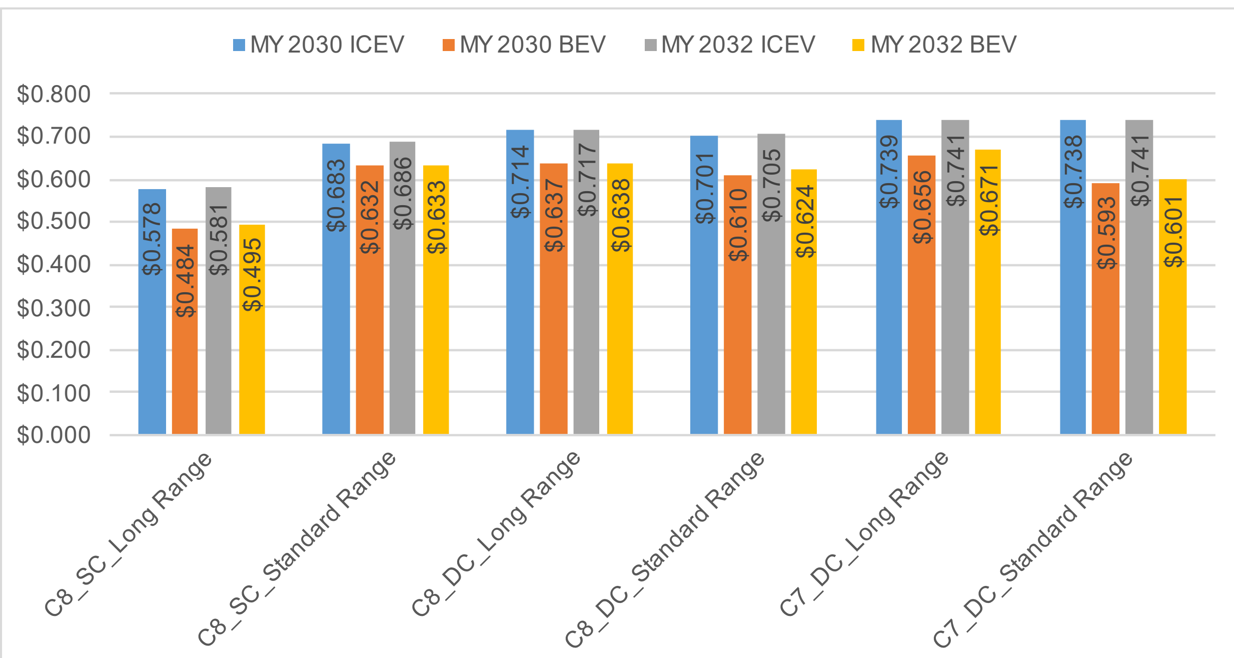


Figure 39: Comparison of the total cost of ownership (TCO) in $/mile in a mixed charging scenario (70% Depot, 30% en route) across MYs 2030 and 2032

Compared to the primary analysis, the payback period for all vehicle categories has increased, with the maximum period extending to 5 years, whereas in the primary analysis, it was observed to be 4 years. However, the payback period for the Class 7 day cab standard range category remains unchanged, consistent with the findings of the primary analysis, as depicted in Table 27.

Table 27: Payback period in a mixed charging scenario

Vehicle Categories	Payback Period (in years)	
	MY 2030	MY 2032
C8_SC_Long Range	2	3
C8_SC_Standard Range	5	5
C8_DC_Long Range	4	4
C8_DC_Standard Range	3	4
C7_DC_Long Range	4	5
C7_DC_Standard Range	1	1

Figure 40 depicts the cumulative net savings, which show a decrease compared to the depot charging scenario analyzed in the primary analysis. Nevertheless, these net savings still amount to significant amounts, totaling several thousands of dollars, with an average value of approximately $40,000.

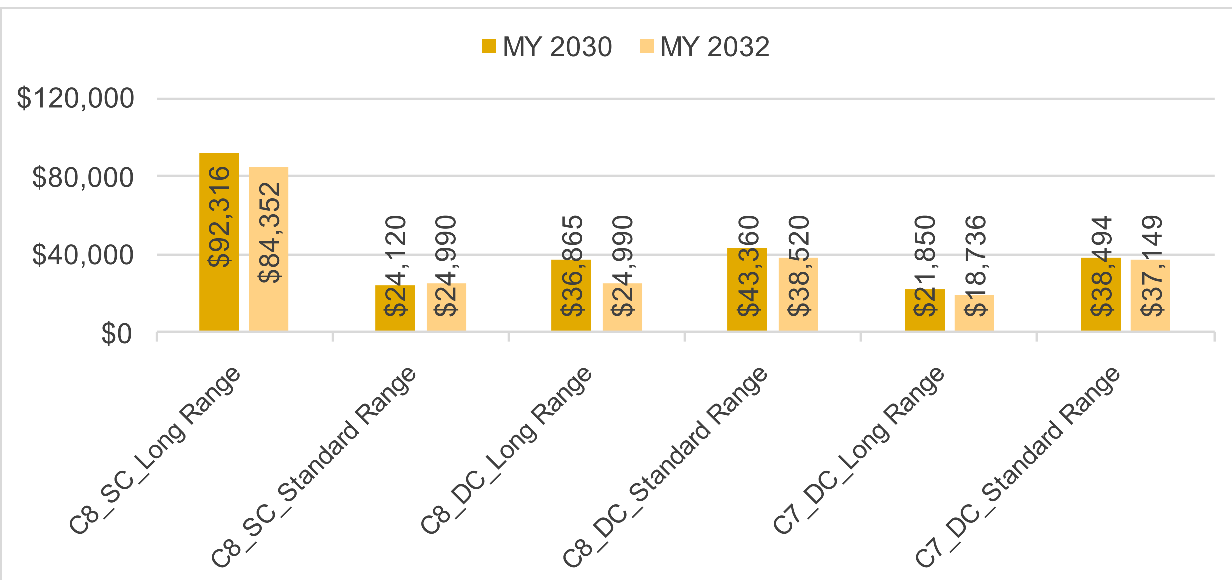


Figure 40: Cumulative Net Savings of BEVs over ICEVs in a mixed charging scenario

Figure 41 illustrates the payback period for Class 7/8 battery-electric trucks in different charging scenarios, involving a combination of depot charging and en route charging. The figure demonstrates that, in most cases, 100% en route charging yields greater benefits, except for the Class 8 sleeper cabs with standard and long ranges. Additionally, attractive payback periods can be achieved by employing a range of charging scenarios, ranging from 100% depot charging to a combination of 50:50 depot charging and en route charging. However, it is worth noting that when the usage of en route charging surpasses 70%, the Class 8 sleeper cabs, regardless of the range, do not achieve breakeven within a 10-year ownership period. This trend is observed across other vehicles in hybrid charging scenarios that involve a higher utilization of en route charging. The reason behind this outcome is the rise in energy costs, which subsequently increases the TCO per mile for the BEVs.

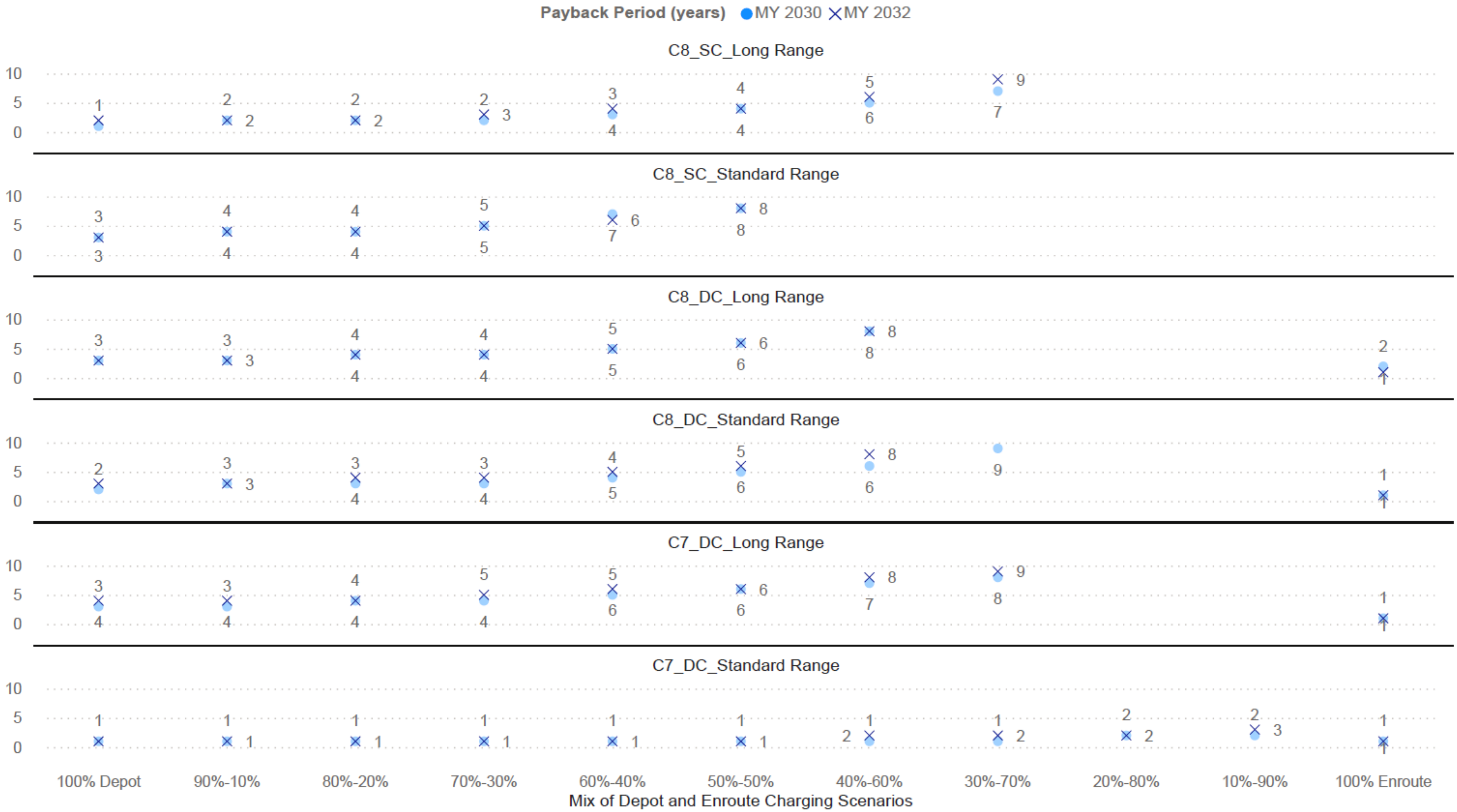


Figure 41: Payback period of Class 7/8 trucks in a varying mix of the depot and en route charging scenarios. In scenarios with "End of life" cases, the respective markers are not shown.

The payback period for all vehicles was calculated based on en route megawatt charging station (MCS) rates ranging from $0.18/kWh to $0.42/kWh, maintaining the same 70:30 ratio of depot-to-en route charging. The lower rate was determined according to the NREL study [35], while the higher rate represents the threshold at which most cases no longer achieve breakeven. Figure 42 demonstrates that when energy rates exceed $0.41/kWh, the majority of vehicles from both model years fail to reach breakeven within a 10-year timeframe. This highlights the significant role that charging rates play in determining the economic viability of en route megawatt charging. Specifically, if the rates surpass $0.40/kWh (assuming a 70:30 depot-to-en route charging ratio in this case), the TCO per mile for BEVs becomes more expensive compared to ICEVs.

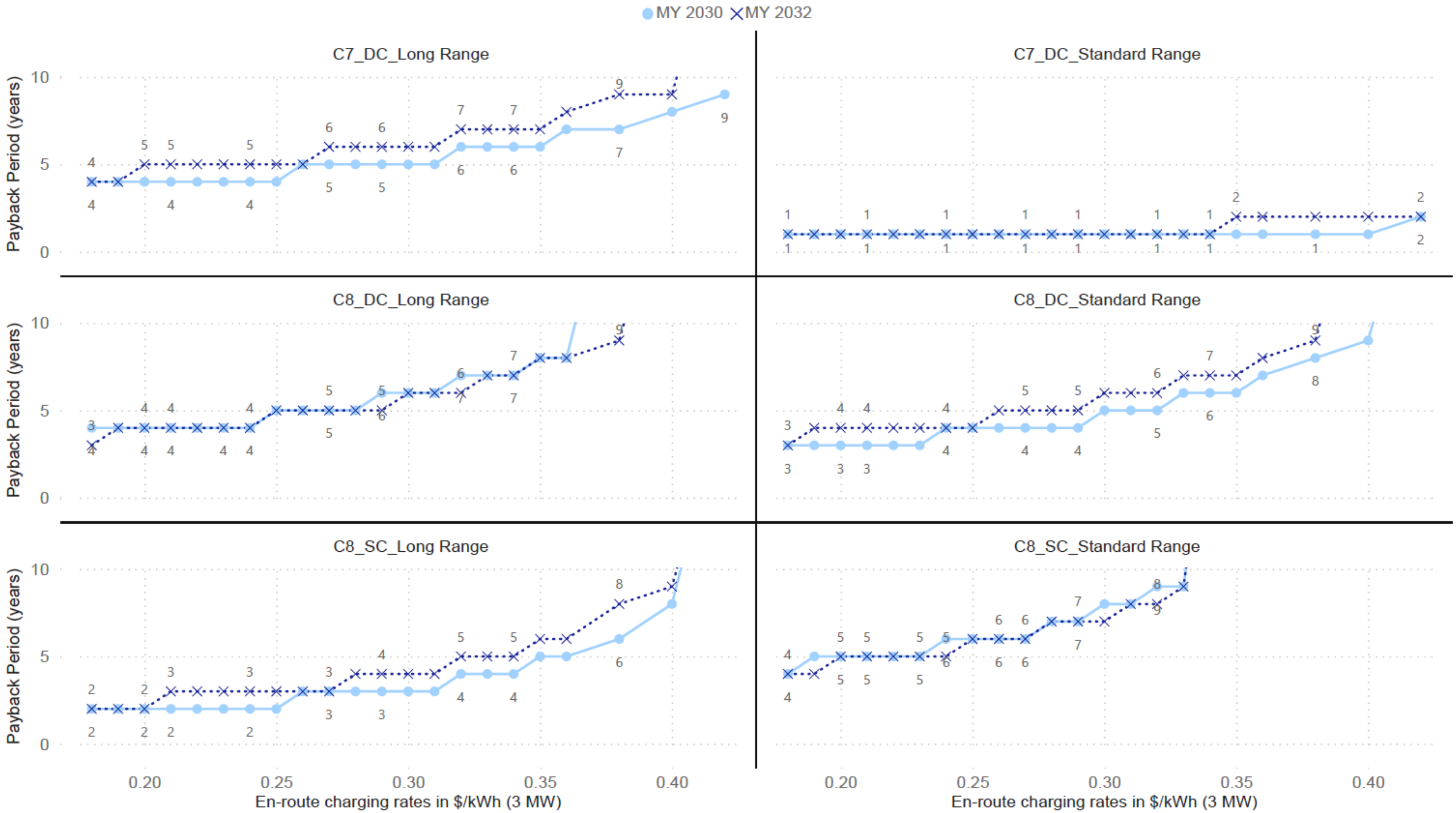


Figure 42: Payback period of Class 7/8 trucks in a mixed charging scenario with varying charging rates in $/kWh. In scenarios with "End of life" cases, the respective markers are not shown.

5.4 Fuel Price Sensitivity

Forecasting oil prices accurately and determining if the EIA projected prices per the AEO 2023 are reliable indicators of future energy costs for ICEVs can be challenging. To explore potential scenarios, we have conducted a sensitivity analysis using the highest recorded diesel retail prices as input for ICEVs. In June 2022, refer to Figure 43, diesel prices reached a record high of $5.754 per EIA data (refer to Appendix 11.1). For this study, we have used a sensitivity input of $5.18 as the diesel price without taxes to assess its impact on the TCO per mile, payback period, and cumulative net savings. Figure 24 provides a visual representation of the results.

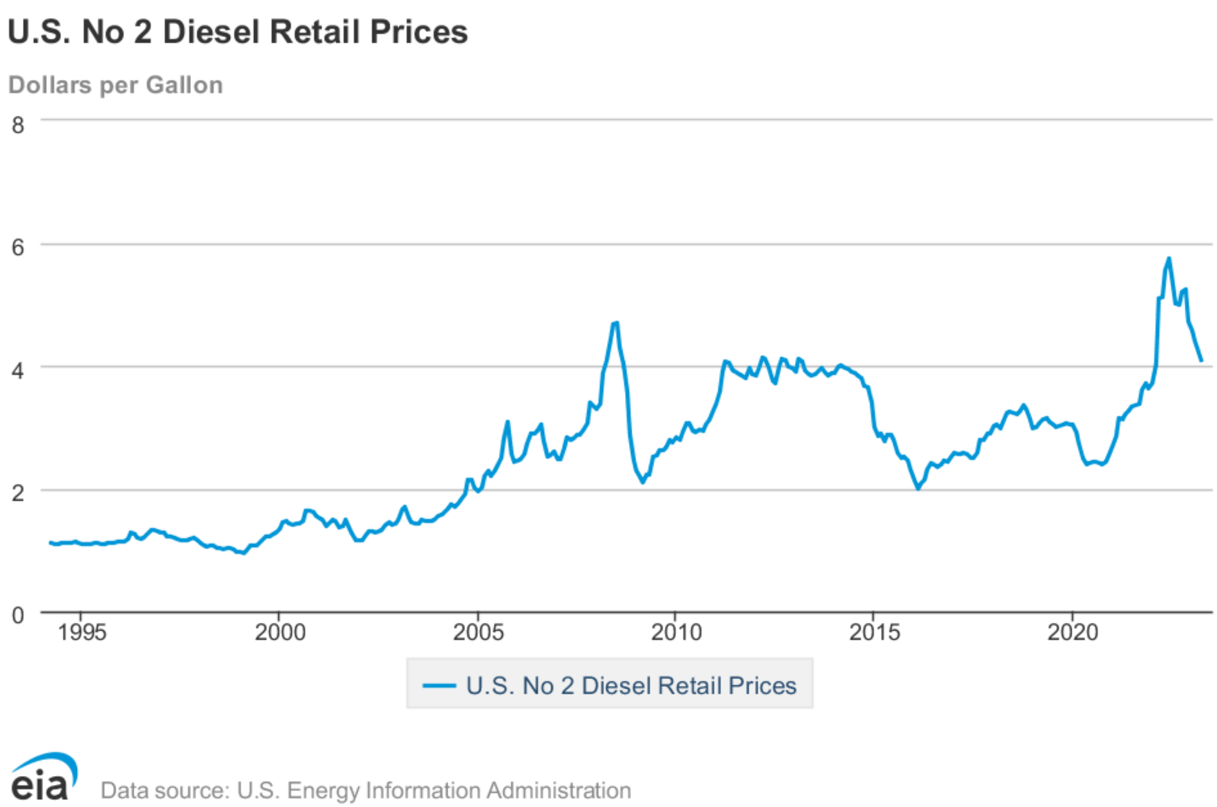


Figure 43: Historical U.S. Diesel Retail Price

The TCO per mile of an ICEV is much higher than comparable BEVs due to the high diesel price (Figure 44). With the uncertain oil prices and diesel vehicle prices due to meeting the regulatory requirements, the TCO of a BEV is much cheaper across all the classes despite the seemingly high upfront 350 kW charger-related costs.

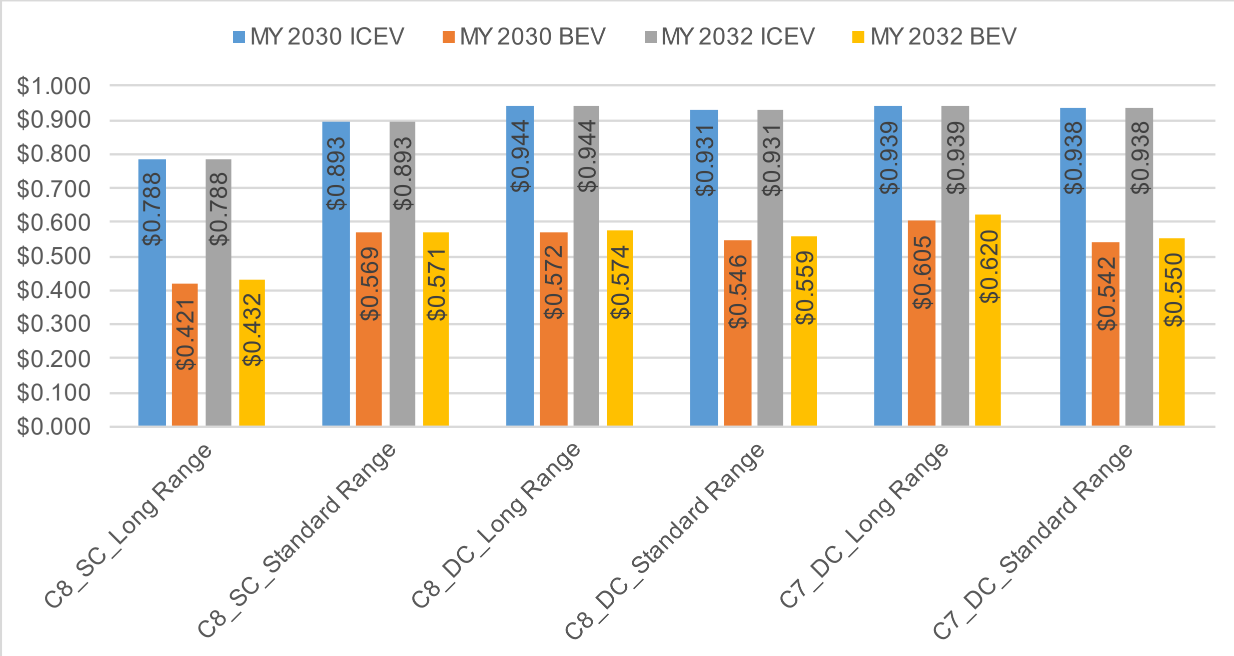


Figure 44: Comparison of the total cost of ownership (TCO) in $/mile in a high diesel price scenario across MYs 2030 and 2032

Table 28 lists the payback period under a high diesel price scenario. It can be observed that the payback period accelerates by 2 years compared to the primary analysis advancing the time to reach parity to 1 or less than 1 year. It provides a compelling glimpse of the sensitivity to real-world oil prices on the cost of ownership of an ICEV in comparison to a comparable BEV.

Table 28: Payback period in a high diesel price scenario

Vehicle Categories	Payback Period (in years)	
	MY 2030	MY 2032
C8_SC_Long Range	<1	1
C8_SC_Standard Range	1	1
C8_DC_Long Range	1	1
C8_DC_Standard Range	1	1
C7_DC_Long Range	1	2
C7_DC_Standard Range	<1	<1

Figure 45 depicts the cumulative net savings in a high diesel price scenario. BEVs offer significant savings of several thousand dollars across all categories with an average savings of about $70,000. This demonstrates that cumulative savings are a major factor that should be considered by fleet owners with a perspective.

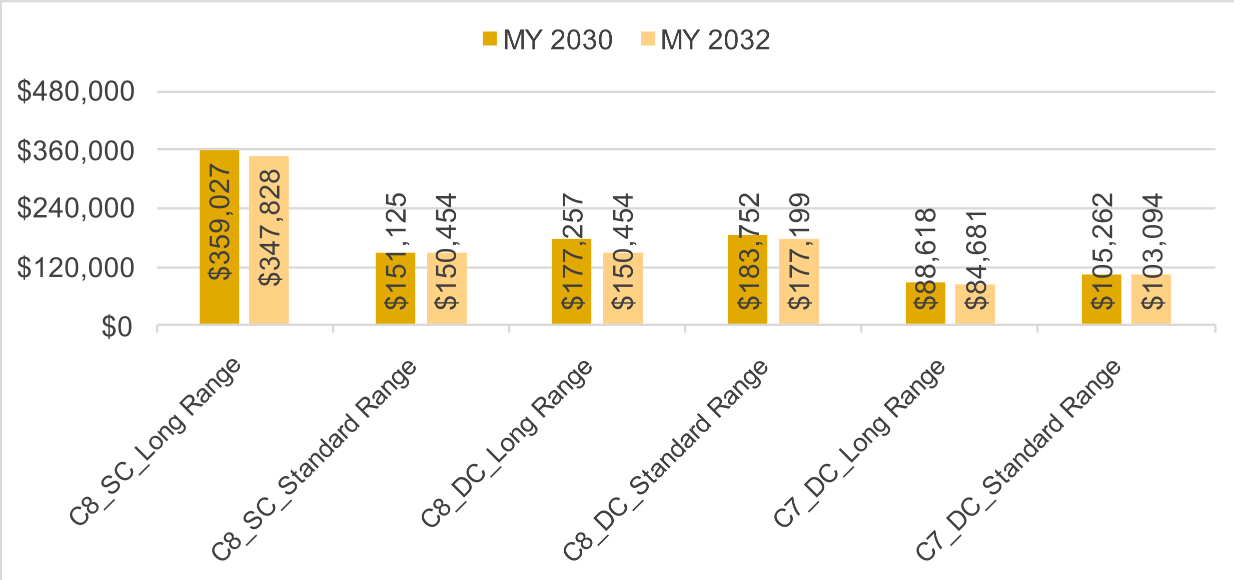


Figure 45: Cumulative Net Savings of BEVs over ICEVs in a high diesel price scenario

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7. Appendix

7.1 Total Cost of Ownership Parity with Depot Charging Scenario (350 kW DCFC)

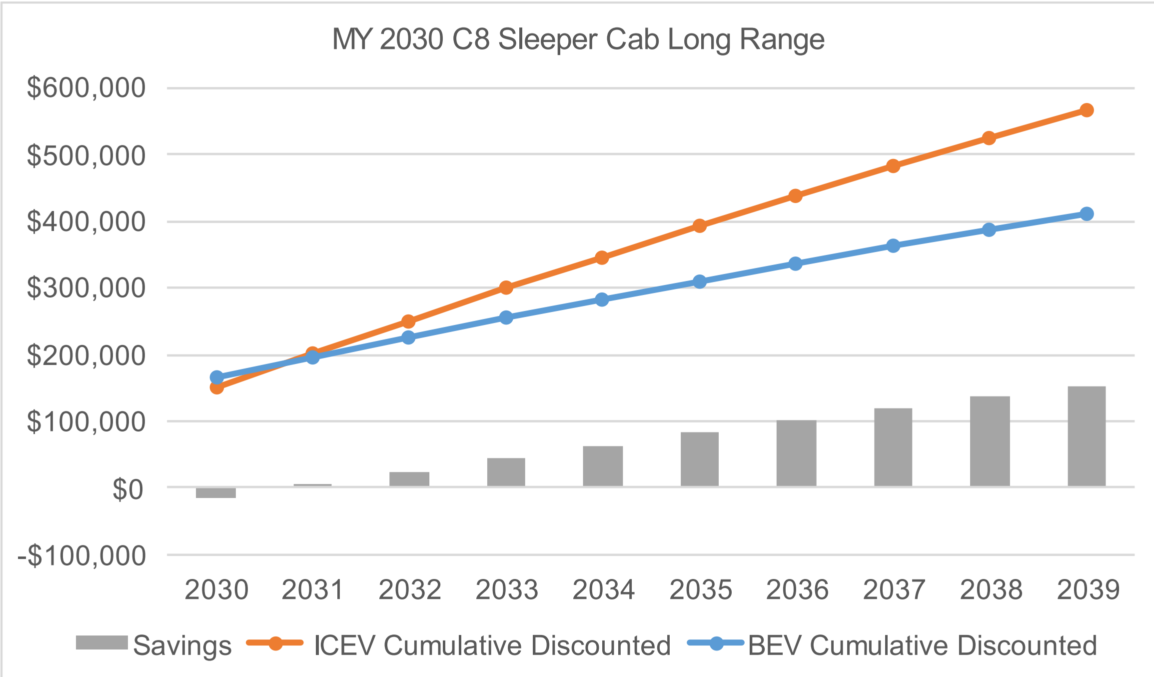

Figure 46: TCO parity of an MY 2030 Class 8 sleeper cab long range with depot charging.

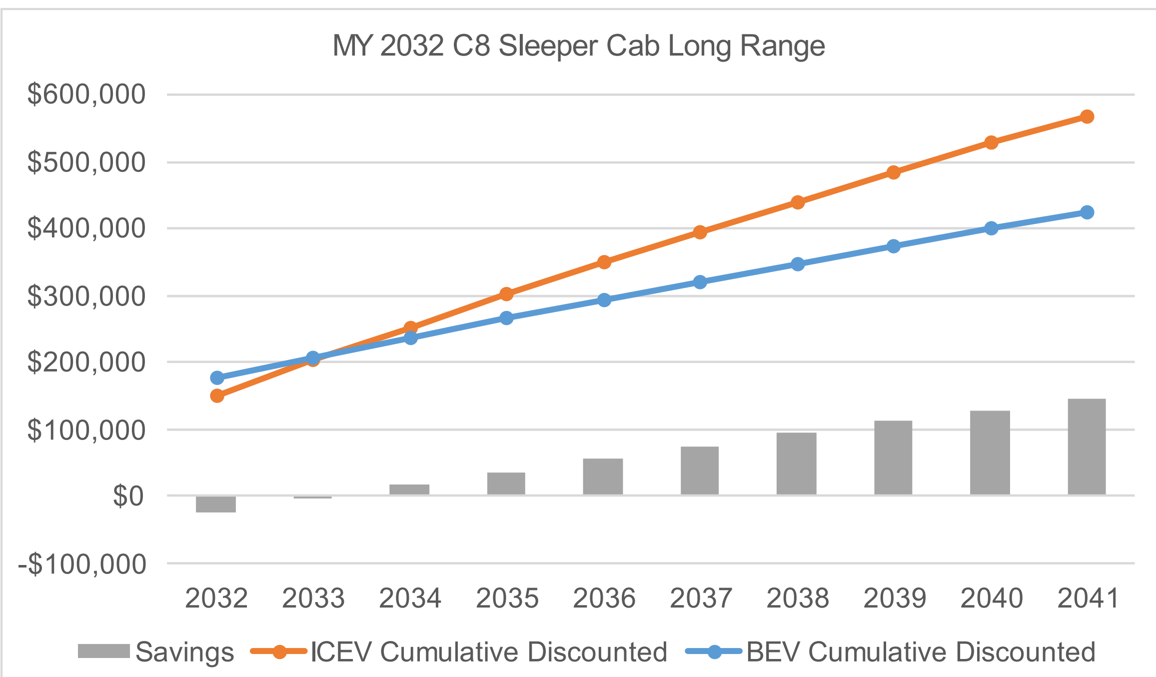

Figure 47: TCO parity of an MY 2032 Class 8 sleeper cab long range with depot charging.

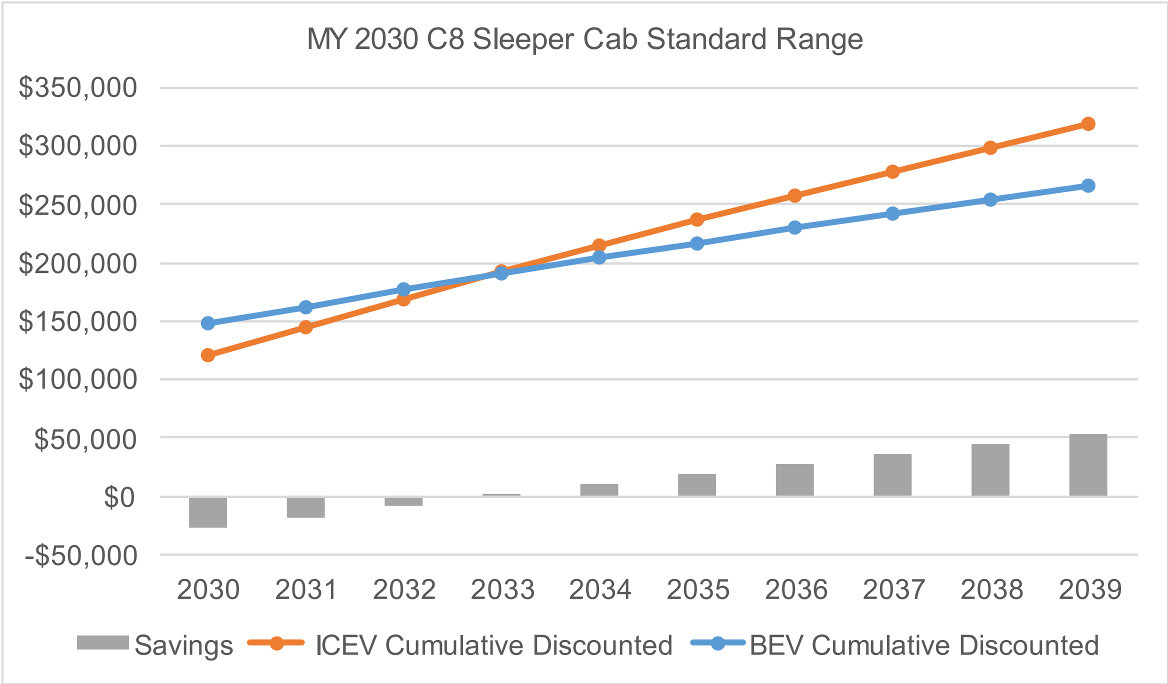

Figure 48: TCO parity of an MY 2030 Class 8 sleeper cab standard range with depot charging.

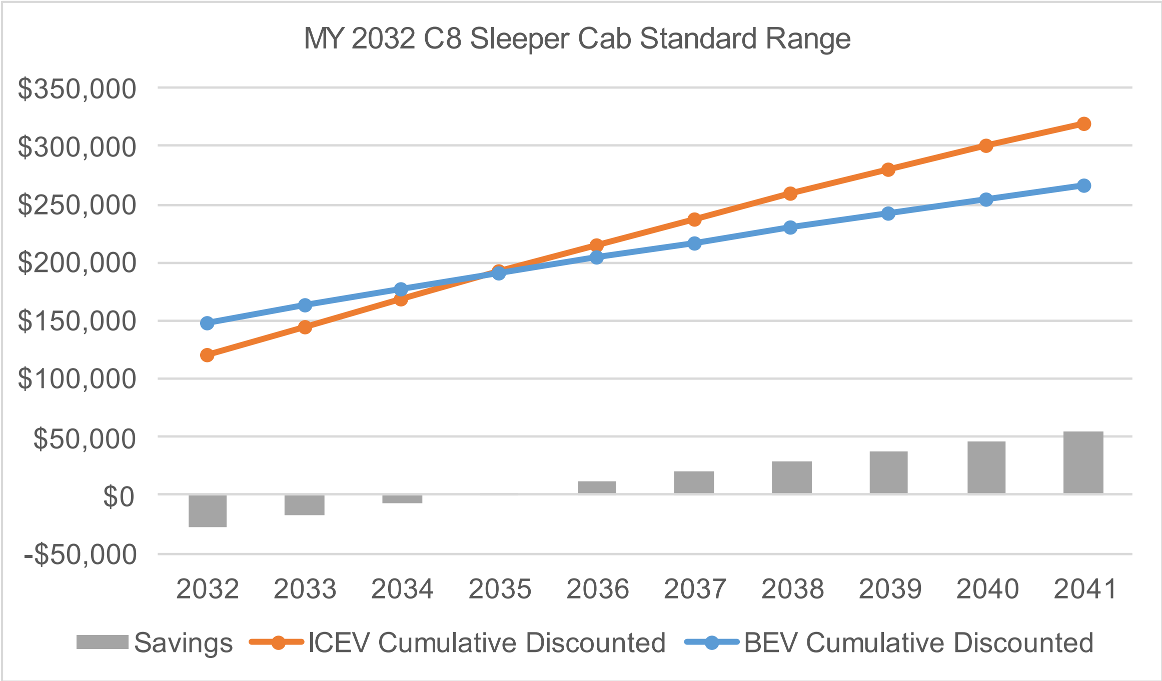

Figure 49: TCO parity of an MY 2032 Class 8 sleeper cab standard range with depot charging.

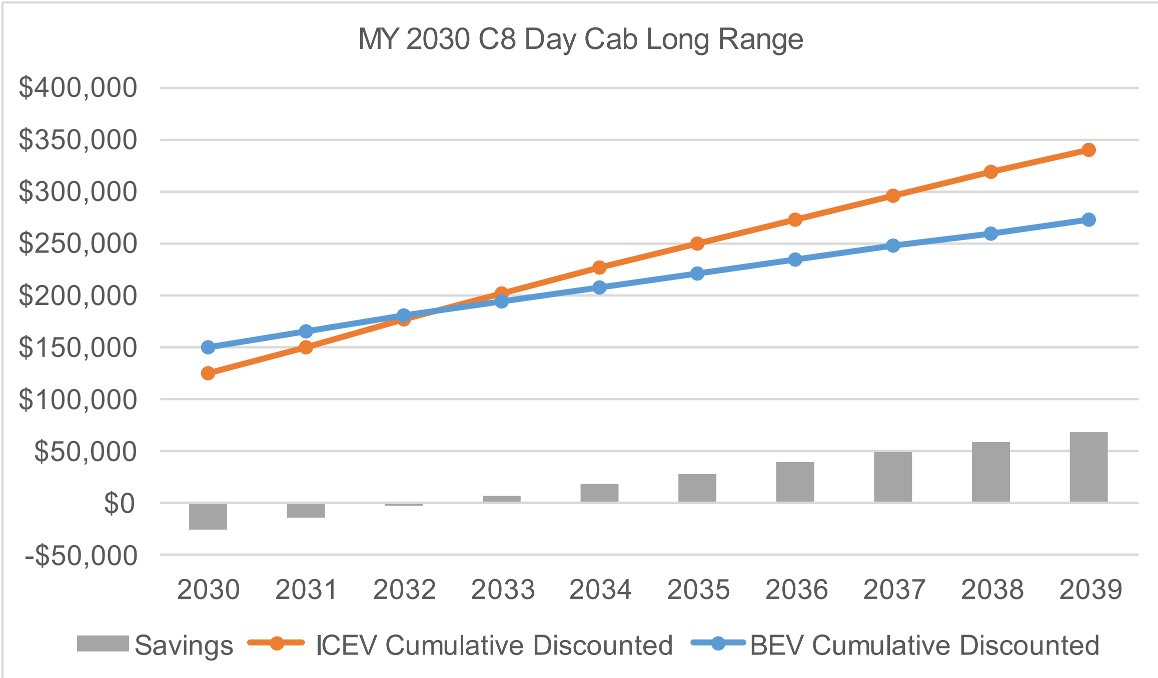

Figure 50: TCO parity of an MY 2030 Class 8 day cab long range with depot charging.

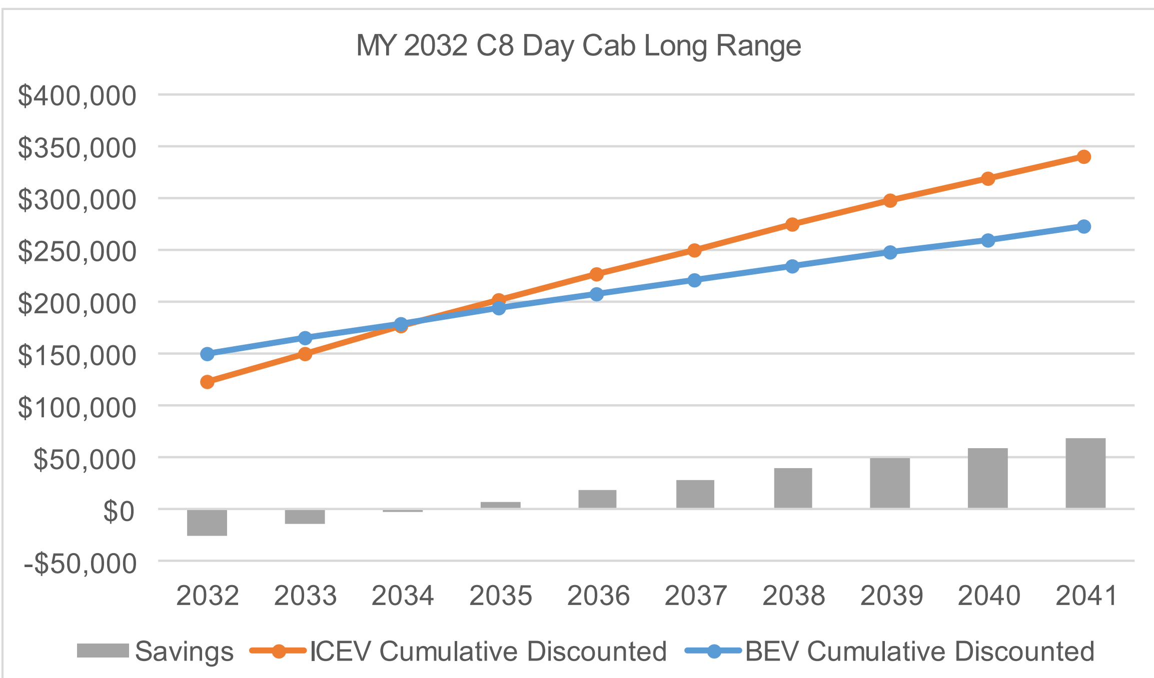

Figure 51: TCO parity of an MY 2032 Class 8 day cab long range with depot charging.

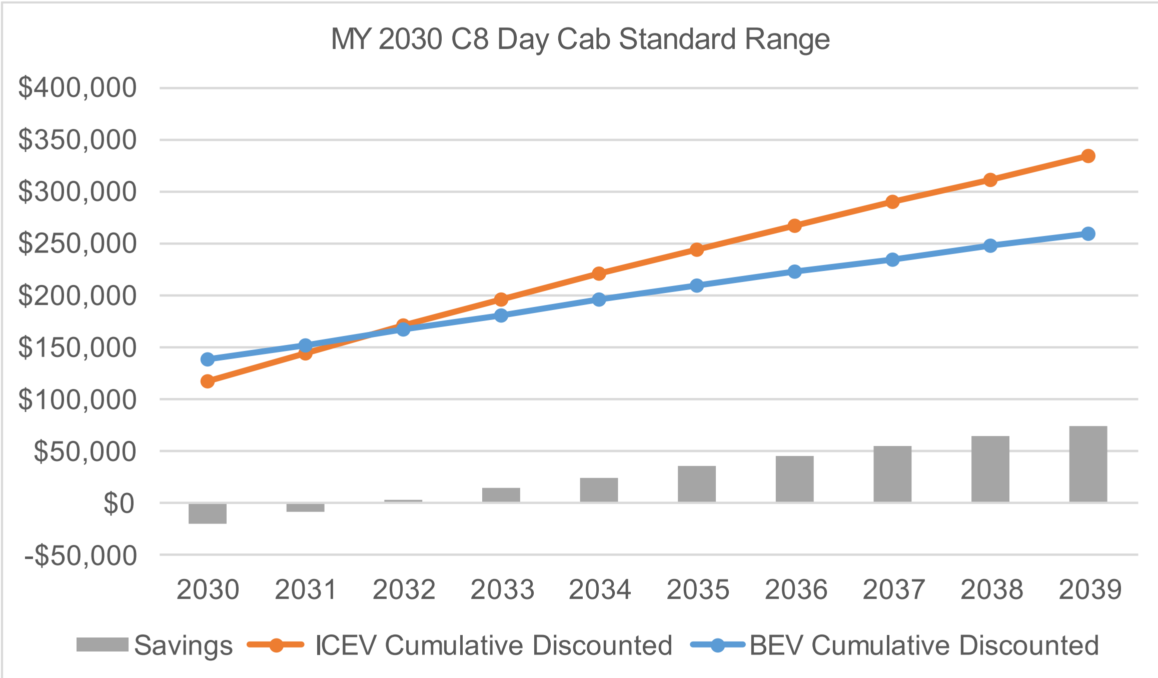

Figure 52: TCO parity of an MY 2030 Class 8 day cab standard range with depot charging.

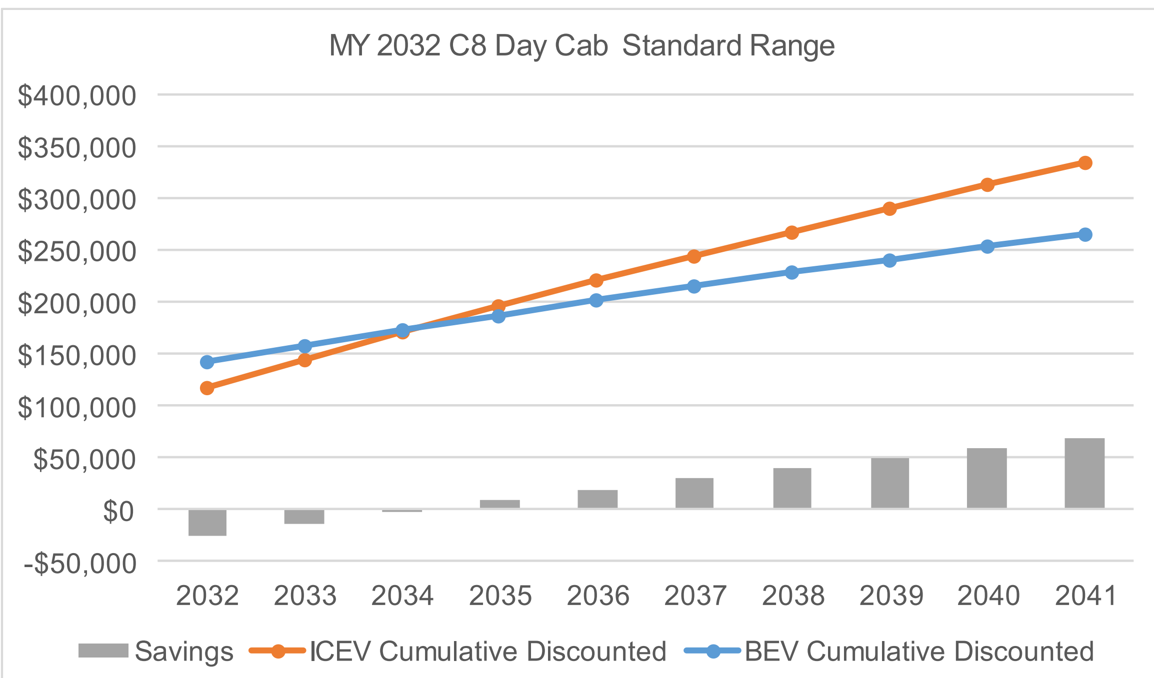

Figure 53: TCO parity of an MY 2032 Class 8 day cab standard range with depot charging.

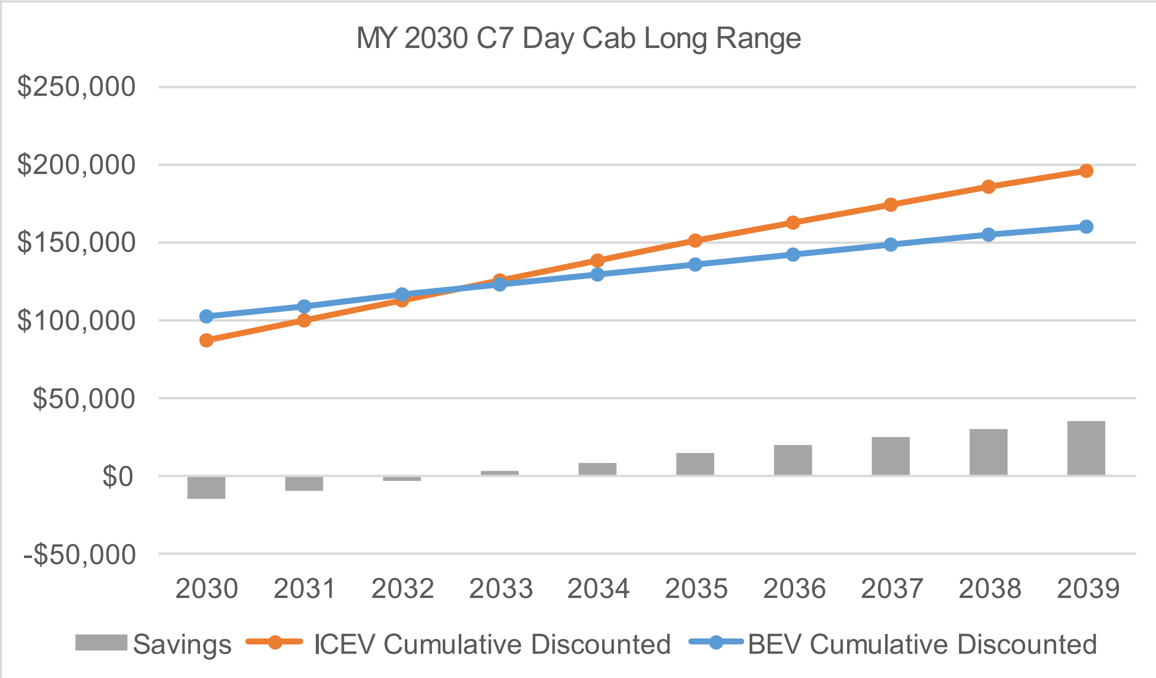

Figure 54: TCO parity of an MY 2030 Class 7 day cab long range with depot charging.

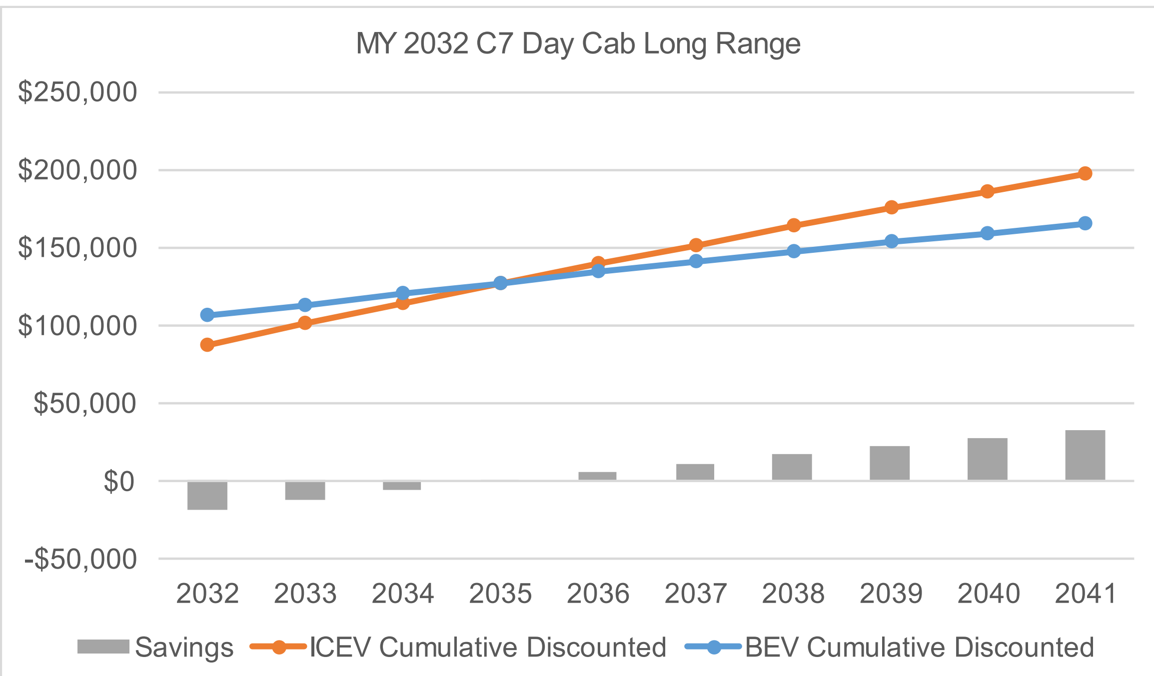

Figure 55: TCO parity of an MY 2032 Class 7 day cab long range with depot charging.

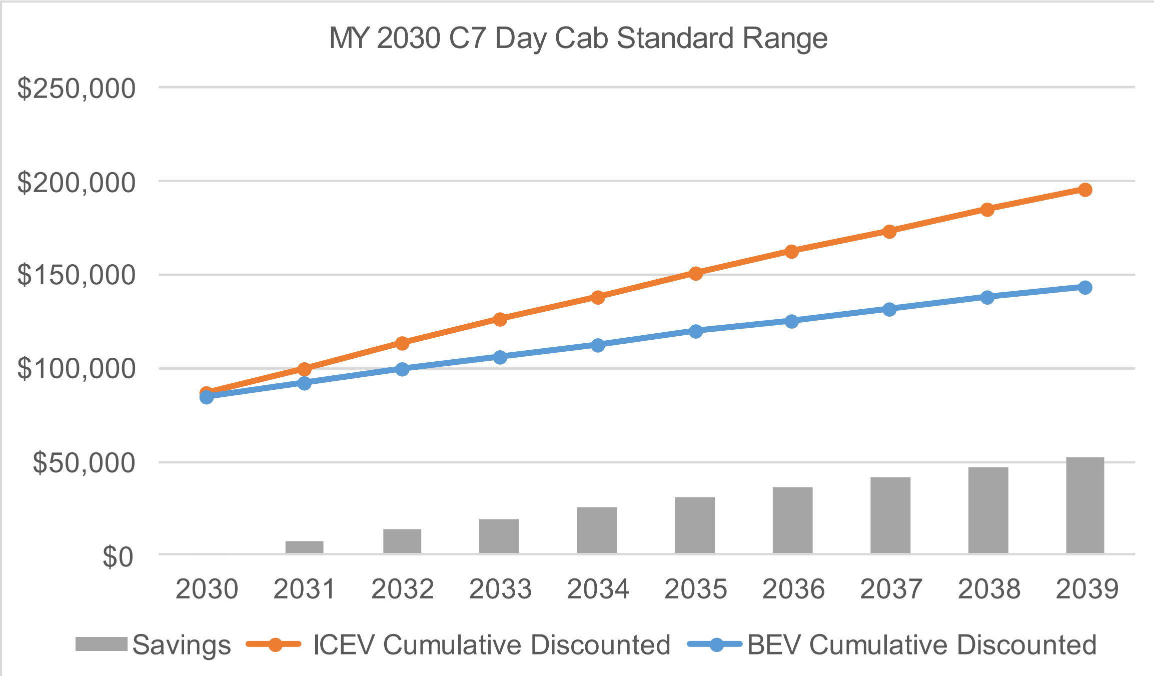

Figure 56: TCO parity of an MY 2030 Class 7 day cab standard range with depot charging.

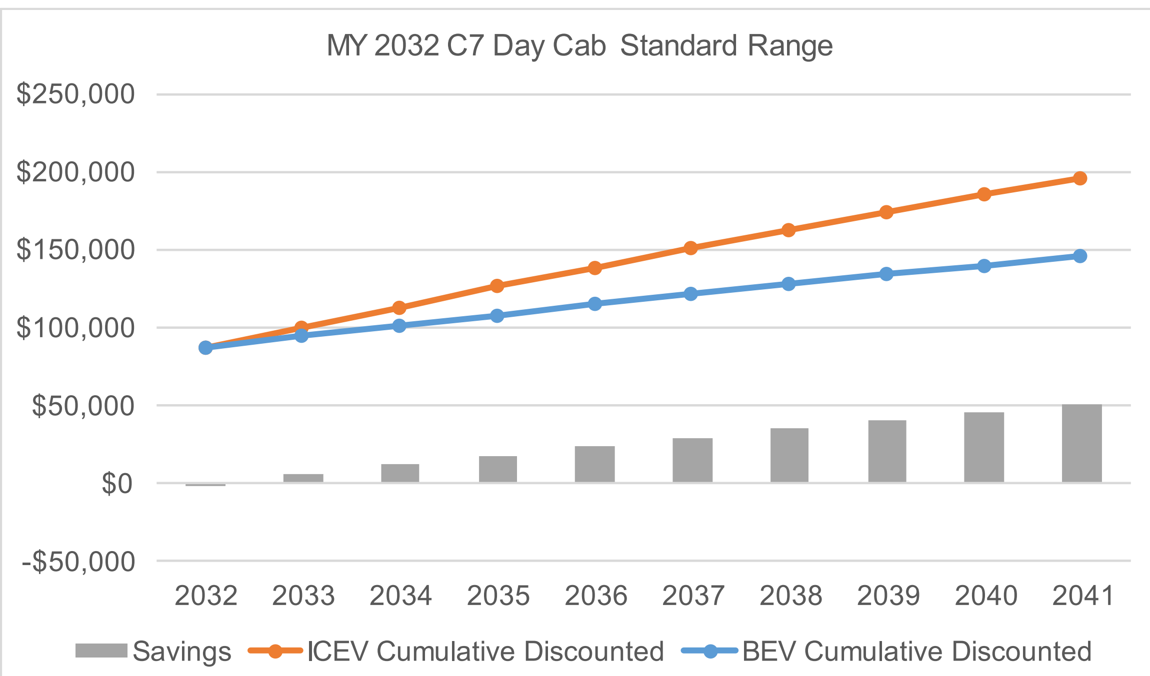

Figure 57: TCO parity of an MY 2032 Class 7 day cab standard range with depot charging.

7.2 Total Cost of Ownership Parity with Mixed Charging Scenario

7.2.1 Parity Timelines

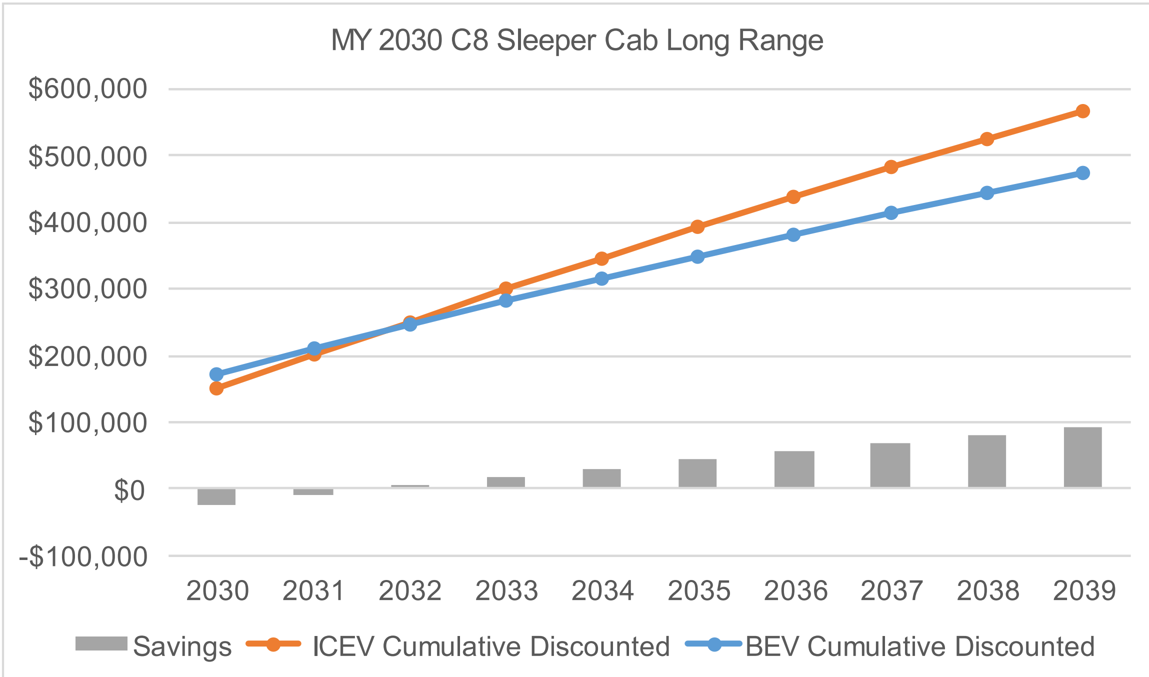

Figure 58: TCO parity of an MY 2030 Class 8 sleeper cab long range with mixed charging scenario.

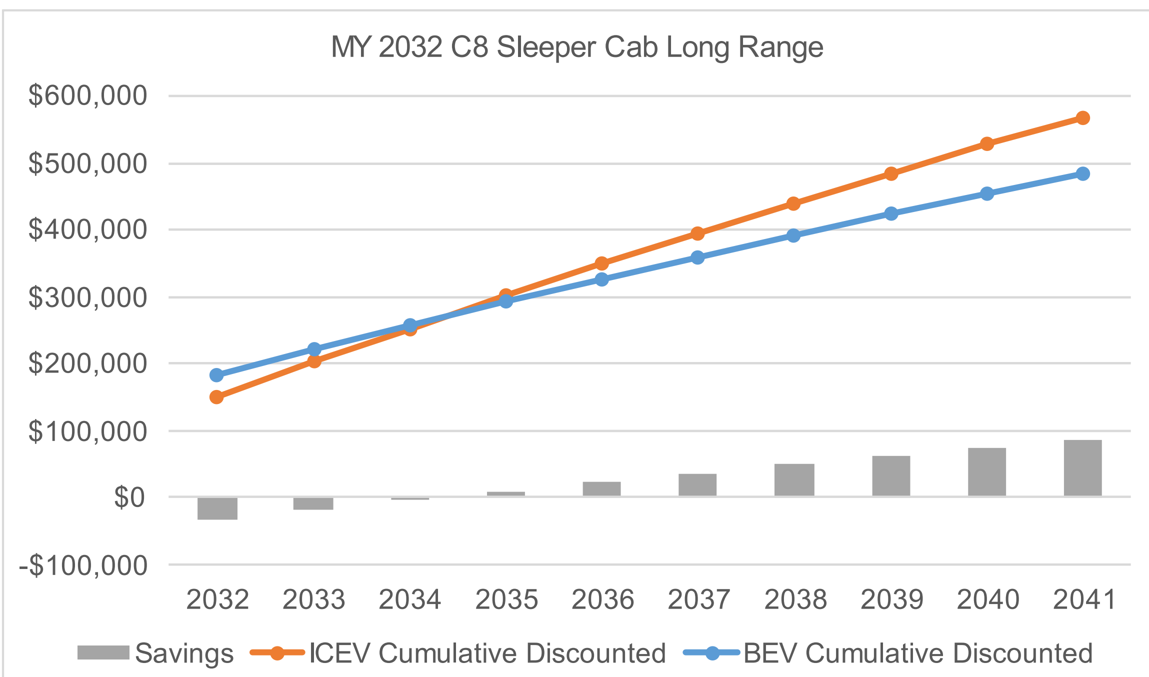

Figure 59: TCO parity of an MY 2032 Class 8 sleeper cab long range with mixed charging scenario.

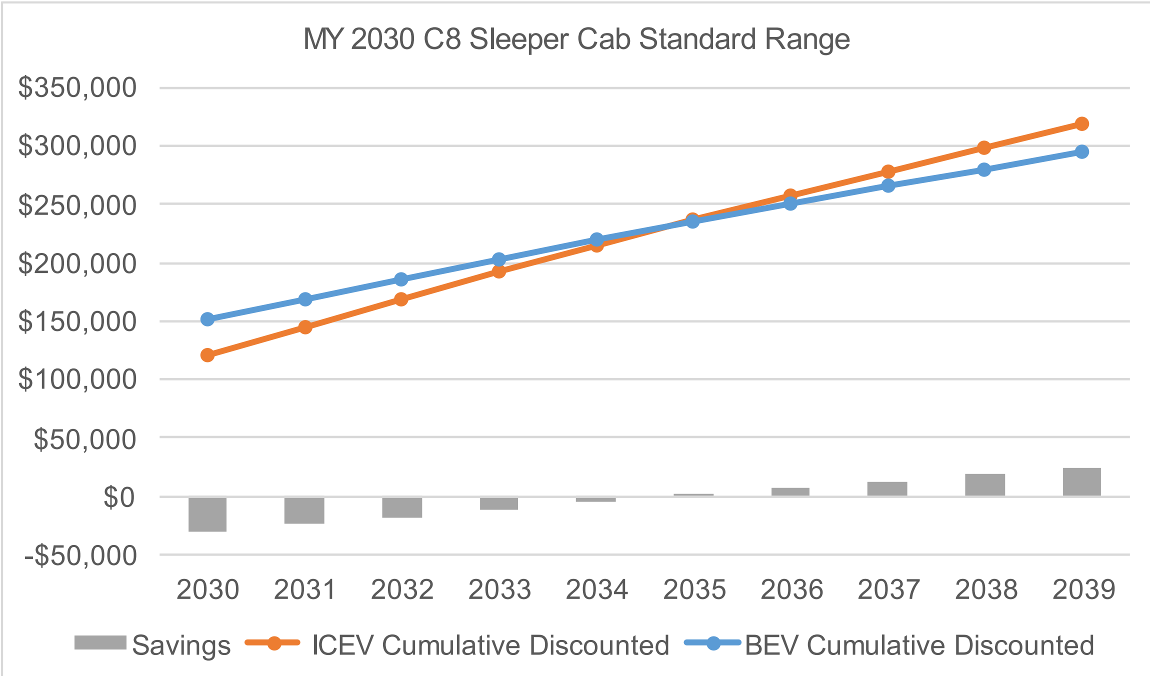

Figure 60: TCO parity of an MY 2030 Class 8 sleeper cab standard range with mixed charging scenario.

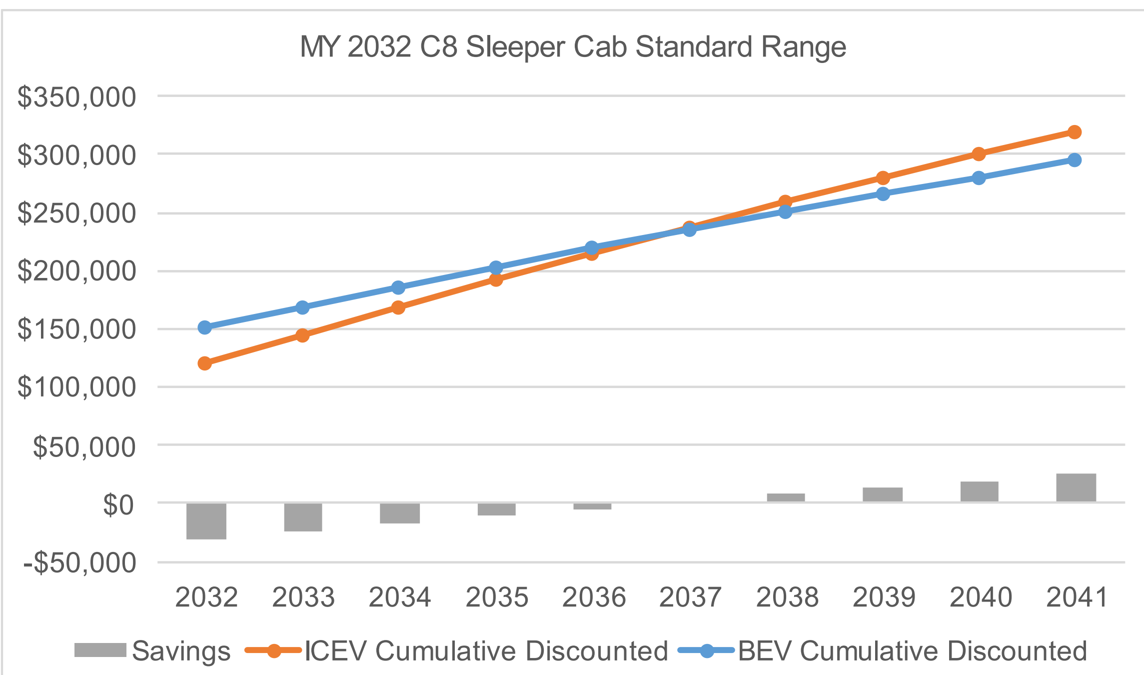

Figure 61: TCO parity of an MY 2032 Class 8 sleeper cab standard range with mixed charging scenario.

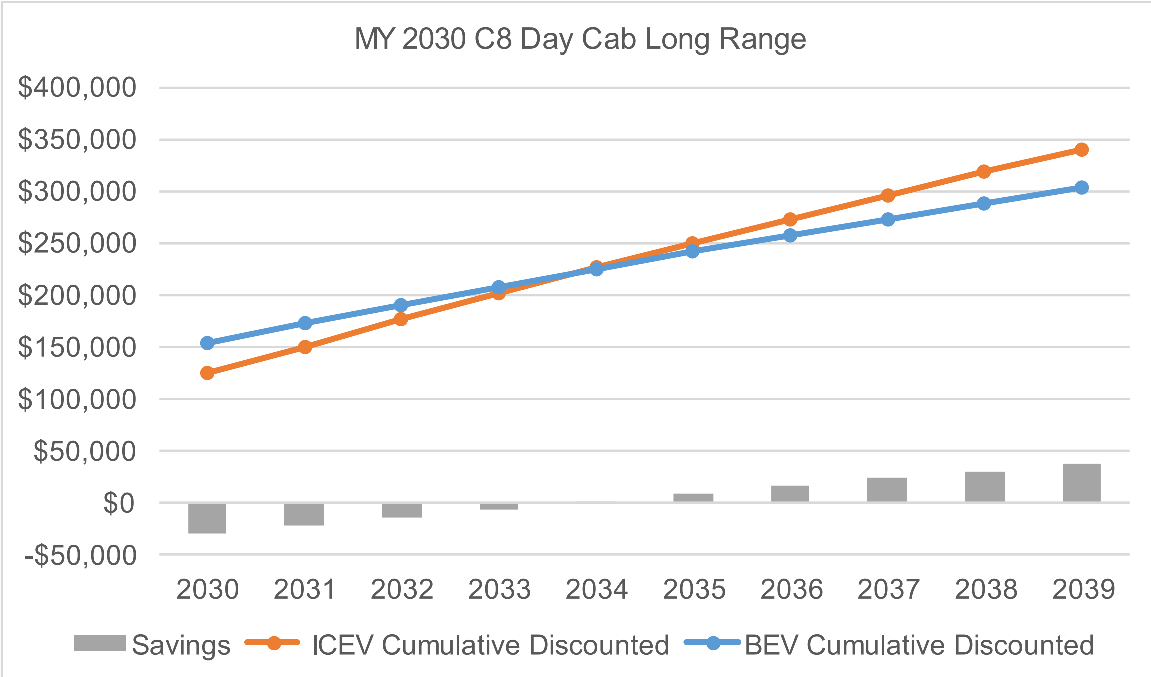

Figure 62: TCO parity of an MY 2030 Class 8 day cab long range with mixed charging scenario.

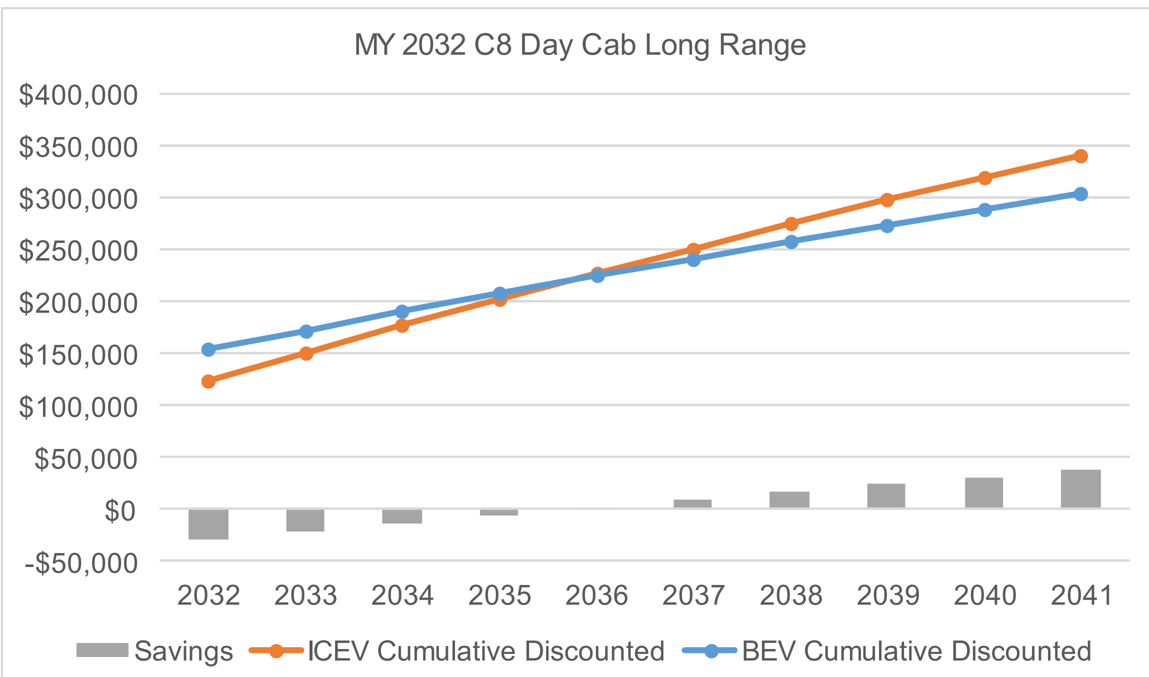

Figure 63: TCO parity of an MY 2032 Class 8 day cab long range with mixed charging scenario.

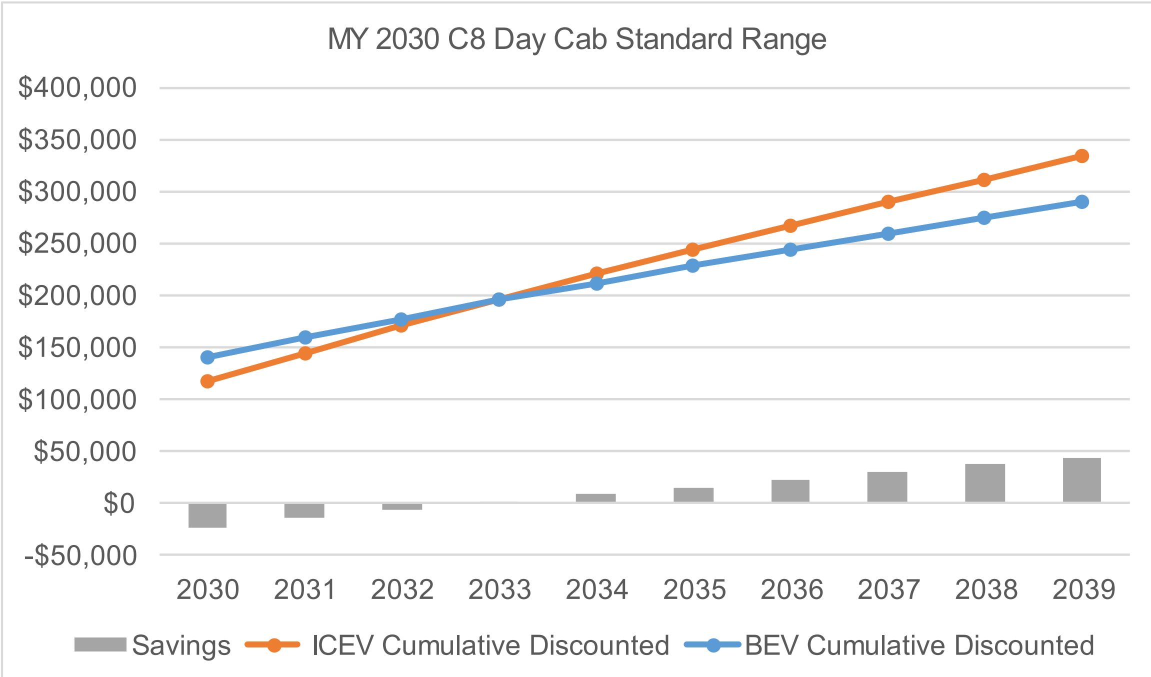

Figure 64: TCO parity of an MY 2030 Class 8 day cab standard range with mixed charging scenario.

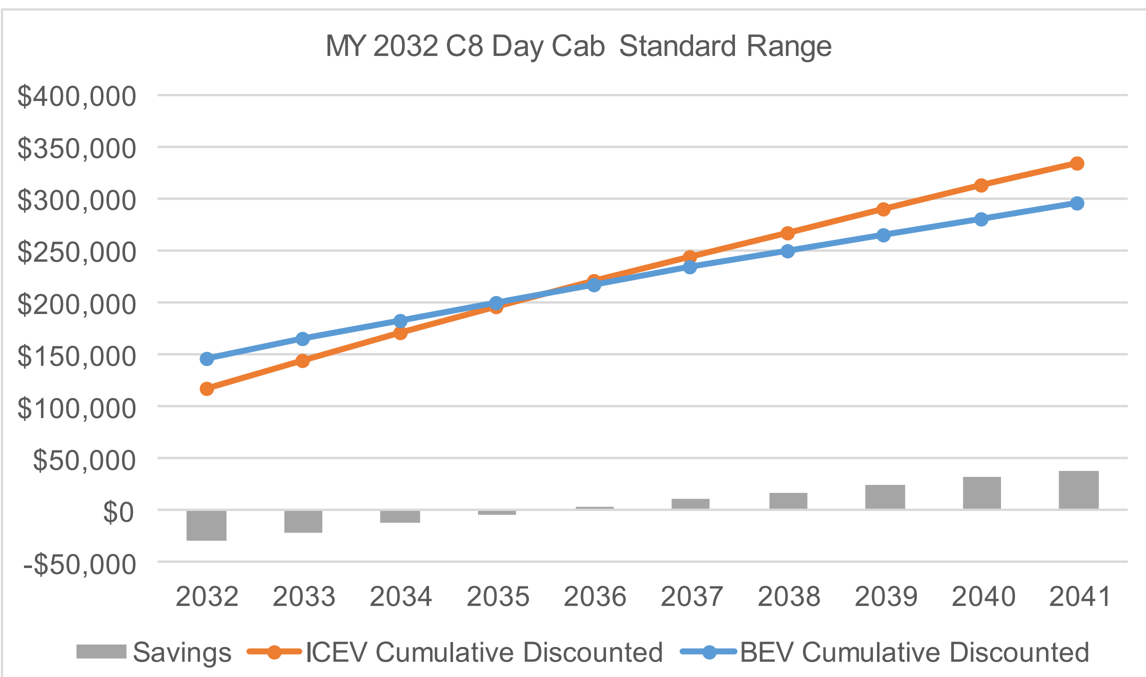

Figure 65: TCO parity of an MY 2032 Class 8 day cab standard range with mixed charging scenario.

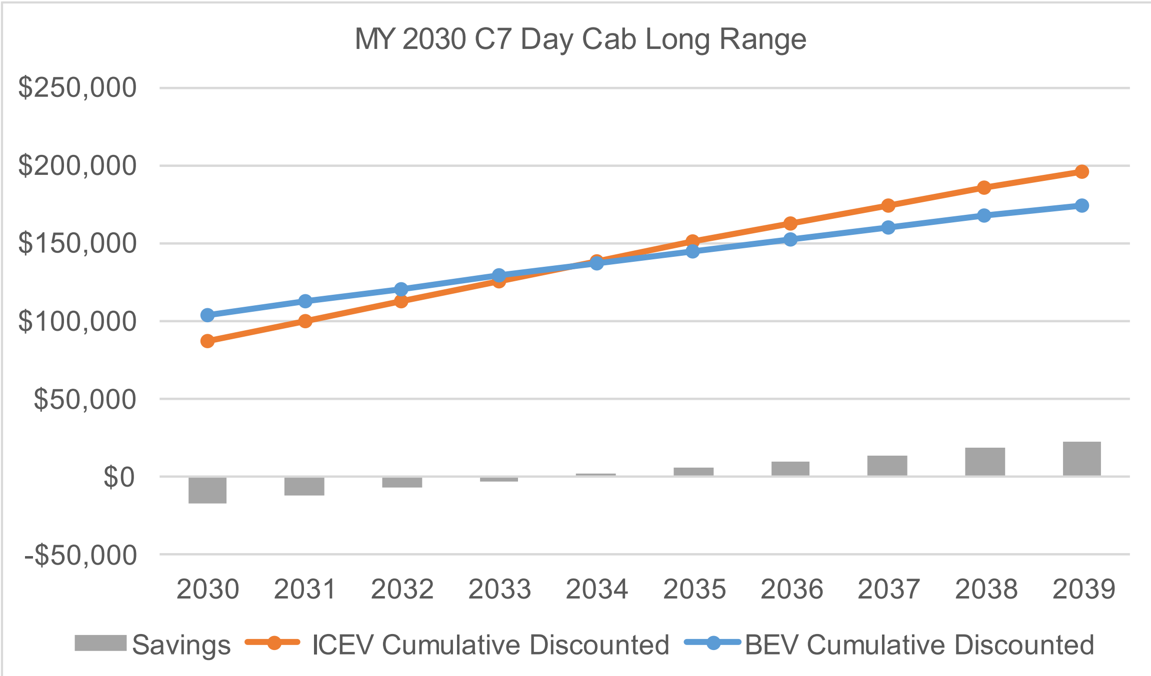

Figure 66: TCO parity of an MY 2030 Class 7 day cab long range with mixed charging scenario.

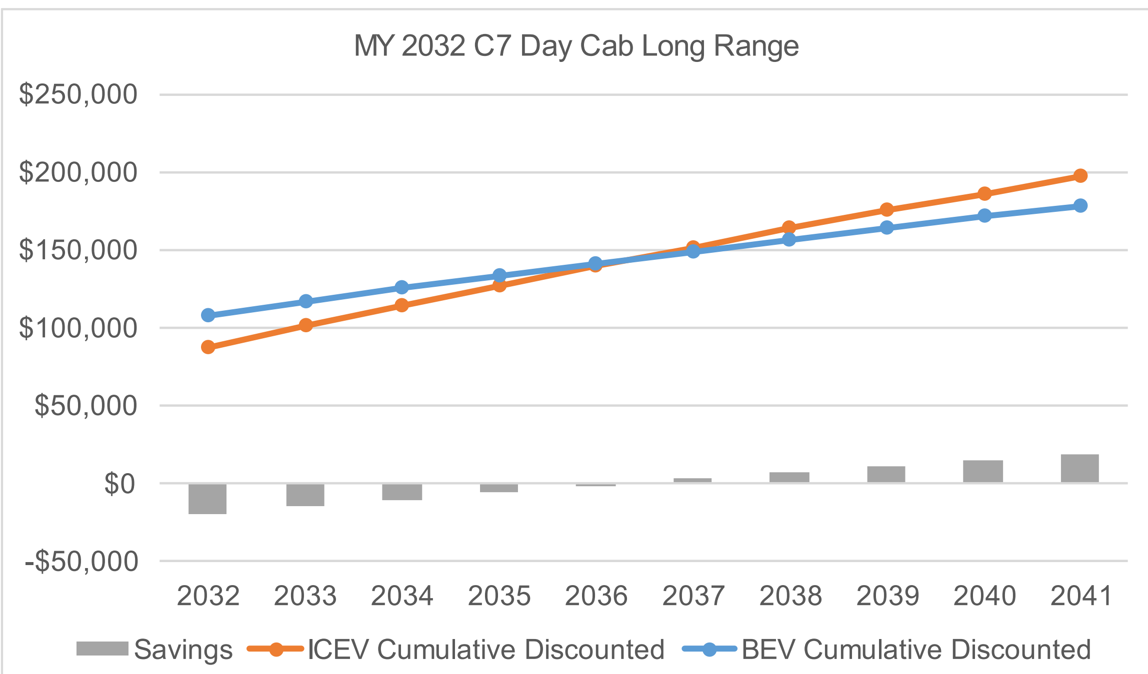

Figure 67: TCO parity of an MY 2032 Class 7 day cab long range with mixed charging scenario.

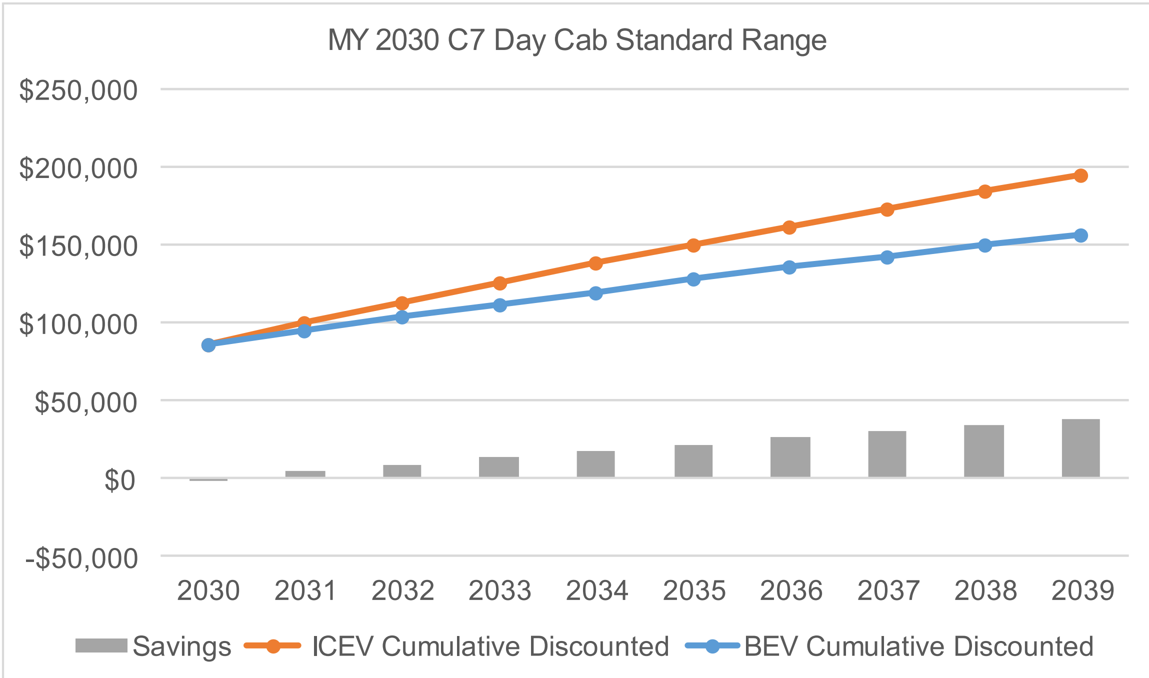

Figure 68: TCO parity of an MY 2030 Class 7 day cab standard range with mixed charging scenario.

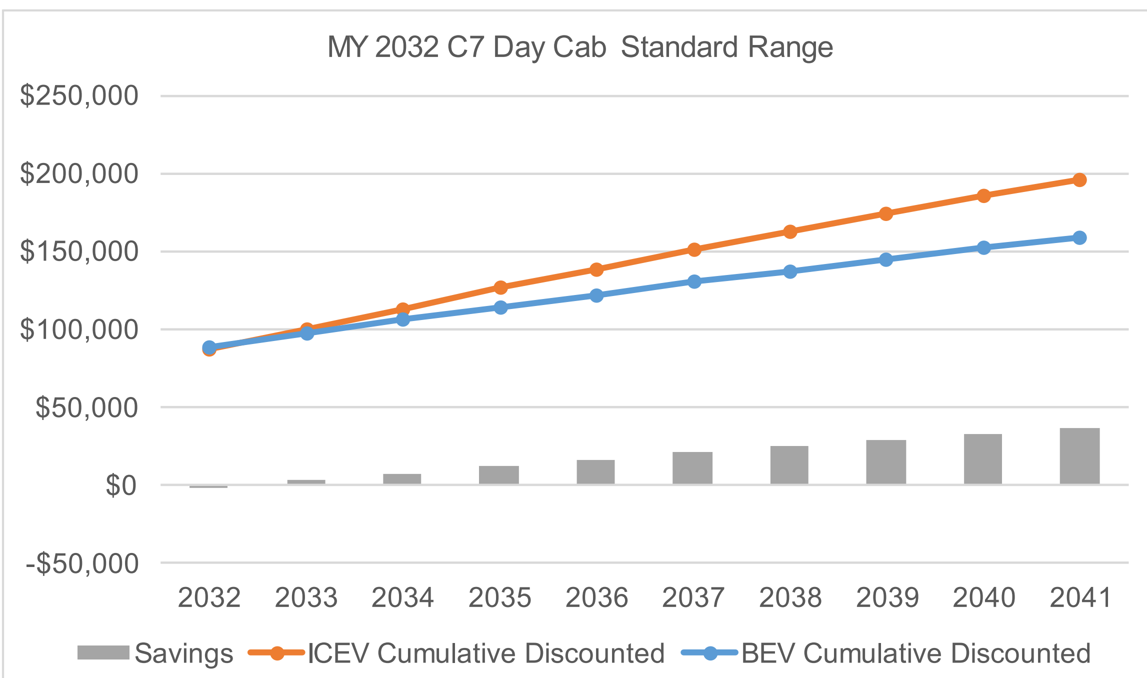

Figure 69: TCO parity of an MY 2032 Class 7 day cab standard range with mixed charging scenario.

7.2.2 Total Cost of Ownership Contributions

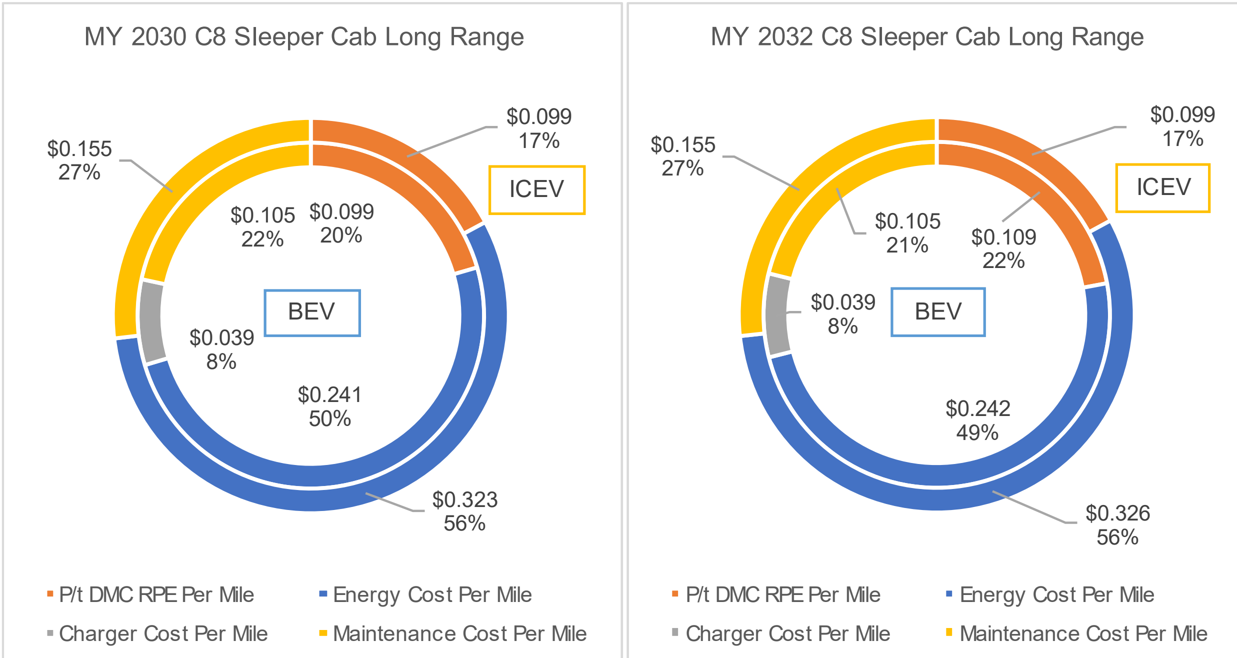

Figure 70: MYs 2030 and 2032 Class 8 Sleeper Cab Long Range ICEV and BEV contributions to TCO in a mixed charging scenario

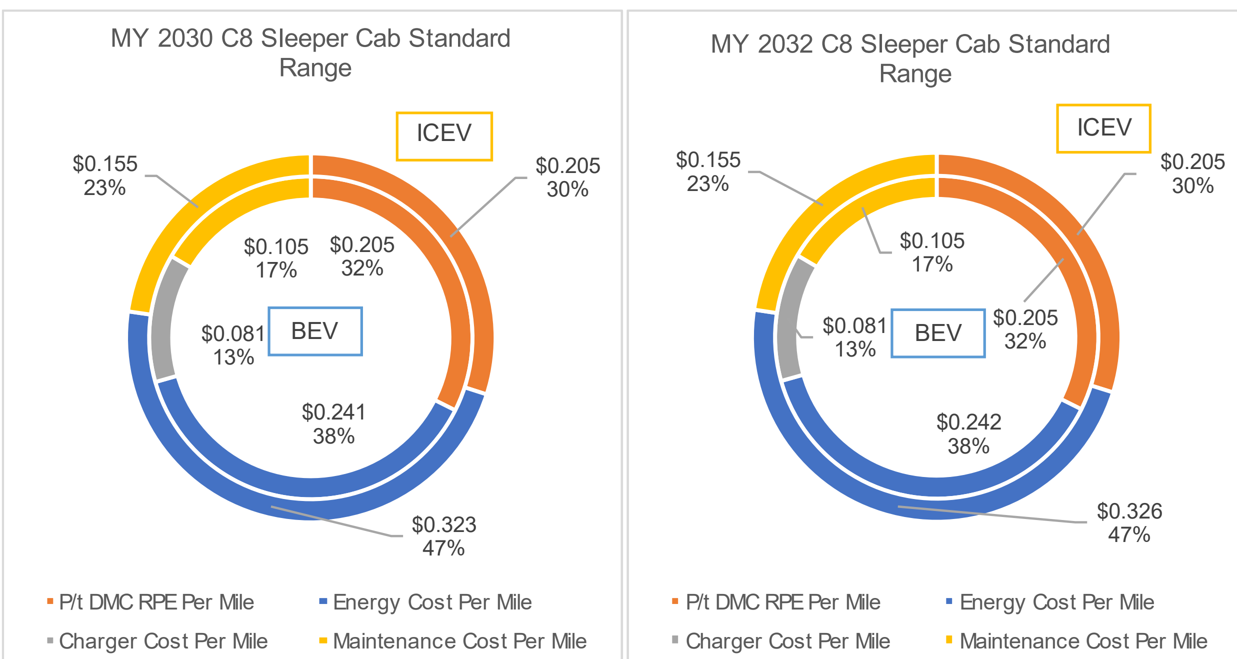

Figure 71: MYs 2030 and 2032 Class 8 Sleeper Cab Standard Range ICEV and BEV contributions to TCO in a mixed charging scenario

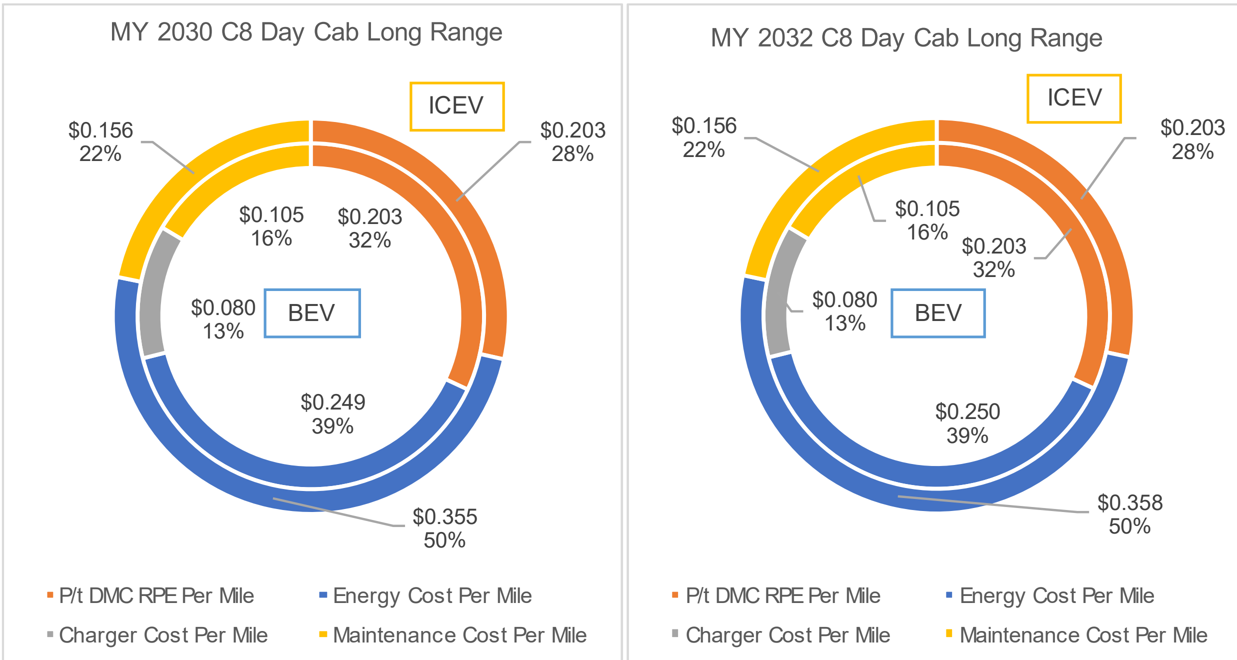

Figure 72: MYs 2030 and 2032 Class 8 Day Cab Long Range ICEV and BEV contributions to TCO in a mixed charging scenario

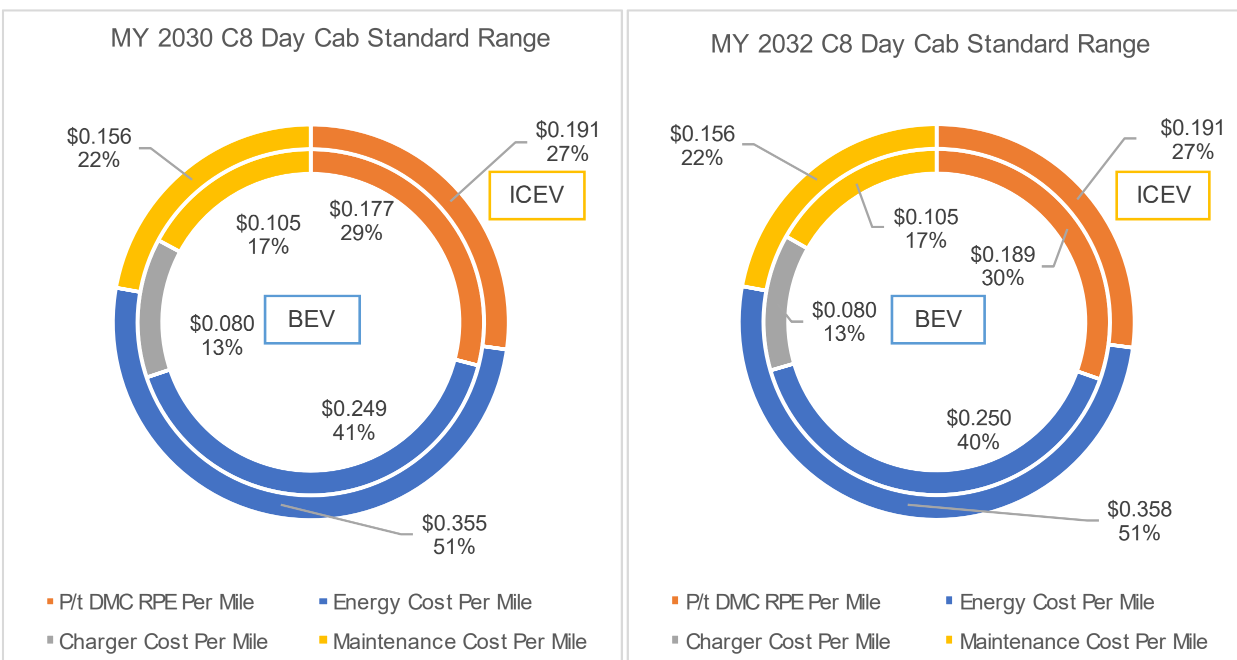

Figure 73: MYs 2030 and 2032 Class 8 Day Cab Standard Range ICEV and BEV contributions to TCO in a mixed charging scenario

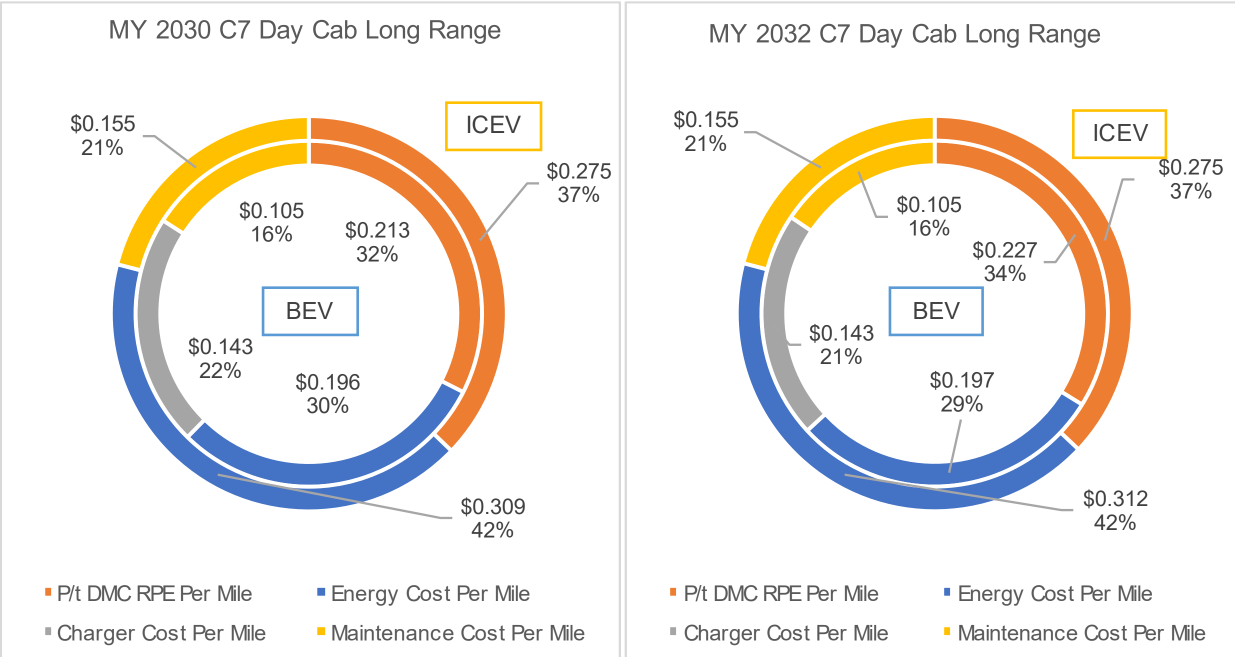

Figure 74: MYs 2030 and 2032 Class 7 Day Cab Long Range ICEV and BEV contributions to TCO in a mixed charging scenario

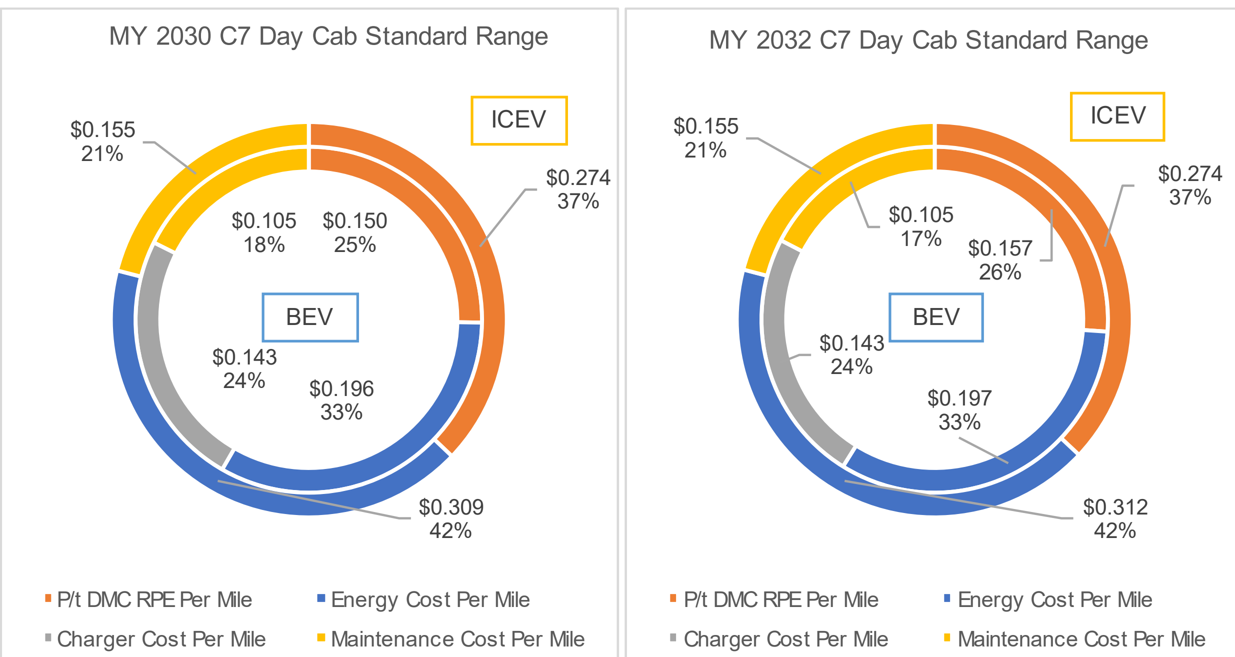

Figure 75: MYs 2030 and 2032 Class 7 Day Cab Standard Range ICEV and BEV contributions to TCO in a mixed charging scenario

7.3 Primary Analysis without Discount Rate of 3%

Table 29: Years to reach TCO parity without discounting

Vehicle Categories	Payback Period (in years)	
	MY 2030	MY 2032
C8_SC_Long Range	1	2
C8_SC_Standard Range	3	3
C8_DC_Long Range	3	3
C8_DC_Standard Range	2	3
C7_DC_Long Range	3	3
C7_DC_Standard Range	<1	1

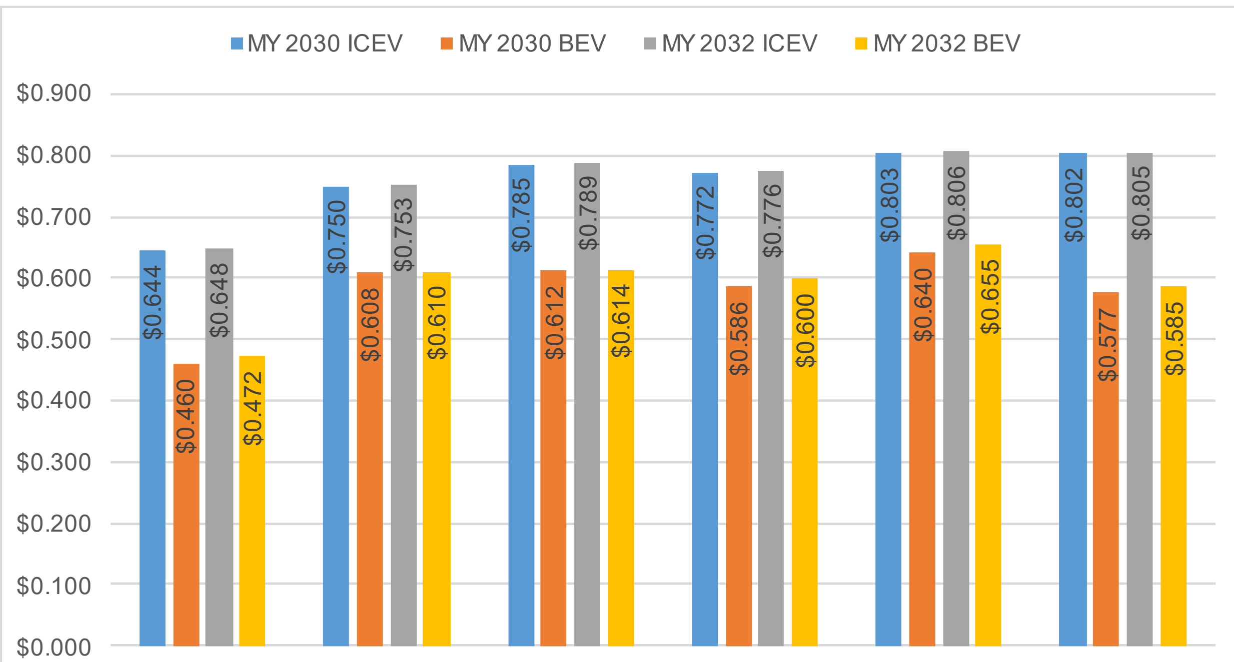

Figure 76: TCO per mile of ICEVs and BEVs in MYs 2030 and 2032 without discounting

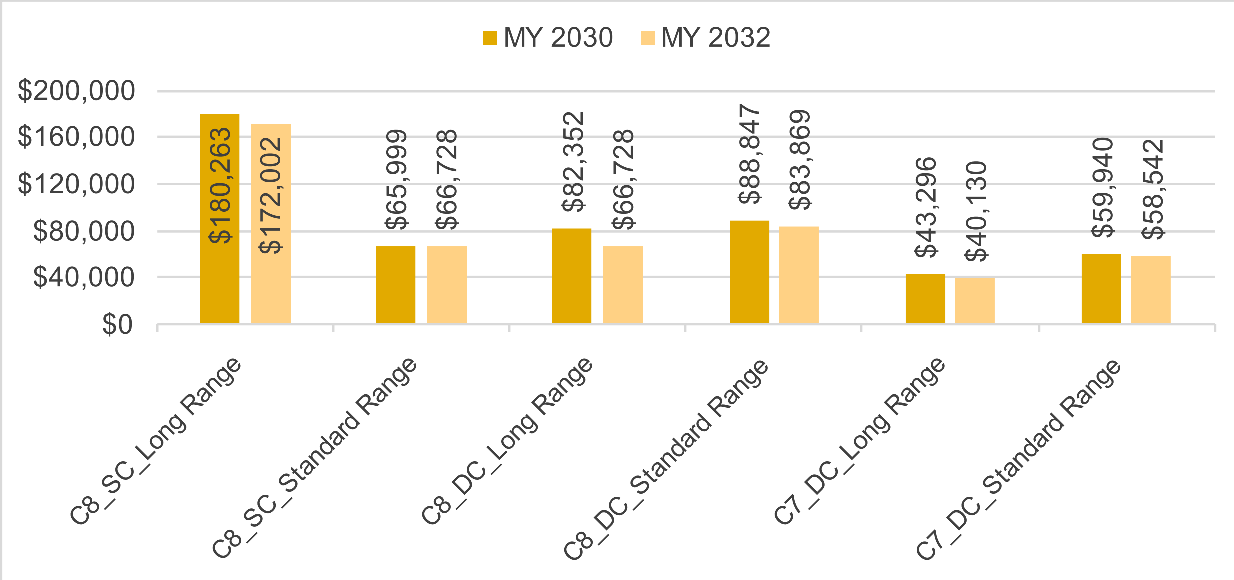

Figure 77: Cumulative Net Savings of BEVs over ICEVs in MYs 2030 and 2032 without discounting