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ASSESSING FINANCIAL BARRIERS TO ADOPTION OF ELECTRIC TRUCKS

A Total Cost of Ownership Analysis

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The transportation sector is now the largest source of greenhouse gas emissions in the United States and medium- and heavy-duty vehicles account for a disproportionate share of those emissions. The Center for Climate and Energy Solutions, David Gardiner and Associates, Atlas Public Policy, and the Retail Industry Leaders Association are investigating barriers to the adoption of electric trucks for freight movement. This paper by Atlas Public Policy provides a total cost of ownership analysis for electric trucks to help retailers, shippers, and other interested parties assess the cost competitiveness of medium- and heavy-duty electric vehicles (EVs) under current market conditions and describes the most relevant factors for consideration when entering into an EV procurement. The results indicate that medium- and heavy-duty EVs are cost competitive in some use cases under current market conditions and the most important factors are the cost of charging and availability of upfront vehicle incentives.

EXECUTIVE SUMMARY

The transportation sector is the largest source of greenhouse gas (GHG) emissions in the United States. Local communities and governments are increasingly focused on reducing GHG emissions from trucking because of the attendant benefits for local air quality. Many corporations and retail companies are also working to reduce emissions of carbon dioxide and other air pollutants through corporate social responsibility, sustainability, and emissions reduction programs. These convey public health benefits to the local communities and governments which these businesses serve. Several are actively engaged with initiatives like the U.S. Environmental Protection Agency's SmartWay program, the Coalition for Responsible Transportation, and EV100.

At the same time, medium- and heavy-duty EVs are a relatively new technology and many freight industry stakeholders lack access to independent analysis to help make informed decisions about electric trucks and charging infrastructure options. This paper assesses the market landscape, challenges, and opportunities for electric truck adoption among major shippers and their transportation partners by performing a total cost of ownership analysis for EVs under a wide range of procurement scenarios and comparing these results with those from an equivalent diesel vehicle procurement.

BACKGROUND

Despite rising tailpipe emission and fuel economy standards, GHG emissions from the transportation sector have grown substantially over recent decades due to a steep increase in yearly vehicle miles traveled (VMT) resulting from factors such as population growth, economic growth, urban sprawl, periods of low fuel prices, and changes in consumer behavior. Medium- and heavy-duty vehicles saw the largest increase in VMT and emissions of all vehicle categories during this timeframe and that figure is only expected to rise as the shipping volumes in the United States continue to increase.

Many companies in the private sector are actively engaged in efforts to curb these emissions, and are exploring alternative fuel options, including electricity and natural gas. At such an early stage however, there are many gaps in the industry's understanding of the feasibility and applicability of various power alternatives, and independent analysis of these issues is not widely available.

Efforts towards electrification of medium- and heavy-duty fleets offer a chance to not only achieve environmental goals, but also potential cost-savings. As battery prices fall and technology improves, the case for medium- and heavy-duty electric vehicles becomes more compelling as these vehicles approach cost parity with their diesel counterparts. An important indicator of the viability of medium- and heavy-duty electric vehicles is the number of manufacturers who are developing models including major manufacturers such as Tesla, Daimler, Peterbilt, and Volvo.

While the deployment of medium- and heavy-duty EVs in the United States has been primarily limited to pilot projects, some of the initial results are promising and have contributed to several significant announcements from U.S. and international companies. Companies such as UPS, FedEx, Walmart, PepsiCo, Sysco, JB Hunt, Anheuser-Busch, and Amazon have all announced orders for medium- or heavy-duty EVs. Although these announcements are encouraging, there have also been examples of failed electrification efforts and many of the orders that prominent companies have announced will be contingent upon manufacturers being able to deliver.

Box ES-1. Charging Definitions

Some helpful definitions for terms used in the discussion below are:

- **Depot Charging:** Vehicle charging that occurs at a fleet-owned depot where the charging infrastructure is owned and operated by the fleet, similar to a private fueling station. The cost of charging is only the price of electricity.
- **Public Charging**: Vehicle charging that occurs at a third-party owned charging site where the charging infrastructure is owned and operated by a third party, similar to a public gas station. The cost of charging is the going rate charged by the third-party owner of the charging infrastructure.

ANALYSIS METHODOLOGY

The aim of this analysis is to examine the barriers to adding medium- and heavy-duty electric vehicles to shipping fleets. To achieve this goal, a multivariate analysis was completed to compare the total cost of ownership of medium- and heavy-duty EVs and their diesel counterparts under a wide array of procurement scenarios. Data was gathered from published sources and interviews with industry experts from Fortune 500 shippers, third-party logistics companies, and a publicly-traded EV manufacturer to determine the types of procurement scenarios to examine and the procurement factors to alter. The analysis objective was to evaluate the sensitivity of total cost of ownership to factors such as vehicle price, yearly VMT, years of ownership, maintenance cost, fuel cost, and charging strategy. In doing so, the analysis would provide insight into two key issues related to medium-and heavy-duty EVs by doing the following:

1. Develop an overall picture of the likelihood that EVs would be cost competitive with their diesel counterparts, and
2. Demonstrate which factors in a procurement were most critical to make EVs cost competitive.

The information obtained during the data gathering process led to the identification of eight use cases along with 14 vehicle models, which capture a representative spectrum of medium- and heavy-duty vehicles. In addition, the analysis evaluated 10 variables to provide insight into the sensitivity of total cost of ownership for EVs under different plausible procurement scenarios. In total, 41,418 procurement scenarios were analyzed.

SUMMARY OF FINDINGS

FINDING: COST COMPETITIVE EV PROCUREMENTS ACHIEVABLE IN CURRENT MARKET

The cost competitiveness of procuring EVs was determined primarily by the presence of two key elements in a procurement: low cost charging and vehicle incentives. EV procurements which did not include these elements were almost categorically non-competitive in the scenarios analyzed. Importantly, because low cost charging is widely available in the current market and vehicle incentives are available in some markets, designing an EV procurement that takes advantage of these elements is a presently achievable goal. For this analysis, low cost charging was achieved through depot charging though lower cost public charging could be attained through purchase agreements between vehicle fleet operators and charging service providers, similar to diesel fuel purchase agreements. Exploring the cost and benefits of these arrangements was out of scope for this analysis.

Box ES-2. Caveats in Considering the Results of this Analysis

This analysis was designed to examine medium- and heavy-duty EVs from a financial perspective. It does not factor in the benefits of EVs to public health, the environment, or public relations. Also not considered are the benefits for companies looking to become market leaders or stay ahead of policy trends. The procurement scenarios analyzed do include variations on a large number of financial factors which could affect the total cost of ownership for electric and diesel vehicles, but did not cover potentially relevant elements such as:

- Potential carbon taxes
- Societal costs and benefits from reduced emissions
- Potential health benefits to drivers
- Consumer interest in companies transitioning to EVs
- Public relations benefits for early adopters
- Potential cap and trade benefits
- Daily variations in charging rates
- Variations in VMT for each use case
- EV-specific electricity rates
- Strategies to lower public charging costs
- Incentives for charging infrastructure
- Variations in charging infrastructure costs
- EV procurements where existing infrastructure exists

The above list is not meant to be exhaustive, but rather an indication of the number of other elements which could impact EV cost competitiveness and provide a basis for further analysis.

FINDING: OVERALL LIKELIHOOD OF EV COST COMPETITIVENESS WAS LOW

While achievable, the likelihood that an EV procurement would be cost competitive with an equivalent diesel procurement under the assumptions of this analysis was low. Roughly 15 percent of the 40,608 EV procurement scenarios were identified as cost competitive in this analysis. Although the overall picture may not appear promising, including just two key elements in a procurement scenario, depot charging and vehicle incentives, substantially improved the cost competitiveness of EVs. Eliminating all scenarios that rely on any public charging more than doubled the share of scenarios where an EV was cost competitive with a diesel vehicle. If both depot charging and vehicle incentives were included, then nearly half of all scenarios became cost competitive.

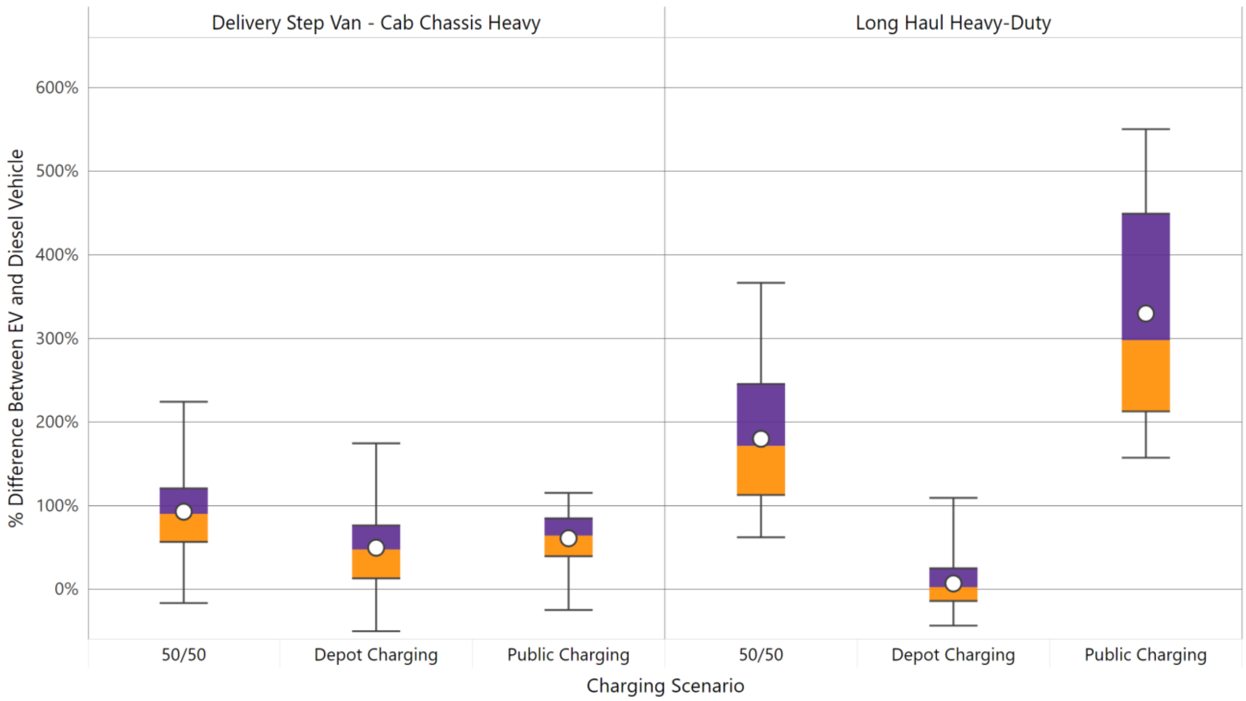
It should also be noted that the procurement scenarios included in this analysis, while wide ranging, do not cover all possibilities for electric and diesel vehicle procurements. Several potentially important factors were not explored and these are detailed in Box ES-2.

FINDING: DEPOT CHARGING CRITICAL TO EV COST COMPETITIVENESS

The choice of charging strategy was the most important decision when procuring a medium- or heavy-duty EV. Depot charging opened up a range of cost saving options for an EV procurement such as lower charging costs than prevailing public charging prices, avoidance of lost productivity by charging during normal downtime, and control over the number and type of charging stations. Including any of the other charging options explored in this analysis resulted in almost total exclusion from being cost competitive. More than 98 percent of cost competitive scenarios included exclusive depot charging. Varying the cost of charging downtime or the price of public charging would have likely impacted this finding, but that was not explored in this analysis. It should also be noted that while the analysis did include an estimate of electricity surcharges such as demand charges that may be incurred by station owners, variations in these surcharges and strategies to reduce them were not modeled.

Figure ES-1 shows the effect of different charging strategies on the average percentage difference in TCO between electric and diesel vehicles with the lowest (Delivery Step Van – Cab Chassis Heavy) and highest (Long Haul Heavy-Duty) annual VMT, respectively.

FIGURE ES-1: EFFECT OF CHARGING STRATEGY ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This box-and-whisker figure shows the change in the percentage difference in TCO between an EV and an equivalent diesel vehicle when varying the charging strategy for an EV procurement. The orange and purple shaded regions represent the second and third quartiles of the dataset for each box and whisker plot. The three options are depot charging where vehicles would charge exclusively at charging stations included as part of the procurement, public charging where vehicles would rely solely on a public charging network, and 50/50 where charging is split equally between depot charging and public charging. (Scenarios Shown: 14,256)

FINDING: PUBLIC CHARGING NOT A VIABLE OPTION WITH CURRENT MARKET PRICES

Relying on public charging networks to charge medium- and heavy-duty EVs was not a viable option due to the high cost of charging. The costs of public charging used in this analysis were based on current market prices and were high enough that EVs were more expensive to fuel on a per-mile basis than their diesel counterparts and fewer than two percent of EV procurement scenarios which included public charging were cost-competitive with a diesel equivalent. Relying exclusively on depot charging was vital to achieving cost competitiveness for EVs, as over 98 percent of all cost competitive scenarios used only depot charging. If companies were able to negotiate lower charging rates via bulk purchase agreements or other methods, then public charging could be a potential option for EVs since fleet managers would avoid the upfront cost of infrastructure. However, this analysis did not explore such strategies. The analysis also did not explore the break-even point for when public charging costs would become cheaper than fueling an equivalent diesel vehicle.

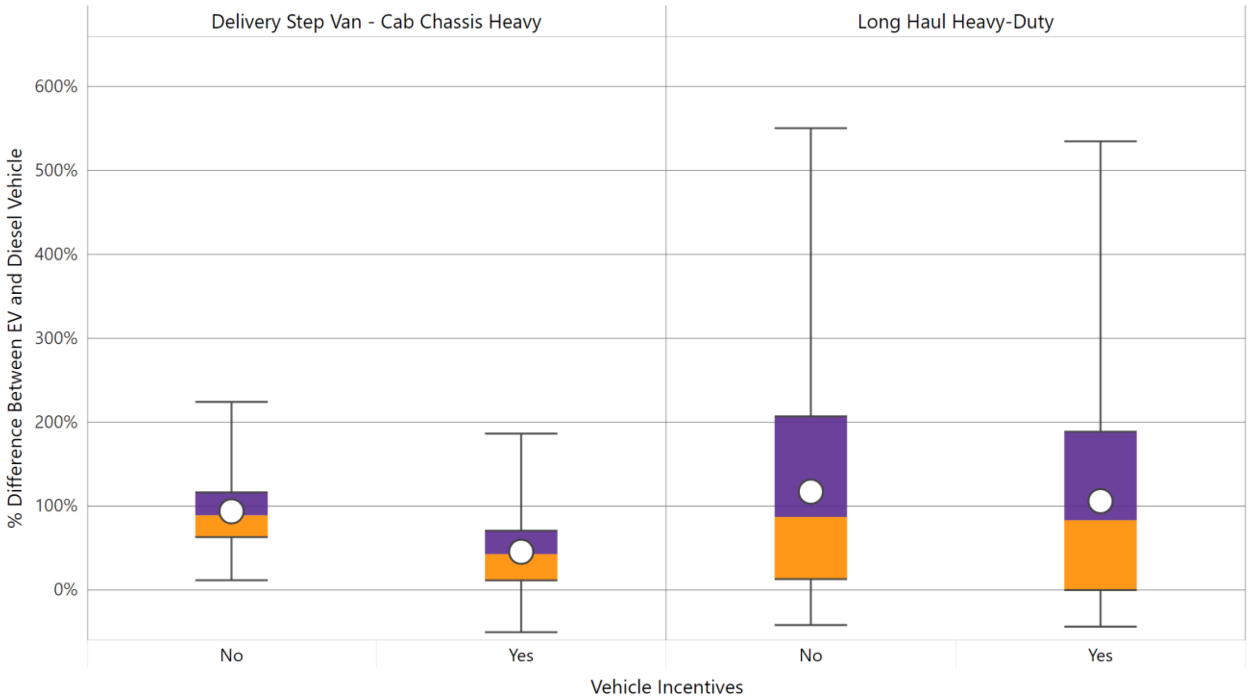
This analysis did not explore the cost competitiveness of EVs if fleets or third-party charging providers employed strategies to reduce the price of public charging. Such strategies could include bulk purchase agreements and onsite power generation or power storage. Also not modeled were potential advances in the energy density of batteries, leading to lower vehicle weights and better fuel economy. Fleet managers or charging service providers could pursue other options to achieve cost effective public charging, but these were beyond the scope of this analysis.

FINDING: STATE EV INCENTIVES HIGHLY IMPORTANT TO BRIDGE PRICE GAP BETWEEN ELECTRIC AND DIESEL VEHICLES, BUT NOT STRICTLY NECESSARY FOR EV COST COMPETITIVENESS

Purchasing an EV in a state with a medium- and heavy-duty EV incentive program is a highly important factor for increasing the likelihood that an EV will be cost competitive with an equivalent diesel vehicle, but second to the decision to pursue low cost charging, such as depot charging. In relation to depot charging, 98 percent of all cost competitive scenarios included depot charging while only 69 percent included vehicle incentives. Among the various use cases, vehicle incentives had a more significant effect on vehicles with lower rates of utilization as they were more sensitive to variations in upfront fixed costs.

Figure ES-2 shows the effect of vehicle incentives on the average percentage difference in TCO between electric and diesel vehicles for the lowest (Delivery Step Van – Cab Chassis Heavy) and highest (Long Haul Heavy-Duty) rate of utilization of all use cases.

FIGURE ES-2: EFFECT OF VEHICLE INCENTIVES ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This figure shows the percentage difference in TCO between an EV and an equivalent diesel vehicle for procurements that either include or do not include state EV incentives. Incentive figures are from the New York Vehicle Incentive Program and cover between 35 and 50 percent of the vehicle price. (Scenarios Shown: 14,256)

FINDING: VARIATIONS IN ELECTRICITY PRICE PRIMARILY RELEVANT FOR VEHICLES WITH HIGH UTILIZATION RATES

The impact of variations in electricity prices was most significant for vehicles with extremely high utilization. A 33 percent reduction in electricity cost resulted in just a two percent drop in average TCO for a medium-duty EV traveling 16,500 miles per year. This drop in TCO increased to 13 percent for a heavy-duty EV traveling 170,000 miles per year under the same conditions.

FINDING: VEHICLES WITH HIGHER UTILIZATION RATES OFFERED GREATER OPPORTUNITY FOR COST SAVINGS

In general, vehicles with higher utilization rates had a greater likelihood of being cost competitive with the top three uses cases by yearly VMT (long and short haul heavy-duty vehicles and terminal tractors), accounting for over 85 percent of all cost competitive scenarios. Because reduced operating costs are the primary financial benefit of EVs compared to diesel vehicles, the more a vehicle is utilized, the greater the potential savings. Under the conditions explored in this analysis, long range heavy-duty EVs, the vehicle with the highest rate of utilization, offered the highest likelihood of a cost savings when compared with an equivalent diesel vehicle, with more than 27 percent of scenarios being cost competitive. Once scenarios with public charging were eliminated, this figure rose to nearly 60 percent. One caveat is that the analysis assumed no deviation from the yearly mileage for each use case across the life of the vehicle. For long and short haul heavy-duty vehicles, this is most feasible when vehicles operate on specific set routes at regular schedules, which would allow sufficient time for recharging.

FINDING: REDUCTIONS IN UPFRONT COST OF EVS FROM TECHNOLOGICAL ADVANCEMENTS OFFER SIMILAR SAVINGS TO A NATIONWIDE EV INCENTIVE PROGRAM

Reductions in EV manufacturer suggested retail price (MSRP) from predicted technological advancements had a similar, albeit smaller, effect on the likelihood of EVs being cost competitive as the presence of vehicle incentives. MSRP reductions do, however, offer the potential of achieving nationwide impact whereas vehicle incentives are currently limited to a few states. An MSRP reduction of 30 percent, a scenario which could occur within a few years, would achieve nearly the same effect as a nationwide incentive program.

FINDING: MAINTENANCE COST REDUCTIONS FOR EVS A MINOR FACTOR FOR EV COST COMPETITIVENESS

Cost savings from reduced maintenance costs for EVs were not an important determinant of EV cost competitiveness. The cost of maintenance in this analysis represented a relatively small portion of the total cost of ownership for both electric and diesel vehicles compared to other cost elements and any reductions in maintenance costs had an equally small effect on TCO.

FINDING: TERM OF OWNERSHIP AND PROCUREMENT METHOD NOT RELEVANT FACTORS FOR DETERMINING EV COST COMPETITIVENESS

Under the assumptions of this analysis, years of ownership had the smallest incremental effect on the cost competitiveness of EVs of all procurement elements analyzed. Increasing the years of ownership by two increased the number of cost competitive scenarios by just over 10 percent on average. In comparison, increasing the savings on maintenance costs for EVs by 30 percent, a change which had a small effect on TCO, increased the number of cost competitive scenarios by nearly 14 percent. The savings from reduced operating costs did not accrue fast enough to substantially increase the number of cost competitive EVs over even a seven-year timeframe.

> *Importantly, this analysis did not explore the cost competitiveness of EVs once charging infrastructure had already been procured. A subsequent EV procurement that was unburdened by the cost of procuring and installing charging infrastructure and had access to low cost charging would be substantially more cost competitive than many of the EV procurements examined in this analysis.*

Choice of procurement method also did not have an appreciable effect on the total cost of ownership for EVs, but did provide a relative advantage when compared to diesel vehicles for cash procurements. The closed-end lease used in the analysis assumed a residual value of $1 at the end of the lease, so the full impact of any differences in upfront cost were realized. The residual value in this case is not realistic, particularly for shorter term leases, but does provide a worst-case scenario for EV resale values. If the negotiated residual value used was more realistic, then comparative advantage of cash purchase over closed-end lease would likely shrink if not disappear entirely.

FINDING: FUEL PRICE FLUCTUATIONS A RELATIVELY LARGER SOURCE OF RISK FOR DIESEL VEHICLES THAN EVS

The total cost of ownership for diesel vehicles was more sensitive to variations in the price of fuel than for EVs. Given the historical volatility of diesel prices compared to electricity prices, fluctuations in the cost of fuel represent a greater source of risk for diesel procurements. While this analysis also did not explicitly model variations in potential carbon taxes, which could disproportionately affect diesel vehicles, the effect of carbon taxes would be similar to the modeled changes in diesel prices.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

INTRODUCTION

The transportation sector is now the largest source of greenhouse gas (GHG) emissions in the United States [1]. While light-duty vehicles including cars and light trucks make up the majority of the emissions from the transportation sector, medium- and heavy-duty vehicles contribute an outsized portion. Accounting for just five percent of vehicles, medium- and heavy-duty vehicles are responsible for over 23 percent of transportation emissions and offer a tremendous opportunity to advance environmental goals [2]. Governments and private entities are becoming increasingly focused on reducing these harmful emissions and have implemented a range of programs designed to either limit or eliminate their impact.

Governments at the federal level have implemented increasingly stringent fuel economy standards designed to reduce emissions as vehicle technology improves [2]. Several state governments are also taking an active role in transitioning to cleaner transportation and have implemented programs like the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project in California and the Truck Voucher Incentive Program in New York, both of which provide vouchers to help defray the costs of purchasing zero-emission electric vehicles [3, 4].

In the private sector, many companies are also doing their part through corporate social responsibility, sustainability, and carbon emissions reduction programs. For example, major retailers have actively focused on strategies to reduce operational emissions and have been exploring innovative technologies to address transportation sustainability. Several are actively engaged with initiatives like the U.S. Environmental Protection Agency (EPA) SmartWay program and EV100 and acted as a source of input for this analysis [5, 6, 7]. These programs are focused on finding ways to accelerate green transportation and reduce the impact of the transportation industry on the environment. Large retailers like these have a global and local presence, employ millions of people, require complicated infrastructure to move goods in their vast supply chains, and touch the lives of all Americans. They are progressive companies and can exert market power to achieve large scale, systemic change that would rapidly accelerate any efforts to achieve cleaner, greener transportation.

One interest of the retail industry is the potential availability of electric vehicles for their medium- and heavy-duty fleets. To explore medium- and heavy-duty fleet electrification, the Center for Climate and Energy Solutions (C2ES), David Gardiner and Associates (DGA), and Atlas Public Policy have collaborated with the Retail Industry Leaders Association (RILA) to assess the current EV market landscape and to better understand the barriers to adoption of electric vehicles for freight trucks. RILA is the trade association for the leading retailers in the United States, representing more than 200 retailers, product manufacturers, and service suppliers, which together account for more than $1.5 trillion in annual sales, millions of American jobs, and more than 100,000 stores, manufacturing facilities, and distribution centers domestically and abroad.

One of the main goals of this work is to conduct an objective financial analysis on the value proposition of EV trucks for freight to aid and engage large retailers and other large-scale shippers across industries. For most companies, EVs are a very new technology and, therefore, they lack independent information and analysis to help them make rapid, unbiased decisions on adopting EV trucks and EV charging infrastructure.

This paper assesses the financial barriers to incorporating medium- and heavy-duty electric vehicles into commercial shipping fleets by performing a total cost of ownership analysis under a wide range of scenarios. This analysis will show major shippers and other interested parties the most important aspects of a medium- or heavy-duty EV procurement for achieving cost savings compared to an equivalent diesel vehicle procurement by drawing on information from published sources, survey data from industry experts, and Atlas Public Policy's Fleet Procurement Analysis Tool. The publicly available Fleet Procurement Analysis Tool (https://atlaspolicy.com/rand/fleet-procurement-analysis-tool) was developed by Atlas Public Policy and equips users with decision-relevant information on the financial viability and environmental impact of light-, medium-, and heavy-duty vehicle fleet procurements.

BACKGROUND

This section of the paper will explore the background of the transportation sector's impact on greenhouse gas emissions, the role of retail within the transportation industry along with efforts retailers have made to reduce their environmental impact, and the current state of the medium- and heavy-duty EV market.

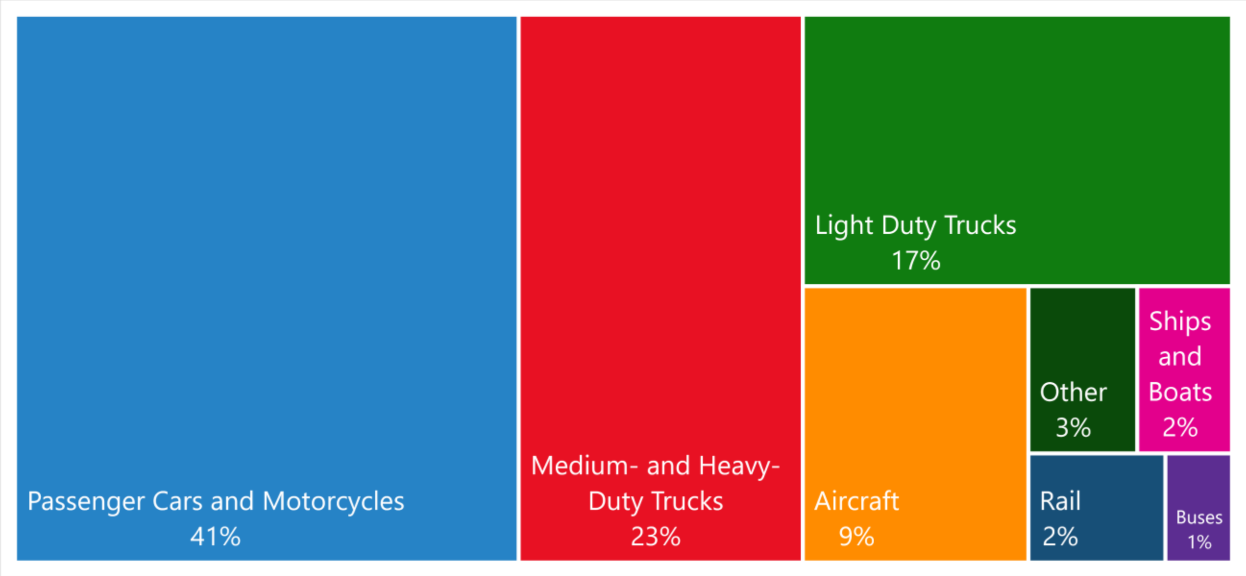
INDUSTRY EFFORTS TO REDUCE TRANSPORTATION EMISSIONS

Greenhouse gas emissions from the transportation sector surpassed those from all other industry sectors in 2015, eclipsing the power sector as the largest contributor of GHG emissions in the United States [2]. If the trend from previous years holds, transportation's share of U.S. GHG emissions will only continue to rise. Despite rising tailpipe emission and fuel economy standards, factors such as population growth, economic growth, urban sprawl, and periods of low fuel prices drove an increase in yearly vehicle miles traveled (VMT) of more than 45 percent from 1990 to 2017 and with it GHG emissions [8]. Medium- and heavy-duty vehicles saw the largest increase in emissions of all vehicle categories during that timeframe. The combined average annual VMT of combination (semi-trailer) and single-unit trucks has more than doubled since 1990 and the associated GHG emissions from these vehicles have risen proportionally [8, 9]. Looking forward, heavy-duty trucks are the fastest growing source of transportation emissions in the United States and U.S. shipment of goods is projected to increase 45 percent by 2040 according to the EPA [10].

Many companies in the private sector are actively engaged in efforts to curb these emissions and efforts towards electrification of medium- and heavy-duty fleets offer a chance to not only achieve environmental goals, but also potential cost-savings. The retail industry in the United States is one private sector group with the potential to have a large impact on medium- and heavy-duty transportation electrification. Large retailers own or hire sizeable fleets of trucks to move their goods over short, medium, and long distances. Thirty-eight members of RILA are critical partners in the U.S. Environmental Protection Agency's SmartWay program because they can influence their carrier partners with vast networks to adopt more efficient trucking technologies. SmartWay is a voluntary effort to accelerate adoption of clean technologies in freight transportation which has saved six billion gallons of fuel, lowered fuel costs by $37.5 billion and reduced pollution from nitrogen oxides, particulate matter, and carbon dioxide by over 134 million tons since the program began in 2004 [11]. A small number of U.S.-operating shippers and service providers who supply retail goods and enterprise solutions are also early signatories of EV100, "a global initiative bringing together forward-looking companies committed to accelerating the transition to electric vehicles (EVs) and making electric transport the new normal by 2030" [12].

Partnership in programs such as SmartWay and EV100 that are dedicated to greener transportation have resulted in some early purchase commitments from large logistics companies and some major shippers. According to research by the consulting firm ICF, the private sector accounted for a majority of the roughly 300 electric trucks on U.S. roads as of late 2018 [13]. These pilot programs have helped to drive investment in the sector and are critical to generating growth in the market. Market transformation requires partnerships among shippers, their third-party carriers where applicable, and vehicle and infrastructure suppliers. Currently, access to independent analysis, particularly around benefits to shippers and the total cost of ownership of EVs [14], is a critical next step in potential medium- and heavy-duty electrification.

FIGURE 1: 2017 U.S. TRANSPORTATION GREENHOUSE GAS EMISSIONS (MMT CO2 EQUIVALENT)



This chart shows the breakdown of transportation-related greenhouse gas emissions by vehicle category. Medium- and heavy-duty trucks account for 23 percent of emissions but just 5 percent of vehicles.

Source: [8]

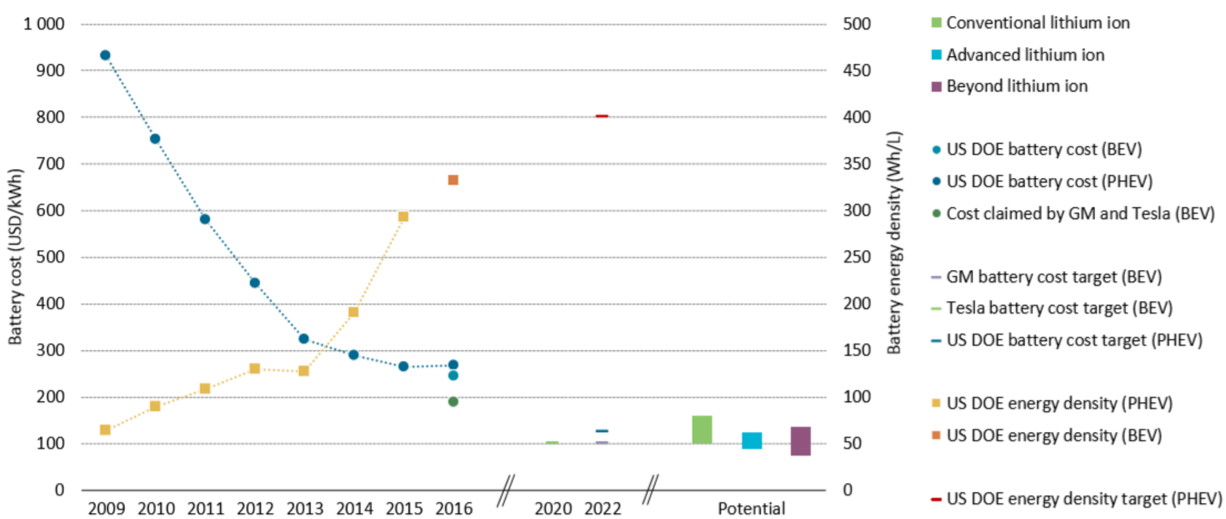
STATE OF MEDIUM- AND HEAVY-DUTY ELECTRIFICATION

The transportation sector is undergoing a significant push towards electrification that is continuing to gain steam. Since early offerings of EVs by General Motors and Nissan in 2010, the number of electric vehicles on the road has been on a steady rise each year. In 2018, year-over-year EV sales rose by more than 80 percent, topping 360,000 units and accounting for over 6 percent of the passenger car market [15]. While the focus of the EV industry to this point has largely been on passenger vehicles, there have been several important advancements in the space of medium- and heavy-duty vehicles.

As battery prices fall and technology improves, the case for medium- and heavy-duty EVs becomes more and more compelling. Battery prices, which can account for over 50 percent of the cost of an EV, have decreased by an average of roughly 20 percent per year since 2009 and are predicted to decrease by an additional two-thirds by 2030 [13]. Battery energy density is similarly expected to increase, which would have the benefit of reducing weight for medium- and heavy-duty vehicles [13]. These improvements along with production cost reductions from economies of scale, would help bring up-front cost parity between electric and diesel medium- and heavy-duty vehicles.

In the interim, several state governments are enacting supportive legislation to help early adopters overcome financial barriers to electrification. The Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project in California and the Truck Voucher Incentive Program in New York provide vouchers that significantly reduce the incremental cost of purchasing eligible medium- and heavy-duty electric vehicles. From 2009 through September of 2019, California's program has paid more than $61 million in vouchers for more than 770 zero emission medium- and heavy-duty vehicles [3].

FIGURE 2: EVOLUTION OF BATTERY COST AND ENERGY DENSITY



This chart shows developments in battery cost and energy density through 2016.

Source: [16]

An important indicator of the viability of medium- and heavy-duty electric vehicles is the number of manufacturers who are developing models. Since 2017, Tesla, Daimler, Peterbilt, and Volvo have all announced medium- or heavy-duty EVs. Beyond traditional large manufacturers, smaller U.S. companies such as Motiv Power, Lightning Systems, Chanje, and Orange EV also offer EV models for purchase. The Chinese market is even further advanced where EV manufacturer BYD has delivered more than 8,000 electric trucks as of May 2019 [17].

While the deployment of these vehicles in the United States has been primarily limited to pilot projects, some of the initial results are encouraging. In a deployment of medium-duty electric delivery vans in 2014, the National Renewable Energy Laboratory (NREL) found that EVs had over three times the fuel efficiency of their diesel counterparts along with a 46 percent reduction in carbon dioxide emissions [18]. UPS has also reported that initial deployments of EVs have performed well and plans to continue to add to their existing fleet of nearly 300 electric vehicles [19]. In more recent deployments, manufacturer Orange EV, which supplies the Class 8 T-Series all electric terminal truck, has seen considerable success with customers reporting fuel savings of up to 90 percent compared to equivalent diesel vehicles with additional significant savings on maintenance due to electric drivetrains having fewer moving parts, no need for oil changes, and regenerative braking [20, 21].

FIGURE 3: TIMELINE OF MAJOR MEDIUM- AND HEAVY-DUTY EV ANNOUNCEMENTS

February 2017 — Smith Electric Vehicles ceases operations

- Smith Electric vehicles ceases operation in 2017 due to lack of funding although maintained hope of restructuring

November 2017 — Tesla unveils the prototype Tesla Semi

- Class 8 all electric semi will have ranges of 300 to 500 miles and have a price between $150,000 and $180,000. Following announcement, several compaines including Walmart, PepsiCo, and UPS place pre-orders

November 2017 — Ryder places order for 125 electric delivery vans

- Ryder, a leader in commercial fleet and supply chain management, orders 125 medium-duty vans from LA-based EV manufacturer Chanje

June 2018 — Daimler unveils its 2 planned electric truck offerings

- Daimler announces plans to offer a heavy-duty truck the eCascadia and medium-duty truck the eM2

June 2018 — UPS orders 950 electric trucks from manufacturer Workhorse

- UPS orders 950 class 5 electric delivery vans contingent on the success of their initial pilot order of 50 electric delivery vans

September 2018 — IKEA announces plans to fully electrify delivery vehicles in several cities

- IKEA Group announces all its home deliveries in the inner cities of Amsterdam, Los Angeles, New York, Paris and Shanghai will be made by EVs or through other zero-emission means by 2020 with all last-mile deliveries coming from EVs or other zero-emission vehicles by 2025

September 2018 — Walmart announces an additional 30 pre-orders of the Tesla Semi

- Walmart adds 30 more vehicles to its existing preorder of 15 Tesla Semis, making it the 5th largest holder of Tesla Semi reservations. Walmart Canada projects to have at least 20 percent of its trucks electrified by 2022 with the remainder powered by alternative fuel sources by 2028

November 2018 — FedEx orders 1,000 electric delivery vans

- Fedex agrees to outright purchase 100 medium-duty electric delivery vans from automaker Chanje and lease an additional 900 from Chanje's distribution and service agent Ryder. FedEx expects to incorporate these vans into their fleet in May 2020

April 2019 — Tesla announces delay of Semi production

- Initially scheduled for production in 2019, Tesla announces that production would be delayed to 2020

June 2019 — Workhorse secures loan to continue operations

- EV manufacturer workhorse, despite having hundreds of outstanding orders from UPS, seeks funding for cash necessary to buy vehicle parts

August 2019 — Daimler delivers first eCascadia electric trucks

- As part of Freightliner's Electric Innovation Fleet, Daimler delivers the first electric trucks to customers Penske Truck Leasing and NFI

September 2019 — Volvo announces plans for heavy-duty electric truck

- Volvo unveils the class 8 VNR electric zero-emissions truck which will be piloted in Southern California and become commercially available in late 2020

September 2019 — Amazon announces order of 100,000 electric delivery vans

- Amazon places an order with EV manufacturer Rivian for 100,000 electric delivery vans, the single largest order of EVs to date with initial units scheduled to ship in 2021

October 2019 — Anheuser-Busch announces plans to deploy 21 BYD Class 8 electric trucks

- Part of the 'Zero Emission Beverage Handling and Distribution at Scale' project, Anheuser-Busch will incorporate 21 BYD electric trucks across four distribution facilities in southern California

The success of the pilot projects mentioned above have contributed to some significant announcements from seven companies for medium- and heavy-duty EVs. UPS and FedEx have each placed orders for 1,000 electric delivery vans from manufacturers Workhorse and Chanje, respectively [19]. Walmart, PepsiCo, UPS, Sysco, and JB Hunt have all placed pre-orders for the Class 8 Tesla Semi [22]. In September of 2019, Amazon announced that it ordered 100,000 electric delivery vans from EV startup Rivian, by far the largest single order of medium-duty EVs to date [23]. These seven companies hope to not only achieve environmental goals and be seen as leaders in electrification among their competitors, but also see cost savings from reduced fuel and maintenance costs. Figure 3 is a timeline listing some of the major announcements in the field of medium- and heavy-duty electric vehicles since Tesla announced their Semi in late 2017.

Although these announcements are encouraging, there are also examples of failed electrification efforts. The NREL study referenced previously demonstrated operational cost savings, but the company that produced those vehicles, Smith Electric Vehicles, shuttered in 2017 due to lack of funding [24]. Many of the orders that prominent companies have announced will be contingent upon manufacturers being able to deliver. Tesla initially planned to start production of their Semi in 2019, but that was delayed to 2020 [25]. Workhorse, one of the companies supplying electric trucks to UPS, has recently experienced financial difficulties and experienced multimillion dollar losses in 2019 along with low sales and sought a loan to continue operations and deliver on their backlog of orders [26]. The Amazon order of 100,000 electric vans was placed with a manufacturer, Rivian, that has yet to commercially produce an electric vehicle and did not include an electric van in its planned models at the time of the Amazon announcement [27].

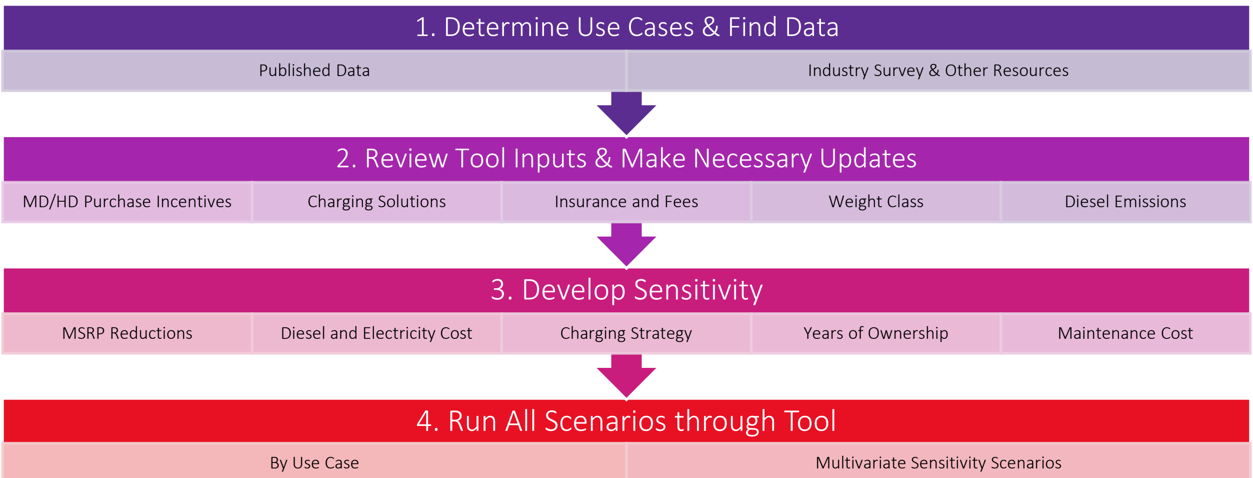
ANALYSIS METHODOLOGY

The aim of this analysis is to examine the barriers to adding medium- and heavy-duty electric vehicles to shipping fleets. To achieve this goal, a multivariate analysis was completed to compare the total cost of ownership of medium- and heavy-duty EVs and their diesel counterparts under a wide array of procurement scenarios. Data was gathered from published sources and interviews with industry experts from Fortune 500 shippers, third-party logistic companies, and a publicly-traded EV manufacturer to determine the types of procurement scenarios to examine and the procurement factors to alter. The analysis objective was to evaluate the sensitivity of total cost of ownership to factors such as vehicle price, yearly VMT, years of ownership, maintenance cost, fuel cost, and charging strategy. In doing so, the analysis would provide insight into two key issues related to medium-and heavy-duty EVs by doing the following:

1. Develop an overall picture on the likelihood that EVs would be cost competitive with their diesel counterparts, and
2. Demonstrate which factors in a procurement were most critical to make EVs cost competitive.

Figure 4 is a diagram describing the process followed to complete the total cost of ownership analysis. First, appropriate vehicles were selected for use in the analysis based on background research and were categorized into different use cases to discern differences in the analysis results for typical uses of medium- and heavy-duty vehicles. The Fleet Procurement Analysis Tool was then updated to support medium- and heavy-duty vehicles along with specific enhancements gleaned from stakeholder interviews. The Fleet Procurement Analysis Tool is a publicly available Excel tool maintained by Atlas Public Policy and designed to compare the total cost of ownership and environmental impact of different vehicle procurements (see Box 1). The most recent version of the Fleet Procurement Analysis tool, which includes these updates, is available for free online. The range of sensitivity variables were then determined and compiled into a master table of all input scenarios. Finally, the multivariate analysis was completed on over 40,000 scenarios using the Fleet Procurement Analysis Tool.

FIGURE 4: METHODOLOGY PROCESS



Box 1. Fleet Procurement Analysis Tool

The Fleet Procurement Analysis Tool equips users with decision-relevant information on the financial viability and environmental impact of light-, medium-, and heavy-duty vehicle fleet procurements. The Microsoft Excel-based tool can evaluate a variety of procurement ownership structures, vehicle types, and procurement scenarios. The tool compares procurements side-by-side on a cost-per-mile basis and provides an analysis of cash flows and location-specific lifecycle emissions. The tool is highly flexible, supports customizable sensitivity variables, and produces user-friendly results summaries.

The tool includes a special mode whereby a multivariate analysis can be completed by running thousands of scenarios that vary input fields. This mode was used to complete the multivariate analysis for this report.

The Fleet Procurement Analysis Tool can be downloaded from Atlas's website here: https://atlaspolicy.com/rand/fleet-procurement-analysis-tool. The tool was originally developed by the Cadmus Group and Atlas Public Policy and has been maintained by Atlas Public Policy since 2017.

DATA USED IN THE ANALYSIS

The data gathering effort for this analysis had several stages. The first of which was to gain information from shippers and trucking companies regarding their experience with EVs. Interviews were conducted with representatives from shipping and logistics companies, retailers, and EV manufacturers to gain insight into their outlook on EVs, difficulties they may have encountered, potential applications of electric trucks, and any information gaps this work could address. These industry experts included representatives from a publicly-traded Fortune 500 company that specializes in freight transportation throughout North America, a privately-held international company that delivers supply chain solutions, a publicly-traded multinational Fortune 500 retail company, a privately-held multinational retail company, and a publicly-traded EV manufacturer. This information will be summarized in a forthcoming report by C2ES and aided in narrowing the focus of this analysis to the most likely applications for EVs and informing data gathering efforts on specific electric and diesel vehicle models.

Next, specifications of medium- and heavy-duty electric vehicles and their associated infrastructure were gathered to inform the financial analysis. Collecting data on medium- and heavy-duty EVs presented a unique challenge given that the industry is still in its infancy. Relatively few models are commercially available and the technology and production processes for these vehicles are still being refined. Manufacturers will typically publish proposed specifications, but not necessarily information on price, maintenance, or charging infrastructure requirements. Information on specific costs for installation of the high-power charging equipment necessary to operate these vehicles is also scarce. To overcome these hurdles, a wide array of published resources was combined and follow-up interviews were conducted with industry representatives to confirm published figures or provide further insight.

The final stage of data gathering was to have relevant industry personnel verify the estimates collected and provide additional information on common use cases of medium- and heavy-duty vehicles. This was accomplished via an online survey which was sent to relevant expert personnel at EV charging service providers and carriers, third-party logistics companies, shippers, government agencies, and non-governmental organizations. The survey included questions on price ranges for different classes of EVs, projected maintenance savings, typical daily mileage of medium- and heavy-duty vehicles in companies' fleets, fleet fueling behavior, and price ranges for EV charging equipment. A copy of the survey is included in Appendix B.

The data gathered in the steps above led to the identification of eight use cases along with 14 vehicle models from eight manufacturers for inclusion in the analysis. The models selected and use cases identified cover a wide range of key vehicle attributes such as price, weight class, range, and VMT designed to capture a representative spectrum of medium- and heavy-duty vehicles. The vehicle models were selected based upon the best available data as of October 2019. More representative models for a given use case may exist, but there is not sufficient data on vehicle price or specifications at the time. This analysis is not intended as a specific model-by-model comparison of vehicles, but rather as a generalized analysis of the total cost of ownership for diesel and electric vehicles.

TABLE 1: VEHICLE DRIVETRAINS, CLASS, MAKES, MODELS, AND USE CASES ANALYZED

Primary Fuel	Weight Class	Make	Model	Use Cases
Diesel	Heavy-Duty Vehicles (Class 7-8)	Freightliner	Cascadia Sleeper Cab	Long Haul Heavy-Duty
Diesel	Heavy-Duty Vehicles (Class 7-8)	Freightliner	Cascadia Day Cab	Short Haul Heavy-Duty
Electricity	Heavy-Duty Vehicles (Class 7-8)	Tesla	Heavy-Duty Extended Range	Long Haul Heavy-Duty, Short Haul Heavy-Duty
Electricity	Heavy-Duty Vehicles (Class 7-8)	BYD	T9	Long Haul Heavy-Duty, Short Haul Heavy-Duty

Primary Fuel	Weight Class	Make	Model	Use Cases
Diesel	Medium-Duty Vehicles (Class 3-6)	Ford	E450 Super Duty Cab Chassis	Delivery Straight Truck-Light, Delivery Step Van – Light
Diesel	Medium-Duty Vehicles (Class 3-6)	Freightliner	M2 106 Cab Chassis	Delivery Straight Truck-Heavy
Diesel	Medium-Duty Vehicles (Class 3-6)	Freightliner	MT55 Step Van	Delivery Step Van- Heavy
Electricity	Medium-Duty Vehicles (Class 3-6)	Ford	E-450 Epic 4 Dearborn 120kWh	Delivery Straight Truck-Light, Delivery Step Van-Light
Electricity	Medium Duty Vehicles (Class 3-6)	Workhorse	E-100 Step Van	Delivery Straight Truck-Heavy, Delivery Step Van-Heavy
Diesel	Medium Duty Vehicles (Class 3-6)	Ford	Transit HD Cargo Van	Cargo Van
Electricity	Medium Duty Vehicles (Class 3-6)	Ford	Transit HD Cargo Van 86kWh	Cargo Van
Diesel	Medium Duty Vehicles (Class 3-6)	Ottawa	T2	Terminal Tractor
Electricity	Medium Duty Vehicles (Class 3-6)	Orange EV	T-Series N Standard Duty	Terminal Tractor

VEHICLE USE CASES

Medium- and heavy-duty vehicles are used in a wide range of applications which are typified by different model specifications and duty cycles. To capture the range of typical uses for medium- and heavy-duty vehicles, eight use cases were defined for this analysis. Each use case is defined by different vehicle models and yearly VMT. A brief description of each use case is included below along with a table listing the vehicle models and VMT for each use case. Yearly VMT for each use case is based upon figures from the AFLEET tool produced by Argonne National Lab. As mentioned previously, this analysis is not intended as a specific model-by-model comparison of vehicles, but rather as a generalized analysis of the total cost of ownership for diesel and electric vehicles when used for various purposes.

- **Long Haul Heavy-Duty:** Based upon survey responses and background research, the Long Haul Heavy-Duty use case covers heavy-duty vehicles used to transport freight over long distances. This use case is characterized by heavy utilization with daily distance traveled in excess of 400 miles.
- **Short Haul Heavy-Duty**: The Short Haul Heavy-Duty use case was included to cover heavy-duty vehicles used to transport freight regionally over shorter distances. This use case is characterized

by heavy utilization, though not as intensive as Long Haul Heavy-Duty, with daily distance traveled in excess of 200 miles, but fewer than 400.

- **Terminal Tractor**: Terminal Tractors, also known as yard trucks or spotter trucks, are used to transport truck trailers around warehouse facilities or cargo yards and are utilized frequently by freight companies. The Terminal Tractor use case is characterized by heavy utilization, long duty cycles, but low average yearly mileage. These tractors are often not used on highways and are restricted to the facility where they operate.
- **Delivery Step Van - Cab Chassis Light**: A typical use for medium-duty vehicles in the freight and retail sector is as a delivery step van. These vehicles are often used for local deliveries between a centralized depot and their final destination, typically traveling on set routes for fewer than 100 miles per day. These vehicles come in a variety of specifications and this use case covers options for smaller delivery step van models.
- **Delivery Step Van - Cab Chassis Heavy**: The characteristics of the Delivery Step Van - Cab Chassis Heavy use case are the same as the Delivery Step Van - Cab Chassis Light use case. This use case covers options for larger delivery step van models.
- **Delivery Straight Truck - Cab Chassis Light**: Another typical use for medium-duty vehicles in the freight and retail sector is as a delivery straight truck or box truck. These vehicles are often used for transport of smaller shipments of freight between distribution centers and their retail destinations and typically travel fewer than 100 miles per day. These vehicles come in a variety of specifications and this use case covers options for smaller delivery straight truck models.
- **Delivery Straight Truck - Cab Chassis Heavy**: The characteristics of the Delivery Straight Truck - Cab Chassis Heavy use case are the same as the Delivery Straight Truck - Cab Chassis Light use case. This use case covers options for larger delivery straight truck models.
- **Cargo Van**: Similar to delivery step vans, cargo vans are typically used for local last-mile deliveries. The capacity of cargo vans is usually smaller than that of step vans and they are often less expensive and in a lower weight class. These vehicles typically travel fewer than 100 miles per day.

Throughout the report, the use cases defined in Table 2 are used as shorthand for the vehicle type and yearly VMT.

TABLE 2: WEIGHT CLASS AND YEARLY VMT OF USE CASES

Use Cases	Weight Class	Yearly VMT	
Long Haul Heavy-Duty	Heavy-Duty Vehicles (Class 7-8)	170,000	
Short Haul Heavy-Duty	Heavy-Duty Vehicles (Class 7-8)	65,000	
Terminal Tractor	Heavy-Duty Vehicles (Class 7-8)	31,500*	

Use Cases	Weight Class	Yearly VMT	
Delivery Straight Truck – Cab Chassis Light	Medium Duty Vehicles (Class 3-6)	23,000	
Delivery Straight Truck – Cab Chassis Heavy	Medium Duty Vehicles (Class 3-6)	23,000	
Delivery Step Van – Cab Chassis Light	Medium Duty Vehicles (Class 3-6)	16,500	
Delivery Step Van – Cab Chassis Heavy	Medium Duty Vehicles (Class 3-6)	16,500	
Cargo Van	Medium Duty Vehicles (Class 3-6)	27,000	

**Terminal Tractor VMT is calculated based upon average yearly diesel usage, not distance traveled*

SENSITIVITY VARIABLES

The primary purpose of the multivariate analysis was to provide insight into two issues for stakeholders interested in incorporating electric medium- and heavy-duty vehicles into their shipping fleets. First, the analysis would provide an overall picture of the likelihood that EVs would be cost competitive with their diesel counterparts. Second, it would demonstrate which factors in a procurement were most critical to make EVs cost competitive. A strength of the multivariate analysis approach is that it provides granular information on the effects of specific factors on a vehicle's total cost of ownership.

After extensive background research and data gathering efforts, several factors were identified that could provide insight into the sensitivity of the total cost of ownership for EVs under plausible scenarios. These variables were intended to change the procurement parameters within the use cases established above and the reasoning behind their inclusion is detailed below. A full list of modeling inputs is included in 45.

- **Charging Strategy:** Charging strategies included depot charging, where the EV owner would purchase charging equipment and charge vehicles during downtime, public charging, where the EV owner would avoid the upfront cost of charging installation and charge only at public stations for a higher price, or an equal split of depot and public charging. Public charging station power was assumed to be 350 kilowatts. One key difference between depot and public charging is the cost of downtime for the time required to charge vehicles. For depot charging, the analysis assumed that all charging would occur during normal vehicle downtime and thus would not incur an additional cost for downtime. For public charging, the analysis assumed that this would occur during normal operating hours and thus would incur an additional cost for time spent charging vehicles. The cost used for charging time was the inflation adjusted hourly rate used by the Federal Highway Administration to calculate the cost of transportation time lost due to traffic.

- Charging Station Power: If a scenario included depot charging, then the charging station power had to be defined. Both a lower and higher power charging option were included to demonstrate the cost differential between a cheaper charging option that was slower and a more expensive charging option which offered increased charging speeds.
- Number of Charing Stations: Like charging station power, the number of charging stations procured was included as an additional input for scenarios that included depot charging. Several options were included to demonstrate the effect of reducing the number of charging stations in order to save cost but have less charging availability.
- Charging Cost: The cost to charge vehicles on a price per kilowatt-hour basis, both for depot and public charging, helped to model regional differences in electricity prices. The price for depot charging was assumed to be the average price of electricity (including fixed and variable costs) in the United States in 2018 ($0.117 per kilowatt-hour). The price for public charging was assumed to be the average price derived from available public charging services in 2018 ($0.50 per kilowatt-hour). States with lower electricity prices or charging service providers with lower costs than those modeled would likely see more cost-competitive results. Daily variations in charging rates, such as higher prices during peak hours, were not modeled. An estimate of electricity surcharges, such as demand charges, was included in the operating costs of each charging station, but variations in these charges and strategies to reduce them were also not modeled.
- Vehicle Incentives: As discussed in the *State of Medium- and Heavy-Duty Electrification,* several states have implemented programs which offer vouchers for anyone purchasing a qualified medium- or heavy-duty EV. To model the effect of these vouchers and demonstrate how public policy can affect the decision to purchase an EV, the voucher amounts from the New York Vehicle Incentive Program were included for eligible vehicles. For the Tesla Semi, the vehicle incentive included was the standard rebate for heavy-duty EVs available in Colorado.
- Maintenance Cost Reductions: One benefit of EVs is the reduced maintenance costs in part due to fewer moving parts in the electric drivetrain. An electric drivetrain requires no regular oil changes, uses a much simpler transmission which requires less maintenance, and can take advantage of regenerative braking to charge the batteries while avoiding any wear on brake pads. Under ideal conditions, there are significant reductions in maintenance costs. Scenarios which limited maintenance savings were also included to account for the additional downtime encountered when learning how to maintain a new piece of equipment and the potential slow development of a reliable nationwide network of trained maintenance staff. Maintenance costs for both EVs and diesel vehicles did not include the cost of replacement tires.
- Diesel Price: Diesel price captured both regional differences in the price of diesel as well as the effect of potential carbon taxes (via increased diesel cost). Scenarios with both high diesel cost and carbon taxes were not modeled. Diesel price was assumed to be the average price of diesel in the United States in 2018 ($3.36 per gallon). Variations of plus or minus 30 percent of this price were included as well. Scenarios involving fluctuations in both diesel price and carbon taxes were not explored. This was the only modeling input that applied specifically to diesel vehicles and was intended to highlight the effect of differential fuel cost between electric and diesel vehicles.
- Manufacturer Suggested Retail Price (MSRP) Reductions: As mentioned in the Background discussion of the *State of Medium- and Heavy-Duty Electrification,* battery costs for EVs as well as battery density are expected to continue falling in the future. Batteries can represent a majority of the costs of an electric vehicle, so as their costs fall there should be a proportionate fall in vehicle prices. To demonstrate the effect of any reductions in MSRP, either as the result of decreased input costs or volume discounts from a large order, the upfront cost of EVs was varied by 10, 20, and 30 percent. A baseline case of no reduction in MSRP was also included.

- **Years of Ownership:** Based on previous research and interviews with industry representatives, the term of ownership was identified as an important potential factor in comparing total cost of ownership between electric and diesel vehicles. EVs typically offer operational cost savings and higher upfront costs, so the payback period is an important factor to explore in order to assess EV owners' ability to recoup potential higher upfront costs.
- **Procurement Method:** A unique strength of the Fleet Procurement Analysis Tool is that it allows users to model a number of different procurement methodologies. Two likely procurement methods were selected, a lease agreement and cash purchase, to model total cost of ownership effect on electric and diesel vehicle procurements.

TOTAL COST OF OWNERSHIP ANALYSIS RESULTS

This section will focus on the results of the multivariate analysis that was detailed in the *Analysis Methodology* section along with key takeaways and data visualizations. The discussion of results will be broken down into three sections. First, the overall total cost of ownership results for electric and diesel vehicle procurements will be compared to determine the likelihood of EVs being cost competitive with diesel vehicles. Second, a distribution of the nominal cost per mile (CPM) of various elements of electric and diesel vehicle procurements will be analyzed to demonstrate the most relevant cost components of electric and diesel vehicles. Finally, an in-depth analysis will be performed on each sensitivity variable included in the analysis to determine the relative effect on the cost competitiveness of EVs.

The analysis included the complete set of possible sensitivity variable combinations for each use case described in the *Analysis Methodology* section and 41,148 scenarios in total were analyzed. This included 14 vehicles from eight manufacturers separated into eight use cases and 10 sensitivity variables. Results are given as the net present value (NPV) of the lifetime total cost of ownership of each procurement scenario where the discount rate is set at 8 percent. The size of the procurement in each scenario was 10 vehicles.

LIKELIHOOD OF EV COST COMPETITIVENESS

Cost Competitive EV Procurements Difficult but Achievable Under Current Market Conditions

The overall likelihood of EVs being cost competitive with diesel vehicles under the procurement scenarios analyzed was low with roughly 15 percent of all scenarios being identified as cost competitive. However, when EV procurements are specifically designed to take advantage of local EV policies and maximize the advantages of reduced operating costs for EVs, EVs can be substantially less expensive than their diesel counterparts. Stark differences in TCO existed between scenarios depending on key factors like the charging strategy. Relying exclusively on depot charging was essential for an EV to be cost competitive. Simply limiting the scenarios to only those that included exclusively depot charging more than doubled the overall rate of EV cost competitiveness. Any scenario that included public charging, on the other hand, was highly unlikely to be cost competitive with less than one percent of scenarios achieving cost competitiveness. Of nearly equal importance was the presence of state vehicle incentives. Limiting the scenarios to only those that included exclusively depot charging and state incentives caused the overall rate of EV cost competitiveness to rise to nearly 50 percent. Other factors which significantly impacted EV cost competitiveness were having more than one vehicle per charging station (in cases that included depot charging), vehicle MSRP reductions from production efficiencies or technological advancements, and reduced electricity costs.

To provide an overall picture of the cost competitiveness of the EVs examined in this analysis, the likelihood of EV cost competitiveness was separated into six categories: Very Likely, Likely, Neither Likely nor Unlikely, Unlikely, Very Unlikely and Nearly Impossible. These likelihood categories were determined based upon the average percentage difference in total cost of ownership between an EV procurement and an equivalent diesel procurement. Electric and diesel vehicle procurements were matched based on common factors, such as use case, years of ownership, and procurement method, in order to create an apples-to-apples comparison for each scenario. The breakdown of the Likelihood categories is included in Table 3. A full breakdown of scenarios by likelihood and sensitivity variables is included in *Appendix C.*

TABLE 3: LIKELIHOOD CATEGORIES

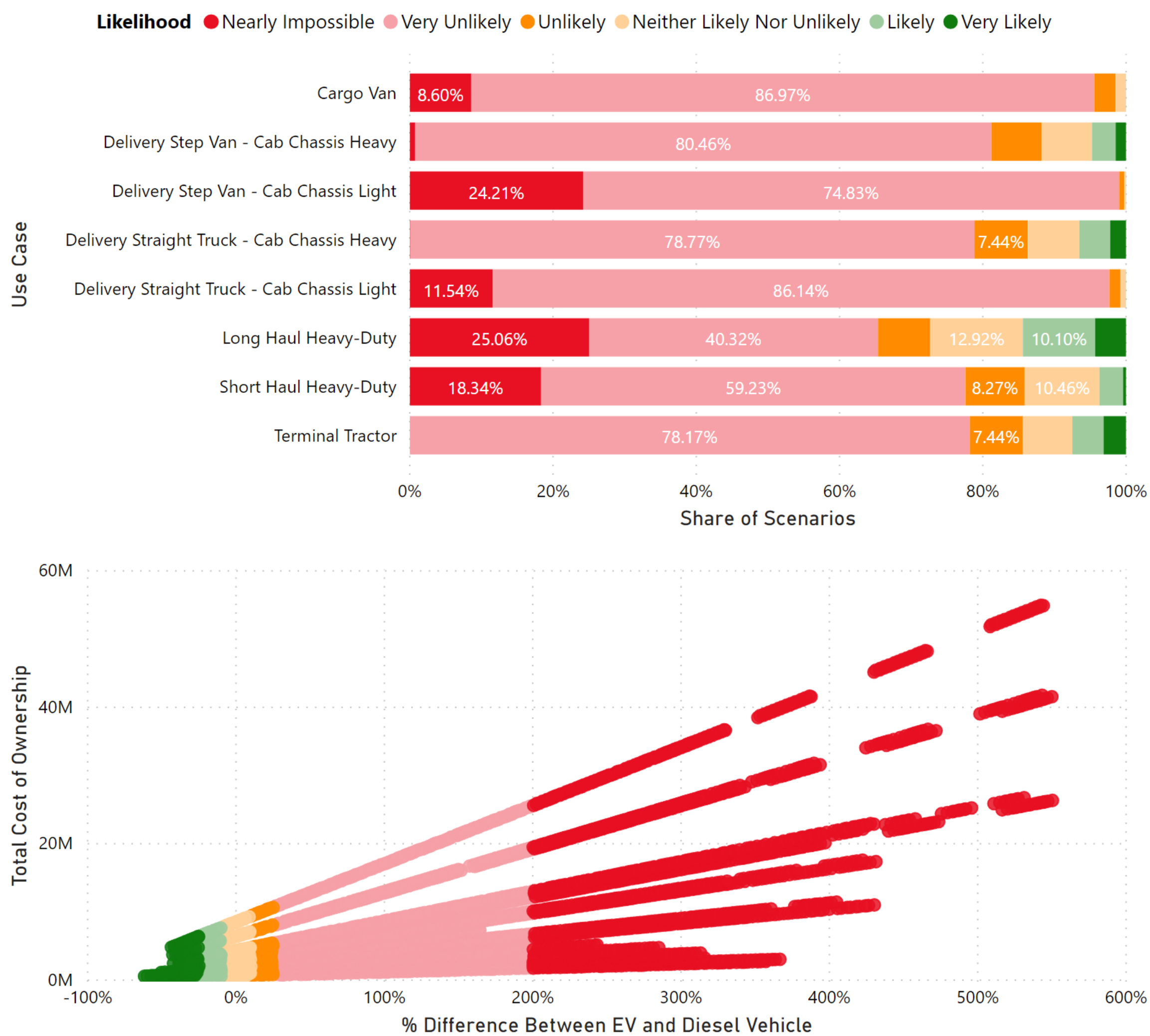
Likelihood Category	TCO Percentage Difference from Diesel Equivalent
Very Likely	At least 25% lower
Likely	Between 10% and 25% lower
Neither Likely nor Unlikely	Between 10% lower and 10% higher
Unlikely	Between 10% and 25% higher
Very Unlikely	Between 25% and 200% higher
Nearly Impossible	More than 200% higher

FULL RANGE OF SCENARIO RESULTS

The full range of TCO results demonstrates that EVs are potentially cost competitive under at least some procurement scenarios for every use case, but most often EVs will likely have a considerably higher TCO under present market conditions. The likelihood that medium- and heavy-duty EVs will be cost competitive with their diesel counterparts is highly dependent on vehicle use case with the most promising use case also having the widest range between total cost of ownership results.

The ranges between the results for a given use case are directly related to the rate of utilization of vehicles as measured in yearly miles traveled; the intended use of a vehicle must be considered when weighing the potential benefits and costs of an EV procurement. As vehicles are more heavily utilized, any cost reductions offered by lower operating costs are amplified, but so too are any operating cost increases. In the most extreme case, the TCO for vehicles in the Long Haul Heavy-Duty use case ranged from under $3 million to nearly $55 million. This large range primarily depended on vehicles' charging costs, which can provide significant savings in some cases and increased costs in others. The figures referenced above for Long Haul Heavy-Duty EVs represent a respective 42 percent reduction and 543 percent increase from an equivalent diesel procurement. TCO ranges for the medium-duty use cases analyzed are considerably smaller due to their relatively lower rates of utilization.

FIGURE 5: LIKELIHOOD RESULTS FOR ALL EV SCENARIOS



The above figures show the likelihood results for all scenarios by use case as well as the TCO of each scenario analyzed. The legend for both figures is the same. Each dot of the scatterplot represents a single scenario. (Scenarios Shown: 40,608)

Figure 5 shows the makeup of all likelihood results for each use case and is accompanied by a scatterplot showing both the likelihood of an EV having a lower TCO than a diesel vehicle and the TCO for each of the over 40,000 scenarios analyzed for EVs. As the figure demonstrates, the expectation when entering into an average EV procurement (as defined by this analysis) would not yield a cost savings on a TCO basis under present market conditions. However, there are a set of scenarios where EVs have a lower TCO than an equivalent diesel vehicle, such as those with depot charging, reduced electricity costs, and state EV incentives. The analysis intentionally covered a broad range of possibilities to capture both optimistic and pessimistic scenarios for EV procurements and in the following subsections, these specific scenarios will be analyzed to determine the likelihood of EVs being cost competitive under potential sets of circumstances. These circumstances, while wide ranging, did not cover factors such as carbon taxes, consumer interest on companies to electrify, societal costs and benefits from reduced emissions, public relations benefits for early adopters, daily variations in charging rates, EV-specific charging rates, and incentives for charging infrastructure among others.

COST COMPETITIVE PROCUREMENT SCENARIOS

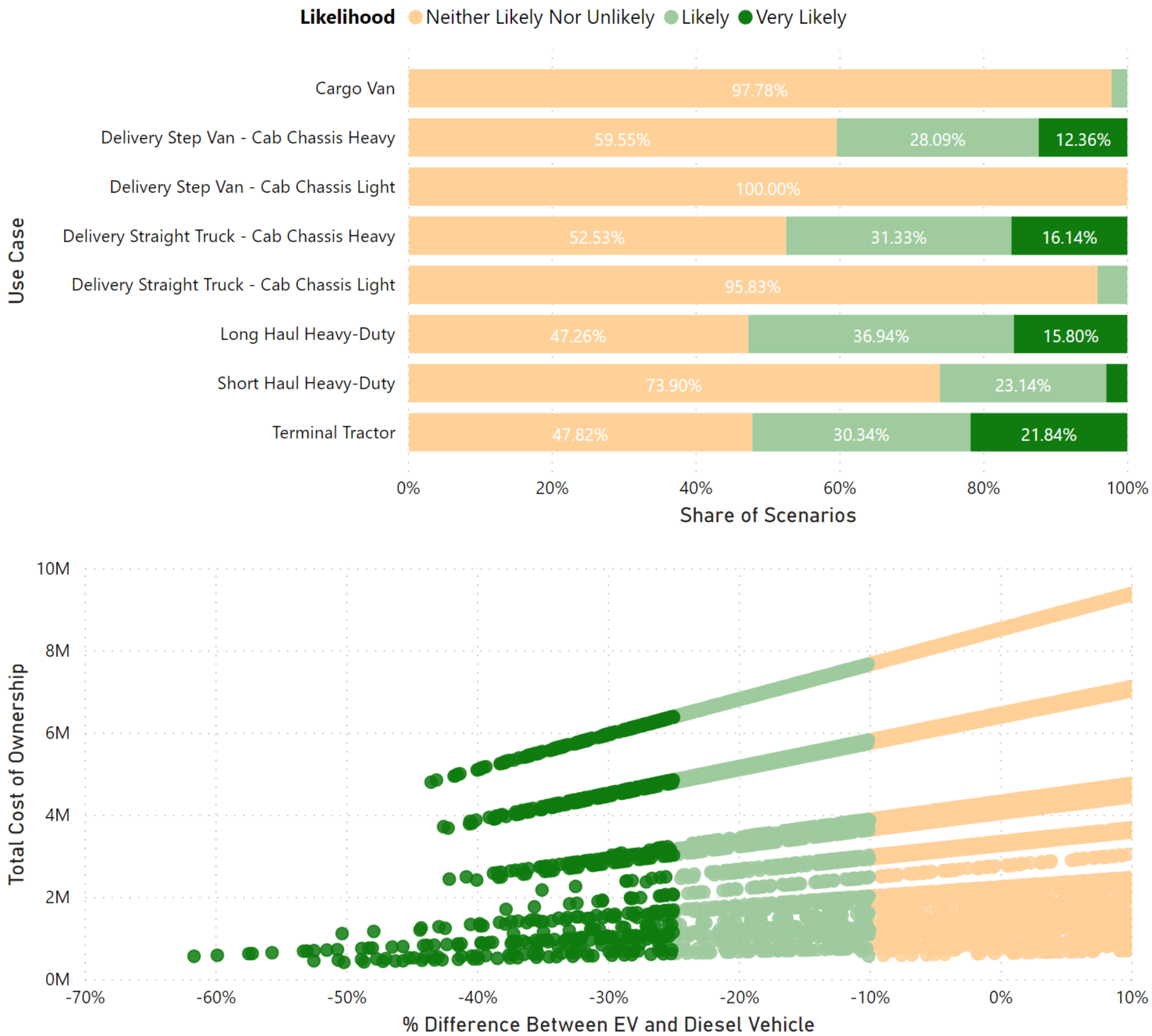
This section will explore the scenarios identified as Very Likely, Likely, and Neither Likely nor Unlikely identified above. These scenarios, identified in this paper as cost competitive, were typified by the following procurement elements:

- Depot charging
- More than one vehicle per charging station
- Reduced electricity costs
- State EV incentives
- EV MSRP reductions
- Maintenance cost reductions for EVS

Scenarios which achieve greater TCO reductions typically include either a greater number of the procurement aspects listed above or a greater degree, such as in the case of a 30 percent MSRP reduction as opposed to a 20 percent reduction. While it is highly unlikely that a present-day medium- or heavy-duty EV procurement meets every favorable condition, a sufficient number of favorable conditions can reasonably be met to make an EV cost competitive in today's market. As the medium- and heavy-duty market matures and predicted cost reductions are achieved, the probability of meeting these necessary conditions should only increase [13].

Figure 6: Likelihood Results for Cost Competitive EV Scenarios shows the makeup of all likelihood results for each use case in a cost competitive procurement scenario and is accompanied by a scatterplot showing both the likelihood of an EV having a lower TCO than a diesel vehicle and the TCO for each of the cost competitive procurement scenarios.

FIGURE 6: LIKELIHOOD RESULTS FOR COST COMPETITIVE EV SCENARIOS



The above figures show the makeup of likelihood results for all EV scenarios that were cost competitive with diesel vehicles by use case as well as the TCO of each scenario analyzed. The legend for both figures is the same. Each dot of the scatterplot represents a single scenario. (Scenarios Shown: 5,493)

When EV procurements are specifically designed to take advantage of local EV policies and maximize the advantages of reduced operating costs for EVs, the case for medium- and heavy-duty fleet electrification becomes much stronger. Under these scenarios, the cost competitiveness of EVs changes dramatically with more than 40 percent of EV procurement scenarios having at least a 10 percent lower projected TCO compared to an equivalent diesel vehicle procurement, with more than 12 percent of scenarios exceeding a 25 percent TCO reduction. Although these projections are not guaranteed, they demonstrate that, under the right circumstances, EVs can be substantially less expensive than their diesel counterparts.

NON-COMPETITIVE PROCUREMENT SCENARIOS

This section will explore the scenarios identified as Unlikely, Very Unlikely, and Nearly Impossible. These scenarios, identified in this paper as non-competitive, were typified by the following set of procurement elements:

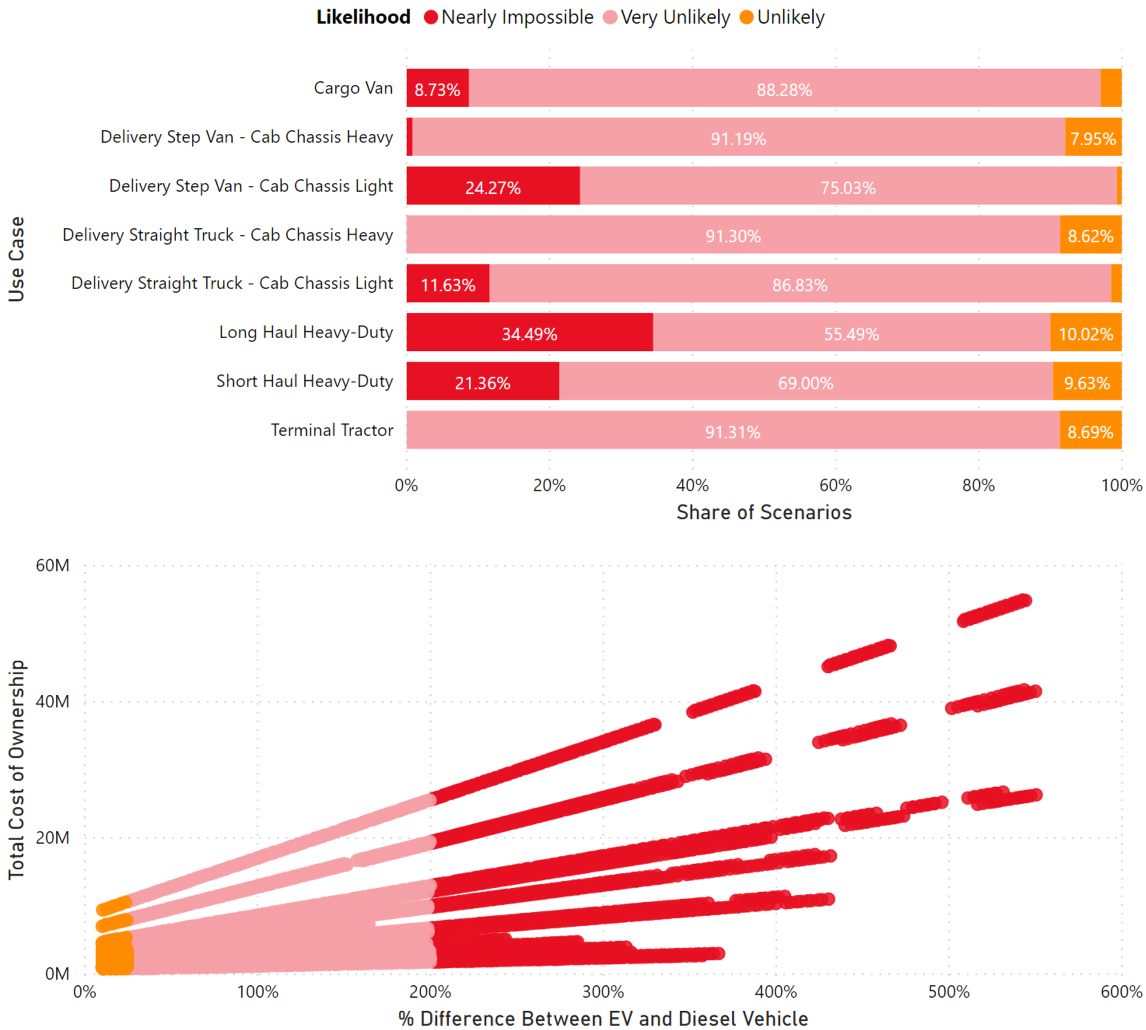
- Public charging or a mix of public and depot charging
- Increased electricity costs
- No state EV incentives
- No EV MSRP Reductions
- No Maintenance Cost Reductions for EVs

Scenarios with larger TCO increases typically include a greater number of the procurement aspects listed above. Unfortunately, the scenarios described above are typical of a present-day medium- or heavy-duty EV procurement. Only California and New York have active medium- and heavy-duty EV incentive programs, the maintenance network required to limit downtime for EVs is not widespread, and cost reductions resulting from technological advancements or production efficiencies are likely to come in the near future but have not yet materialized. Until the conditions described above change, EV procurements will need to be carefully designed to avoid cost increases.

If an EV procurement does not properly account for the difference in costs associated with the various options for purchasing and operating an EV, there is a potential for substantial cost overruns when compared to a diesel vehicle procurement. In the worst cases, EVs have a projected total cost of ownership that is over 500 percent higher than a diesel equivalent; here, EVs are relying on more expensive public charging networks, which can cause the fuel cost for EVs to exceed that of diesel vehicles. When compounded by the increased vehicle costs for EVs and the cost of downtime associated with time spent charging vehicles, the increase in vehicle TCO can be substantial.

Figure 7 shows the makeup of all likelihood results for each use case under non-competitive procurement scenarios and is accompanied by a scatterplot showing both the likelihood of an EV having a lower TCO than a diesel vehicle and the TCO for each of the non-competitive procurement scenarios.

FIGURE 7: LIKELIHOOD RESULTS FOR NON-COMPETITIVE EV SCENARIOS



The above figures show the makeup of likelihood results for all EV scenarios that were not cost competitive with diesel vehicles by use case as well as the TCO of each scenario analyzed. The legend for both figures is the same. Each dot of the scatterplot represents a single scenario. (Scenarios Shown: 34,665)

COST PER MILE BREAKDOWN

Managing Charging Station and Charging Downtime Costs are Critical to Achieve EV Cost Competitiveness

The cost of lost productivity from time spent charging and charging station installation and operation cost are critical to determining the cost competitiveness of an EV. These two components can make up the majority of the total cost per mile for an EV and procurements must be designed such that they limit their influence.

The upfront vehicle cost, although in some cases substantial, was not as large a contributor to the average cost per mile as were the cost elements related to vehicle charging. Vehicle incentives and MSRP reductions were important to reduce the average total cost per mile, but not necessarily the deciding factor for the cost competitiveness of EVs.

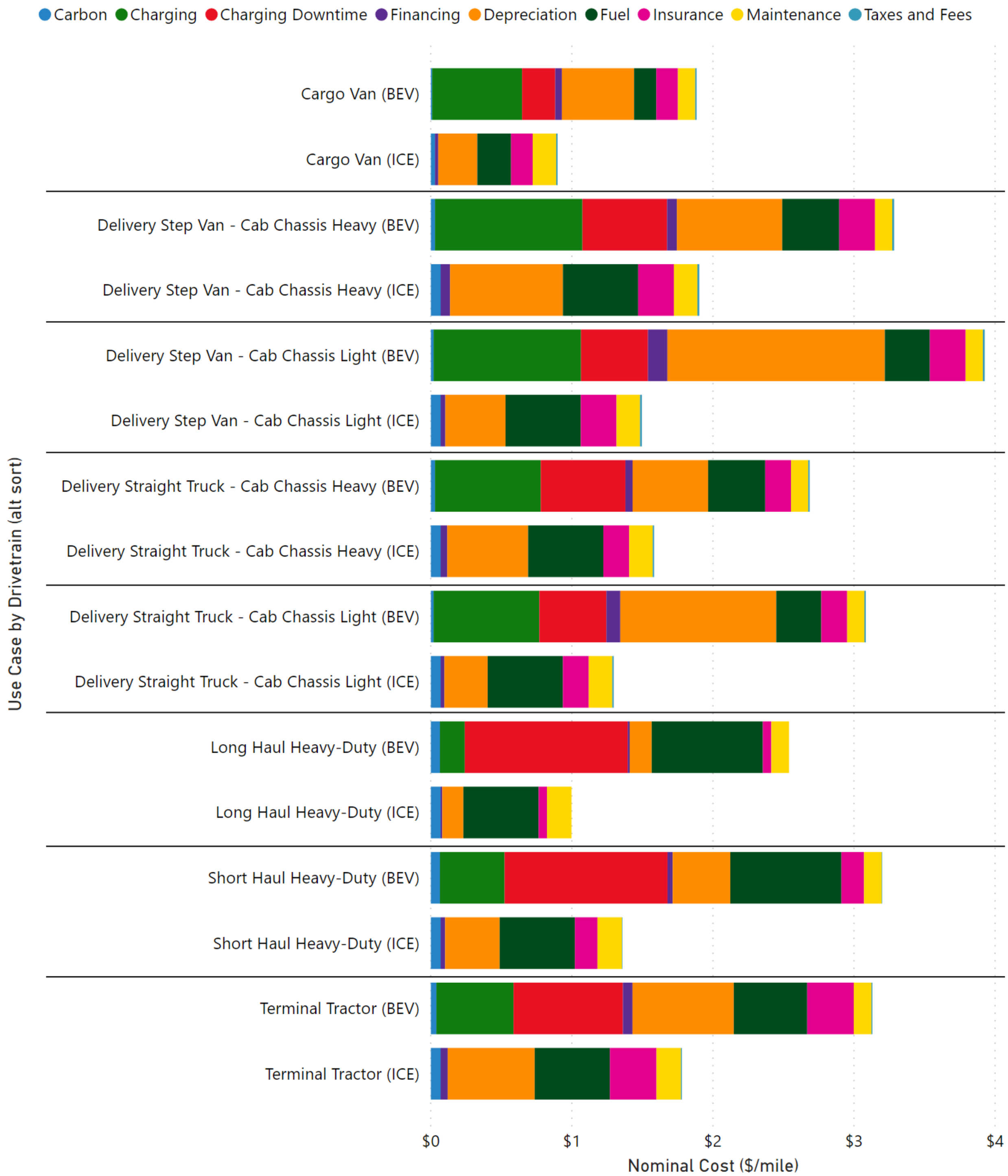
Finally, the differences in average cost per mile for fuel were not as stark as initially expected. Despite EVs being more fuel efficient than diesel vehicles, the analysis found that EV procurement scenarios which relied on public charging had higher average per-mile fuel costs than their diesel equivalents. Scenarios which relied exclusively on depot charging had lower average per-mile fuel costs. This finding reinforces the importance of vehicle charging strategies for EV procurements.

The nominal lifetime cost per mile (CPM) of a vehicle procurement, a key metric provided by the Fleet Procurement Analysis Tool, allows for a greater understanding of the difference between two procurements and the ability to gauge the relative importance of procurement variables on the overall total cost of ownership of a vehicle. This section of the paper explores the components of the CPM and identifies the most relevant cost components when comparing an EV procurement with its diesel equivalent.

In the scenarios analyzed, the average total CPM of EVs was higher than the average CPM of diesel vehicles in all use cases. In keeping with the results of our likelihood analysis in the previous section, the CPM results demonstrated that the average electric vehicle procurement was not cost competitive with its diesel counterpart and in some cases EVs were substantially more expensive. However, there were also many scenarios in which EVs were the cheaper option. The factors leading to these variances in the TCO between the two types of vehicles were numerous, but several key elements emerged as the primary drivers of cost differences.

Figure 8 is a comparison of average nominal CPM between diesel and electric vehicles for all scenarios analyzed by vehicle use case and drivetrain; in this and subsequent graphs, the acronyms ICE (internal combustion vehicle) and BEV (battery electric vehicle) denote diesel and electric vehicles, respectively.

FIGURE 8: AVERAGE CPM RESULTS FOR ALL EV AND DIESEL SCENARIOS



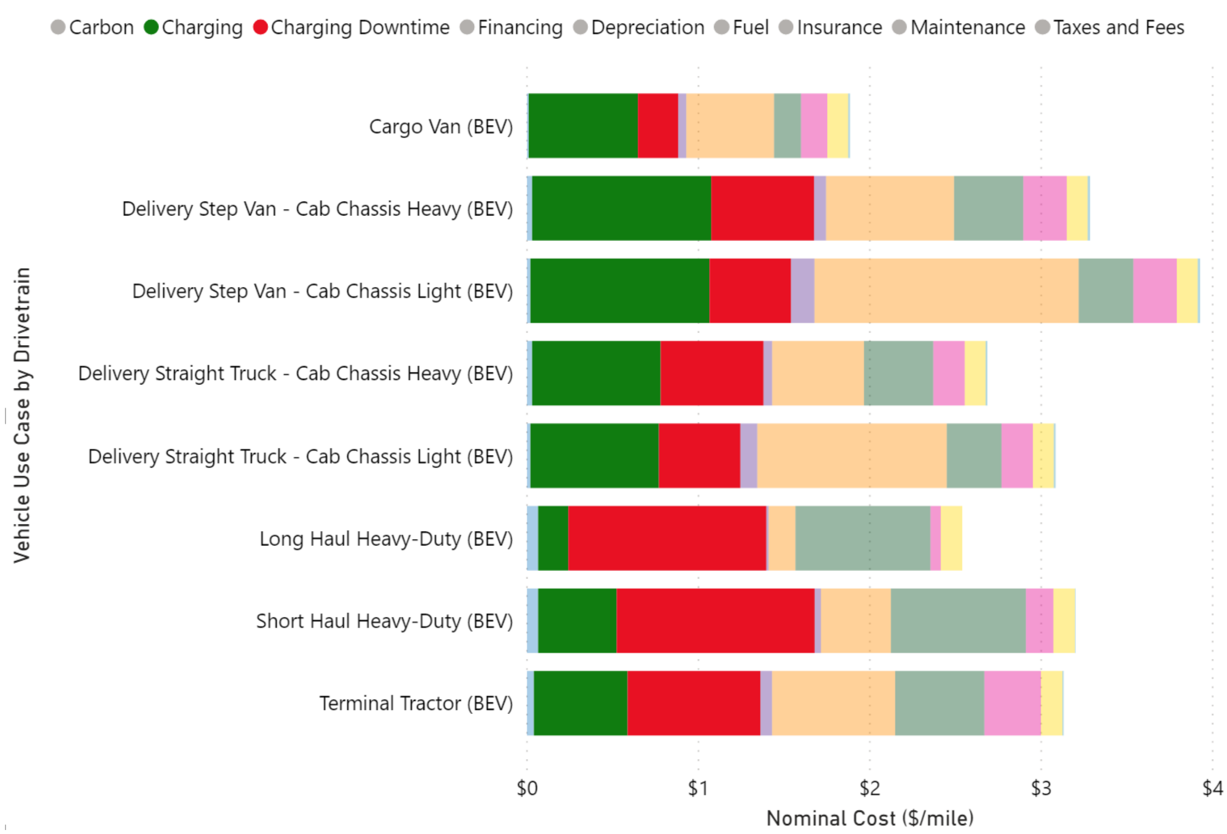
The chart above shows the average cost per mile by procurement component for all scenarios included in the analysis. The acronyms ICE (internal combustion engine) and BEV (battery electric vehicle) denote diesel vehicles and electric vehicles, respectively. (Scenarios Shown: 41,148)

The immediate takeaway is that EV procurements include additional cost components outside of diesel procurements which contribute substantially to the lifetime nominal cost per mile of a procurement. These cost components are the lost productivity time from charging (charging down time) and the charging station procurement (charging) and highlight the unique considerations necessary when purchasing an EV. It should be noted that all costs related to the purchasing, maintenance, and operation of charging infrastructure, except for the cost of electricity, are contained within the "Charging" cost category. Despite serving the same function, EV operations are distinctly different from diesel vehicles and these differences can offer both advantages and disadvantages.

CHARGING DOWNTIME AND CHARGING STATION COST

Charging down time, calculated as the hourly cost of lost productivity times the length of time EVs spend charging at public charging stations, and charging station procurement are, on average, the most important factors contributing to the CPM for electric vehicles. Importantly, the analysis assumes a worst case scenario in which charging at a public station would have to be done during normal working hours, so all charging time would come at the expense of productivity. This provides an upper bound on the cost of public charging downtime and could be minimized or eliminated if this charging were to occur during scheduled breaks or otherwise "off the clock" hours. Given the ability of diesel vehicles to refuel during regular short breaks, the cost of diesel fueling downtime was assumed to be zero.

FIGURE 9: AVERAGE CPM RESULTS FOR CHARGING DOWNTIME AND CHARGING STATION COST



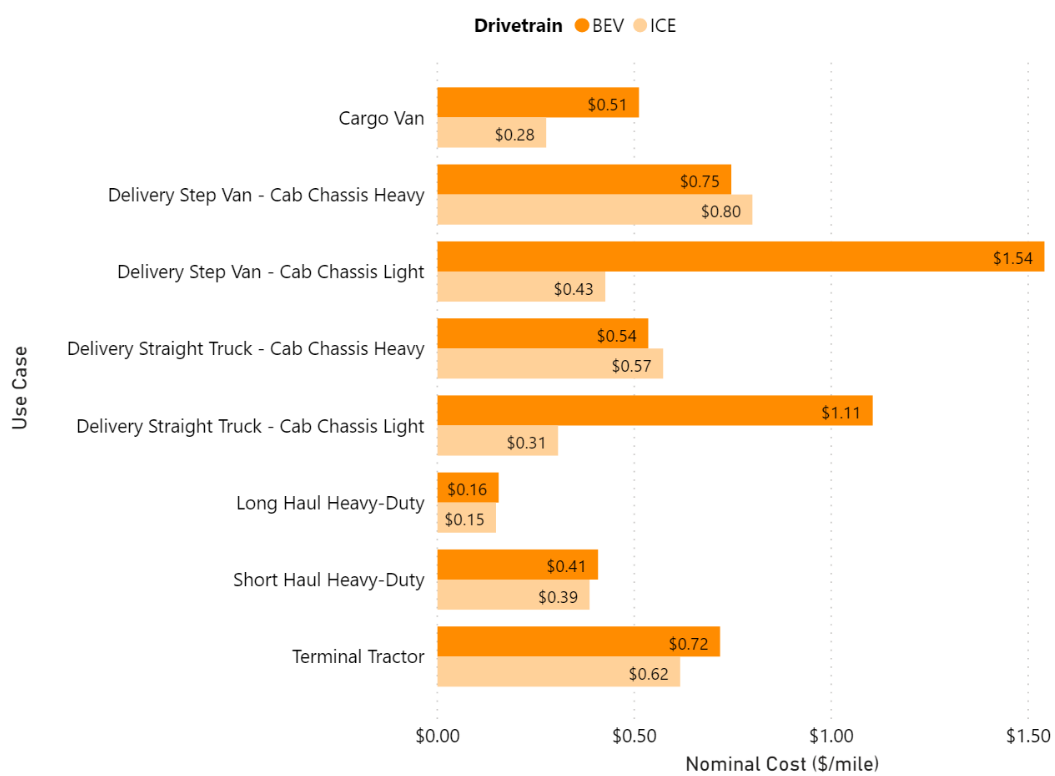
The chart above highlights the average cost per mile for charging downtime and charging station cost for EVs. (Scenarios Shown: 40,608)

In the case of Long and Short Haul Heavy-Duty vehicles, these two cost components account for more than 50 percent of the total cost per mile of these vehicles. These vehicles are used to carry heavy loads over long distances and require large battery packs; the battery pack for the Extended Range Tesla Semi is planned to be 950 kilowatt-hours which is eight to nine times larger than battery packs for the medium-duty EV models included in this analysis. These battery packs would take several hours to charge at a public charging station even with a charging station operating at 350 kilowatts and, as demonstrated by the large CPM of charging downtime, the value of that time is substantial. However, the greater the cost per mile, the greater the opportunity for cost savings; methods to reduce the cost of downtime and charging installation will be explored further in the next section, *Key Drivers of EV Cost Competitiveness*.

VEHICLE COST

Contrary to research gathered during the initial phases of this analysis, depreciation, the cost factor related to the upfront cost and residual value of an EV, was much closer to parity with diesel vehicles than initially expected. The cost of depreciation and the vehicle residual value included in this analysis are not based on real world data and were calculated based on the depreciation estimates from the AFLEET tool from Argonne National Laboratory. The market for medium- and heavy-duty EVs is in its infancy and resale values could vary substantially from those included in the analysis.

FIGURE 10: AVERAGE CPM RESULTS FOR VEHICLE DEPRECIATION COST



The chart above compares the average depreciation cost per mile for EV and diesel vehicle procurements. (Scenarios Shown: 41,148)

The upfront cost of vehicles is often cited as a key concern for companies interested in pursuing electrification of their vehicle fleets [28] and is a concern several states have sought to address via medium- and heavy-duty EV incentive programs. Although the average cost per mile related to the upfront cost of a vehicle, here defined as the depreciation cost category, is higher in all cases for electric vehicles, the difference is not striking outside of the Delivery Step Van- Cab Chassis Light and Delivery Straight Truck- Cab Chassis Light use cases. It should be noted that in both use cases mentioned above that the models selected were the most expensive versions of the EV models researched and less expensive models are available.

EV incentives, although highly important for bridging the gap between EV and diesel vehicle total cost of ownership, may not be strictly necessary for making EVs cost competitive. Depending on the utilization of the vehicle in question, any differences in upfront cost between EVs and diesel vehicles can be insignificant when considered over the lifetime of the vehicle.

Figure 10 shows the average depreciation cost per mile by drivetrain for each use case.

FUEL COST

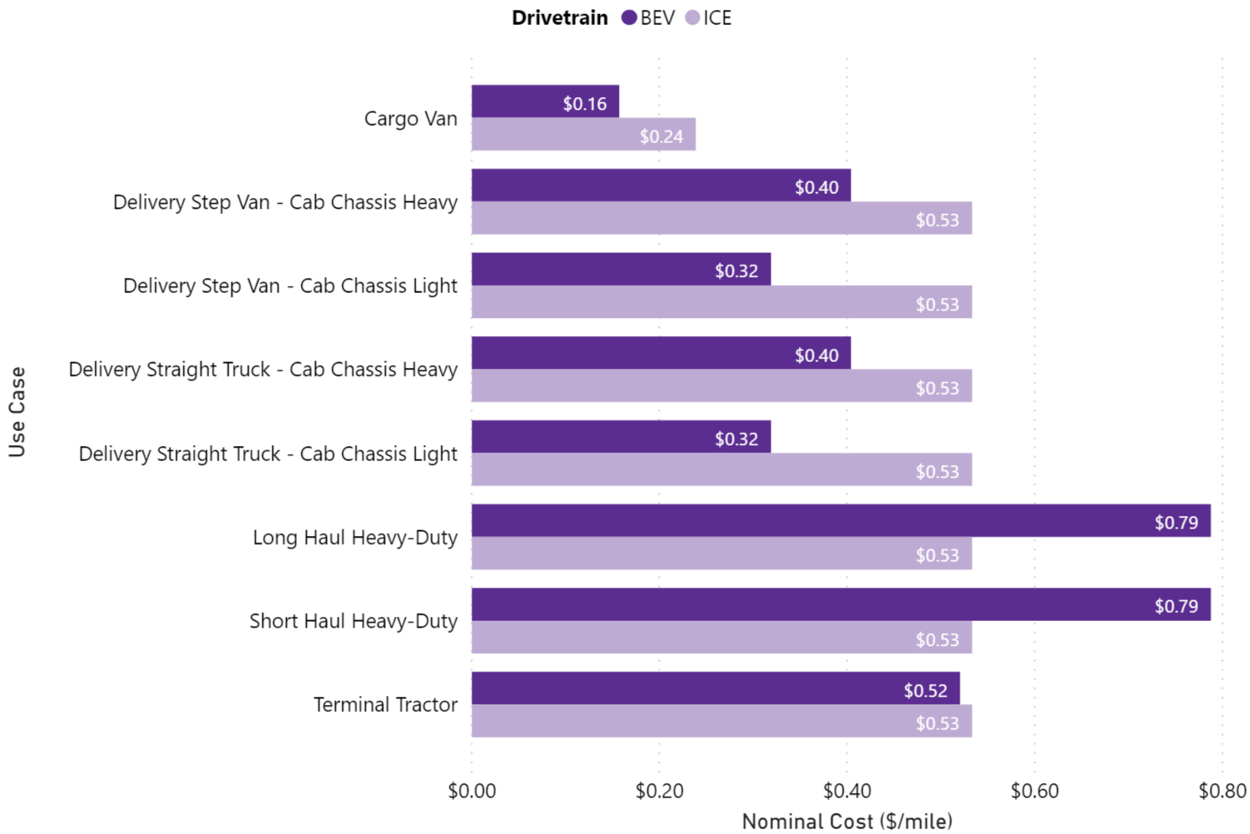
Another key takeaway from the cost per mile analysis is that fuel costs are not necessarily cheaper for electric vehicles. Rather than an indication of overall fuel costs for EVs, this highlights the difference in costs to charge EVs using depot charging versus using public charging infrastructure. The analysis found that EV procurement scenarios which relied exclusively on depot charging had lower average per-mile fuel costs than their diesel equivalent whereas scenarios which included public charging had higher average per-mile fuel costs. This finding is further explored in the *Charging Strategy* section.

Fuel costs in this analysis are calculated based upon the cost of the fuel itself, in this case electricity or diesel, and the fuel economy of the vehicles. Although the results demonstrate that, on average, fuel costs for all use cases other than Long and Short Haul Heavy-Duty are lower for EVs than diesel vehicles, the average fuel savings are only 40 percent in the best case, well below results from case studies which saw fuel cost savings between to 68 and 88 percent [18, 21, 20]. In the worst cases of Long and Short Haul Heavy-Duty vehicles, average cost per mile for fuel was over 45 percent greater. At face value, electricity costs less than diesel fuel on an energy equivalent basis. However, small changes in the price per kilowatt-hour to charge a vehicle can quickly add up and even exceed the cost of diesel on a per-mile basis.

Given the historical stability of electricity prices relative to diesel prices [29], this threshold will almost certainly not be reached for any procurement which includes depot charging. As a result, depot charging was the preferable option for almost any EV procurement in this analysis. Procurements that rely on public charging infrastructure, however, will pay considerably more to charge vehicles as the price would reflect not just the cost of electricity, but also the depreciation on the charging station, operating overhead, and the profit margin of the charging service provider. The total of these costs can result in EVs being more expensive to fuel than diesel vehicles.

For electric vehicles to be cost competitive with diesel vehicles it will be critical to manage fueling costs, such as by adopting a depot charging strategy, such that the cost of charging an electric vehicle is always lower than the cost of refueling an equivalent diesel vehicle. Otherwise, the fuel efficiency of electric vehicles, often touted as one of the main benefits of transportation electrification, will be negated by fuel price. Figure 11 shows the average fuel cost per mile by drivetrain for each use case.

FIGURE 11: AVERAGE CPM RESULTS FOR FUEL COST



The chart above compares the average fuel cost per mile for EV and diesel vehicle procurements. (Scenarios Shown: 41,148)

KEY DRIVERS OF EV COST COMPETITIVENESS

Depot Charging and Vehicle Incentives Drive EV Cost Competitiveness; Maintenance Savings and Procurement Strategy Less Important

The choice to rely exclusively on depot charging was critical to achieving a lower projected TCO for EVs. The effect of charging options was greatest for use cases with heavy rates of vehicle utilization as it allowed for significant reductions in operating cost. For vehicles with lower rates of utilization, charging strategy was still the most important for determining EV cost competitiveness, but to a lesser degree.

EV incentives were the next most important factor for determining EV cost competitiveness. Although not strictly necessary for EVs to be cost competitive, the presence of vehicle incentives produced marked reductions in the TCO of EVs particularly for vehicles with low rates of utilization that were more sensitive to changes in fixed upfront costs. Technological advancements which could result in MSRP reductions offered similar, albeit smaller, reductions in TCO. However, these MSRP reductions would apply to EVs nationwide, thus opening up the market for medium- and heavy-duty EVs beyond the few states which offer generous EV incentive programs.

The TCO of diesel vehicles was more sensitive than EVs to equivalent percentage swings in fuel cost. Given the historic volatility of diesel prices compared to electricity prices, fluctuations in the price of fuel represent a greater risk to diesel vehicle procurements.

Reductions in maintenance cost for EVs, years of ownership, and procurement method offered small TCO reductions relative to other procurement elements and were not a significant factor in determining the cost competitiveness of EVs in this analysis.

In this section, the relative effect of each of the sensitivity variables described in the *Analysis Methodology* section on TCO will be investigated to determine which factors play the largest roles in the likelihood of EVs being cost competitive with their diesel counterparts. This level of analysis would be most useful for individuals responsible for implementing a vehicle procurement, as it details the changes in TCO that result from different procurement options. For the purposes of this analysis, procurement options have been grouped together based upon the area of the procurement which they affect, including charging, market, technology, procurement, and diesel price. Although not identified as a sensitivity variable, the effect of vehicle use case will also be examined.

As mentioned in the *Analysis Methodology* section, each purpose that medium- and heavy-duty vehicles serve necessitates either a different type of vehicle model or level of utilization. These variations in models and duty-cycles make the TCO for each procurement vary greatly; what works for one vehicle may not work for another.

In general, the trends observed in the results indicate that for use cases involving heavier vehicle utilization, the most relevant procurement elements were related to vehicle operation such as electricity cost and charging strategy whereas use cases involving lighter utilization were more affected by elements which affected upfront cost such as EV incentives, MSRP reductions, or the number of charging stations to procure. As vehicles are more heavily utilized, the share of the total cost of ownership related to operating costs grows and can even exceed the upfront fixed costs.

To demonstrate the range in results between use cases, each of the variables investigated below will include results from the use case with the highest rate of utilization, Long Haul Heavy-Duty at 170,000 yearly VMT, and the use case with the lowest rate of utilization, Delivery Step Van at 16,500 yearly VMT.

VEHICLE CHARGING

The results of this analysis show that vehicle charging could be the most important factor in determining the cost competitiveness of medium- and heavy-duty EVs. As a result, a primary focus for fleets interested in incorporating medium- or heavy-duty EVs should be their vehicle charging strategy. Detailed knowledge and planning around vehicle duty-cycles, daily range, charging availability, and charging station installation and operation will be necessary to increase the likelihood of achieving cost savings from an EV procurement. The sensitivity variables discussed below evaluate the effect of charging strategies along with variations in the price of electricity.

Importantly, if depot charging is used in a procurement, many of the costs for the charging infrastructure can be used for more than the first procurement. That is, the construction and electrical upgrades, along with the equipment in some cases, are not incurred in a subsequent procurement. This analysis did not consider procurements with depot charging that had no charging equipment and installation costs. One can estimate these costs by simply reducing or eliminating the CPM costs for charging.

CHARGING STRATEGY

The ability to recharge vehicles at a low cost per kilowatt-hour is paramount for achieving cost competitiveness for electric vehicles, particularly when vehicles are heavily utilized, such as the Long and Short Haul Heavy-Duty use cases. In this analysis, scenarios with depot charging had a significantly lower per-mile fuel cost than scenarios with only public charging and those with a combination of public and depot charging.[1] In fact, nearly 60 percent of procurement scenarios for Long Haul Heavy-Duty EVs that included depot charging were cost competitive with an equivalent diesel procurement while no scenarios involving public charging had a lower TCO. Further, the worst case scenario for a Long Haul Heavy-Duty EV procurement with depot charging was less expensive than the best case scenario for a Long Haul Heavy-Duty EV procurement which relied solely on public charging. The effect is less pronounced for vehicles that have lower annual mileage.

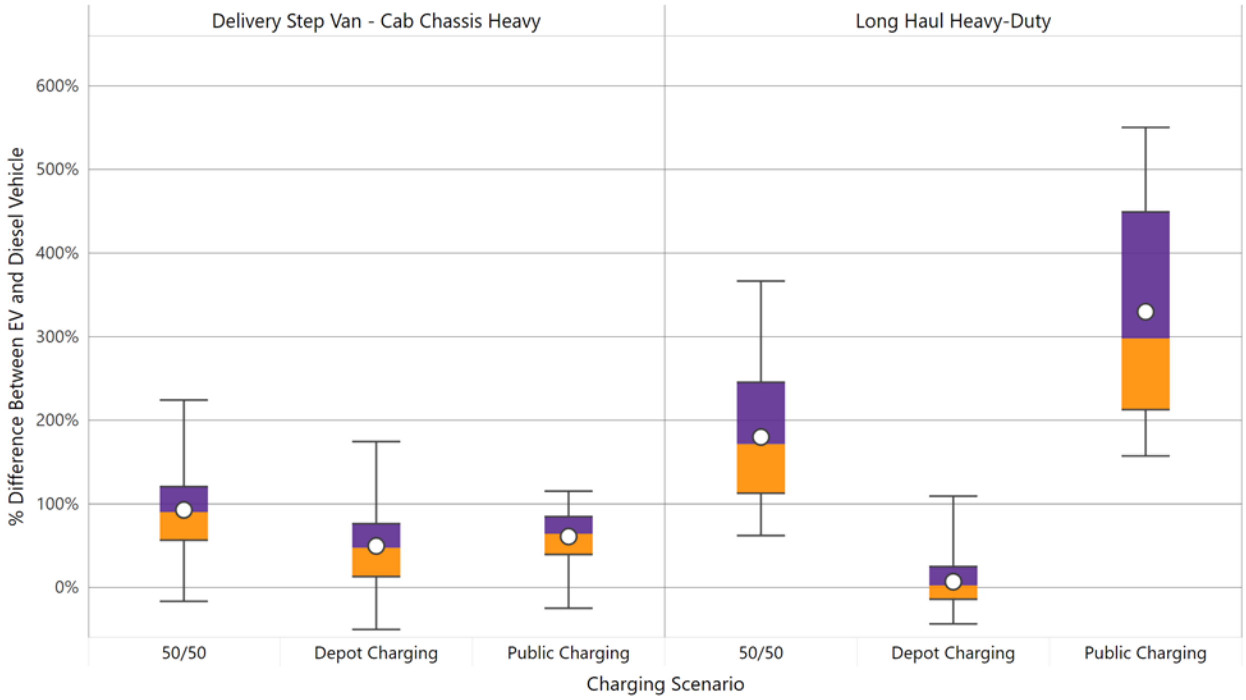
The ability to charge at a depot allows fleets to more easily take advantage of lower charging costs and avoid paying the higher cost for public charging present under current market conditions. Increasing the cost of electricity for a Long Haul Heavy Duty EV in this analysis by $0.04 per kilowatt-hour caused an increase in average TCO of nearly 14 percent, or over $850,000. In this analysis, the average charging costs at a public charging station were nearly $0.40 per kilowatt-hour higher than for depot charging.

As with other alternative fuels like natural gas, installing charging equipment on site is a common solution to achieve low cost refueling when public refueling is either scarce or prohibitively expensive to use exclusively. It also allows fleet operators to schedule vehicle charging that more easily takes advantage of regularly scheduled periods of downtime instead of devoting time to recharging that would otherwise be spent hauling freight. As demonstrated in the CPM results in the previous section, the cost related to vehicle downtime can account for a significant portion of the TCO for an EV and a depot charging solution offers the ability to avoid this cost.

[1] It is possible for entities to enter into bulk purchase agreements with public charging service providers and greatly reduce the cost per kilowatt-hour of the service. This concept was not explored in this report.

Figure 12 shows the effect of different charging strategies on the average percentage difference in TCO between electric and diesel vehicles for the Delivery Step Van – Cab Chassis Heavy and Long Haul Heavy-Duty use cases, the vehicles with the lowest and highest annual VMT, respectively.

FIGURE 12: EFFECT OF CHARGING STRATEGY ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This figure shows the change in the percentage difference in TCO between an EV and an equivalent diesel vehicle when varying the charging strategy for an EV procurement. The three options are for depot charging where vehicles would charge exclusively at charging stations included as part of the procurement, public charging where vehicles would rely solely on a public charging network, and 50/50 where charging is split equally between depot charging and public charging. The orange and purple shaded regions represent the second and third quartiles of scenarios, respectively. (Scenarios Show: 14,256)

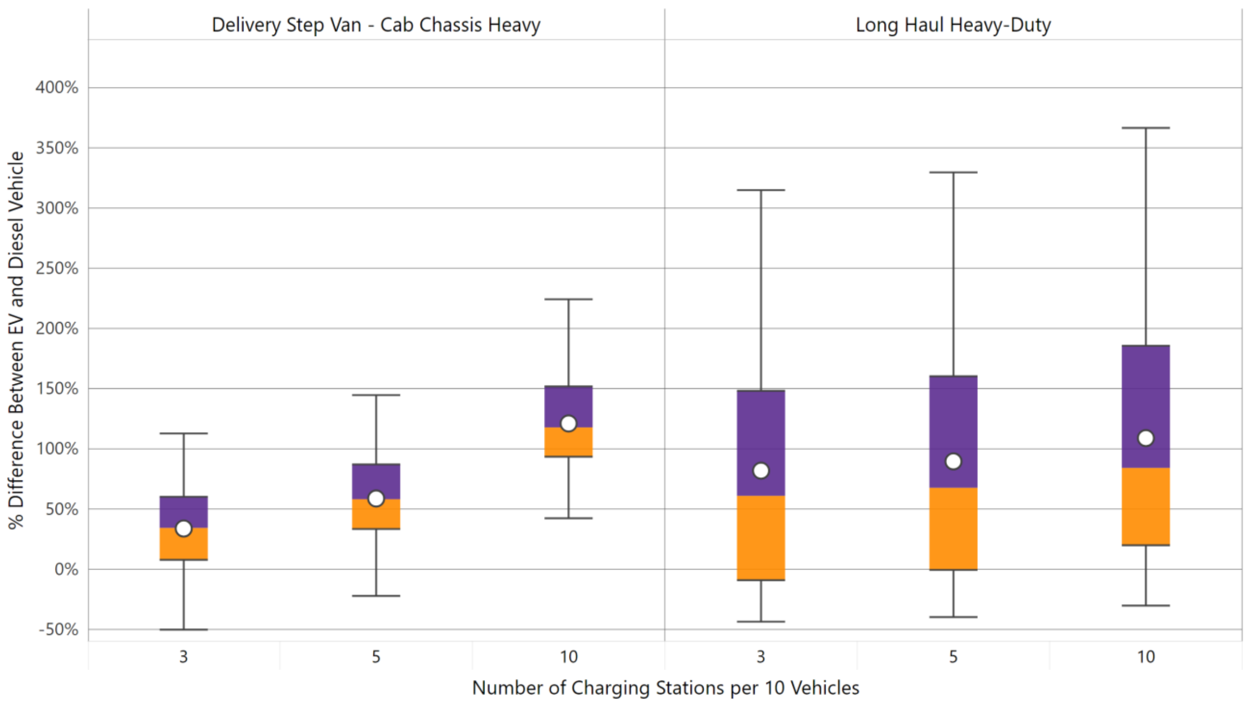
NUMBER OF CHARGING STATIONS

In general, the fewer charging stations needed for a procurement with depot charging, the lower the TCO. In the analysis results, this is most starkly evident in the case of Delivery Step Vans whose low rate of utilization made them sensitive to changes in fixed upfront costs. The average TCO of a Delivery Step Van – Cab Chassis Heavy procurement that included three charging stations was almost 40 percent lower than if the same procurement included 10 charging stations. For context, the difference in average TCO between Delivery Step Van – Cab Chassis Heavy scenarios that included a 50 percent vehicle incentive and those that did not was only 24 percent.

This result highlights a key advantage of depot charging in the ability to manage the number of charging stations needed in order to efficiently charge the EVs in the fleet. As mentioned above, detailed knowledge of vehicle duty-cycles and charging availability are critically important factors when considering an EV procurement. If the duty-cycle of a vehicle is such that there are several hours of downtime over the course of the day which would allow for vehicles to charge in a staggered manner, then significant savings can be achieved by using one station to charge two or three vehicles instead of only one EV. Across all scenarios that included depot charging, the number of potentially cost competitive scenarios increased by nearly 40 percent when going from five charging stations to three charging stations.

Figure 13 depicts the effect of the number of charging stations procured on the average percentage difference in TCO between electric and diesel vehicles for the Delivery Step Van – Cab Chassis Heavy and Long Haul Heavy-Duty use cases.

FIGURE 13: EFFECT OF CHARGING STATIONS NUMBER ON DIFFERENCE BETWEEN EV AND DIESEL TCO



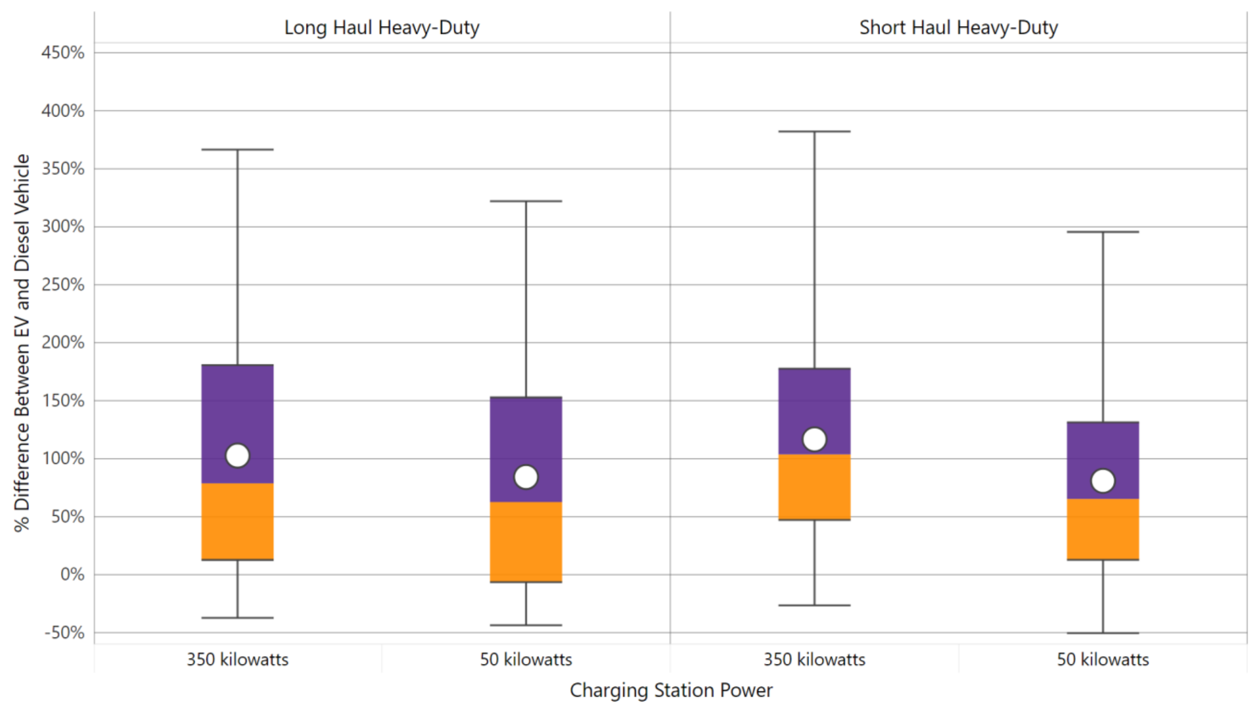
This figure shows the change in the percentage difference in TCO between an EV and an equivalent diesel vehicle when varying the number of charging stations for an EV procurement with depot charging. (Scenarios Shown: 12,960)

CHARGING STATION POWER

The choice between a 50 kilowatt fast charging station and a 350 kilowatt fast charging station depends on the charging needs of the fleet. A 50 kilowatt station costs considerably less for the equipment and the intensive power grid upgrades than a 350 kilowatt station but also takes much longer to fully recharge vehicles. The 350 kilowatt charging option included in this analysis is almost three times more expensive than the 50 kilowatt option, so a procurement scenario with 350 kilowatt charging stations will always be more expensive than one with the same number of 50 kilowatt stations. Even with the substantially increased cost of a 350 kilowatt charging station, there are scenarios in which the cost increase is less burdensome and time savings afforded by a 350 kilowatt charging station may be worth the additional cost. Although not examined in this analysis, the time savings afforded by a 350 kilowatt charging station could more than offset a moderate increase in TCO if there are significant constraints on the amount of vehicle downtime.

The analysis results show that if an EV is being utilized often enough to make 350 kilowatt charging a practical solution, then the effect on the TCO is insignificant compared to a 50 kilowatt charging station. However, this requires heavy utilization, as using a 350 kilowatt station resulted in an increase in the average TCO difference for Long Haul Heavy-Duty EVs of less than 18 percent whereas the increase for Short Haul Heavy-Duty EVs was more than 28 percent. Put differently, it required an increase of 105,000 in yearly VMT to minimize the effect of increased upfront costs for 350 kilowatt charging stations. It should be noted that all scenarios which included depot charging assumed that charging occurs during normal downtime, so it was not possible to account for any savings related to reduced time spent charging with the 350 kilowatt station.

FIGURE 14: EFFECT OF CHARGING STATION POWER ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This figure compares the percentage difference in TCO between an EV and an equivalent diesel vehicle when procuring 50 kilowatt charging stations and 350 kilowatt charging stations. (Scenarios Shown: 20,736)

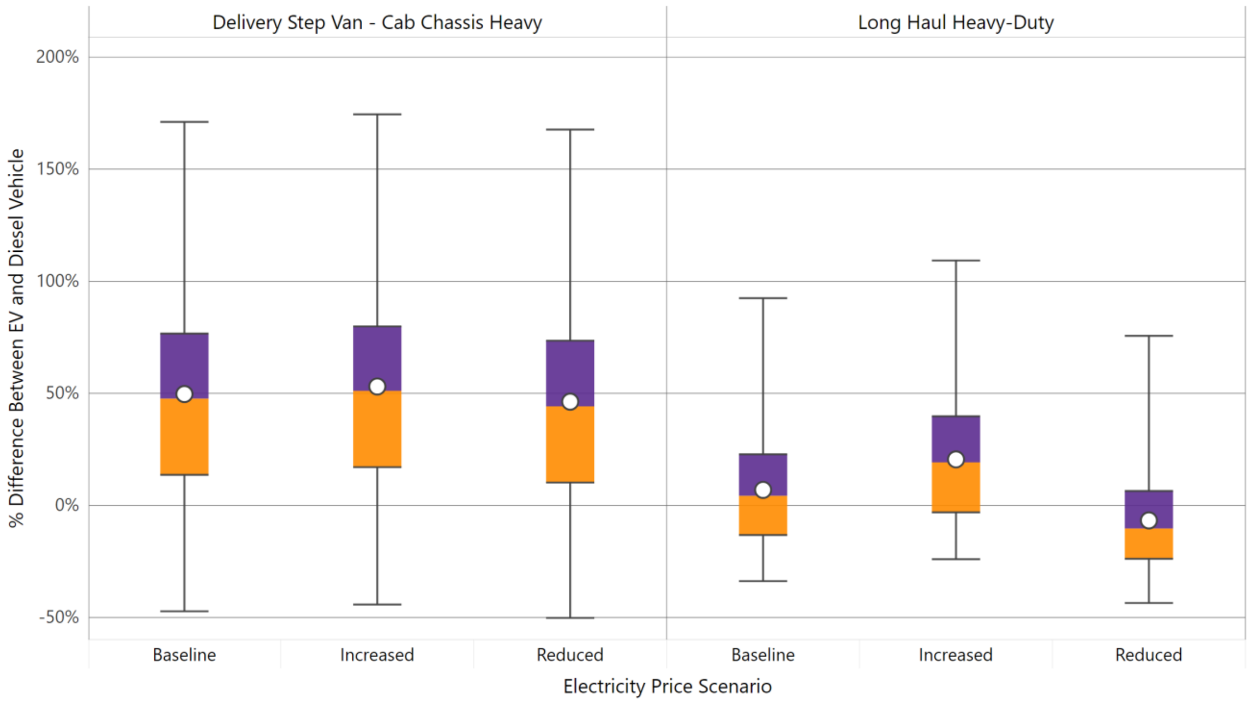
Due to the lower utilization for the medium-duty vehicles included in this analysis, a 350 kilowatt station was considered an impractical charging solution and the option for 350 kilowatt charging stations was only included for Long and Short Haul Heavy-Duty scenarios. These charging stations can cost several hundred thousand dollars between the cost of the station itself, installation, and utility upgrades and the likelihood that there would be a net savings for any of the medium-duty procurement scenarios examined in this analysis was very low.

Figure 14 shows the effect of the charging station power level procured on the average percentage difference in TCO between electric and diesel vehicles for the Long and Short Haul Heavy-Duty use cases.

CHARGING COST

The effect of variations in charging cost on the TCO for EVs is highly dependent on which charging strategy is employed. If an EV procurement includes depot charging, then the fleet manager can charge vehicles by paying for electricity at standard rates directly from the electric utility. When relying on public charging, vehicles are subject to prices set by third party charging companies that will reflect the price of electricity, cost of depreciation for the charging unit, operating overhead for the charging company, and any profit margin. The difference in charging cost between depot and public charging can be substantial and can severely restrict the cost competitiveness of EVs.

FIGURE 15: EFFECT OF CHARGING COST VARIATION FOR DEPOT CHARGING SCENARIOS



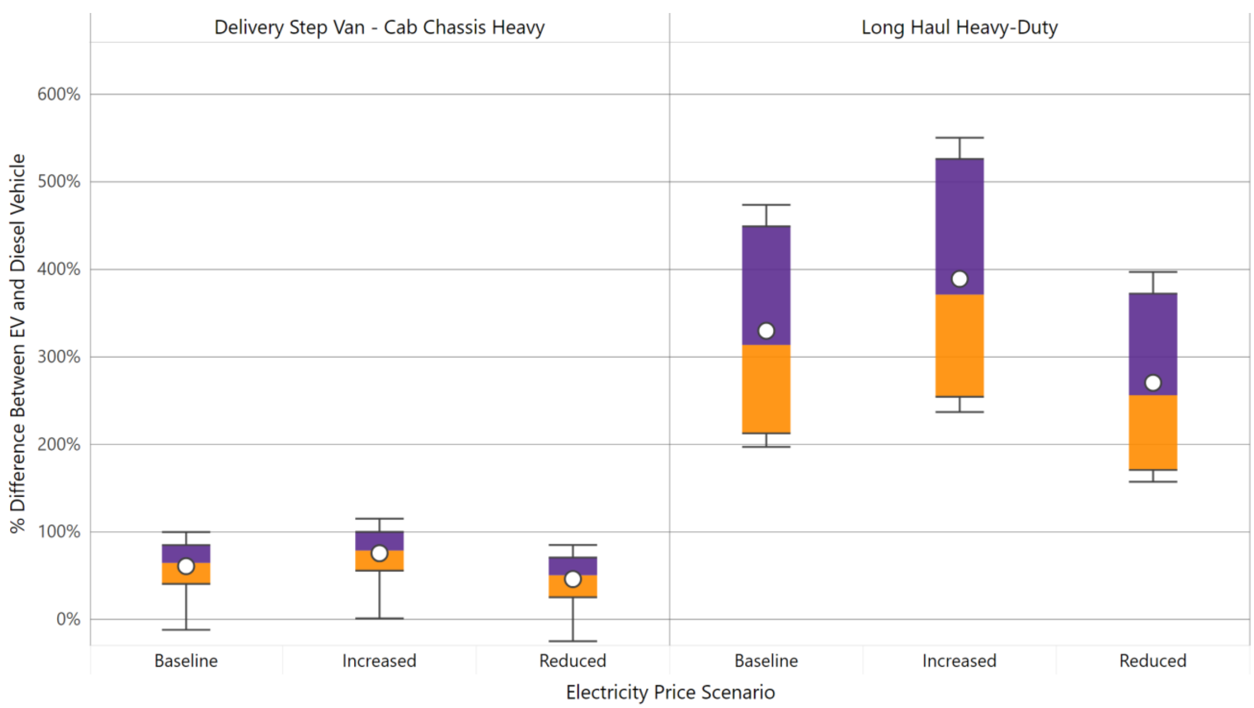
This figure shows the percentage difference in TCO between an EV and an equivalent diesel vehicle when varying the cost of charging by plus or minus 33 percent (labeled here as increased and reduced, respectively), from the baseline for EV procurements that exclusively use depot charging. The baseline in this analysis was the average price of electricity in the U.S. for 2018. (Scenarios Shown: 6,480)

In the case of depot charging, the price of electricity is low enough that the variations in electricity which were explored in this analysis, plus or minus 33 percent from the current U.S. average, had a relatively small effect on the TCO for an EV depending on the rate of utilization. For the Delivery Step Van – Cab Chassis Heavy use case, decreasing the cost of electricity for depot charging by 33 percent, in this case nearly $0.04 per kilowatt-hour, reduced the average TCO just over two percent. For Long Haul Heavy-Duty EVs, decreasing the cost of electricity for depot charging by the same amount reduced the average TCO by nearly 13 percent. To achieve the same reduction in TCO as a Long Haul Heavy-Duty, a Delivery Step Van would need to increase its yearly VMT by an order of magnitude; the sensitivity to small absolute changes in electricity prices for vehicles which are not being heavily utilized is very low.

Figure 15 shows the effect of the cost of electricity when a procurement includes only depot charging. In depot charging scenarios, the only cost to charge vehicles is the price of electricity, so the scenarios in the graph below of Baseline, Increased, and Reduced represent the average price of electricity in the United States in 2018 ($0.117), a 33 percent increase in that price ($0.078), and a 33 percent decrease in that price ($0.156), respectively. It should be noted that the width of the box and whisker plots is a result of the range of scenarios being covered, not the effect of variations in the cost of charging. The effect of changes in charging cost are to be inferred from the relative changes between the box and whisker plots for the three scenarios of Baseline, Increased, and Reduced for each use case.

In the case of public charging, costs are sufficiently high that an equivalent percentage variation in price can raise the TCO of an EV substantially. Increasing the cost of public charging by 33 percent from $0.50 per kilowatt-hour to $0.67 per kilowatt-hour raised the average TCO of a Long Haul Heavy-Duty EV by over $3.8 million. Although the percentage change in average TCO was roughly the same as the depot charging example at just under 14 percent, the dollar value of that change was over four times higher. The Delivery Step Van – Cab Chassis Heavy use case was somewhat insulated from the higher charging costs due to lower utilization, but it nonetheless saw a nine percent increase in average TCO under the same circumstances. The range in charging cost in the examples above may seem large, but there is currently a similar level of variation in the public charging price between regions of the country and charging service providers [30, 31, 32].

FIGURE 16: EFFECT OF CHARGING COST VARIATION FOR PUBLIC CHARGING SCENARIOS



This figure shows the percentage difference in TCO between an EV and an equivalent diesel vehicle when varying the cost of charging by plus or minus 33 percent (labeled here as increased and reduced, respectively), from the baseline for EV procurements that exclusively use public charging. The baseline in this analysis was the average of several public charging rates in the U.S. for 2018. (Scenarios Shown: 1,296)

Depending on the fuel efficiency of the EV, the per-mile cost of charging at public charging rates can easily exceed the cost for an equivalent diesel vehicle. At $0.50 per kilowatt-hour, it would cost the Tesla Semi $475 to travel its maximum estimated range of 500 miles. The same $475 would purchase roughly 136 gallons of diesel fuel at the U.S. average price used in this analysis and allow a Freightliner Cascadia to travel nearly 1,000 miles. At the public charging prices examined in this analysis, the likelihood that an EV using public charging will be cost competitive is extremely low with less than two percent of cost competitive scenarios including public charging. Figure 16 shows the effect of the cost of electricity when a procurement includes only public charging. In public charging scenarios, the cost to charge vehicles includes the price of electricity, depreciation on the charging station, operating costs like rent and overhead, and any profit margin for the charging service provider. The scenarios in the Figure 16 of Baseline, Increased, and Reduced represent the average of several U.S. public charging rates in 2018 ($0.50), a 33 percent increase in that price ($0.67), and a 33 percent decrease in that price ($0.33), respectively.

PUBLIC POLICY AND LABOR MARKET

The second most important group of procurement elements for determining the cost competitiveness of an EV are those related to the market in which the vehicle will be purchased and operate. The types and focuses of EV policy vary widely across the United States, with some states actively promoting transportation electrification while others have enacted less substantial legislation or are content to sit on the sidelines. Similarly, states with more developed EV markets will have more mature maintenance networks leading to reduced repair times for EVs. The sensitivity variables discussed below capture the effect of purchasing an EV in a state with a medium- and heavy-duty EV incentive program or well-developed EV maintenance network.

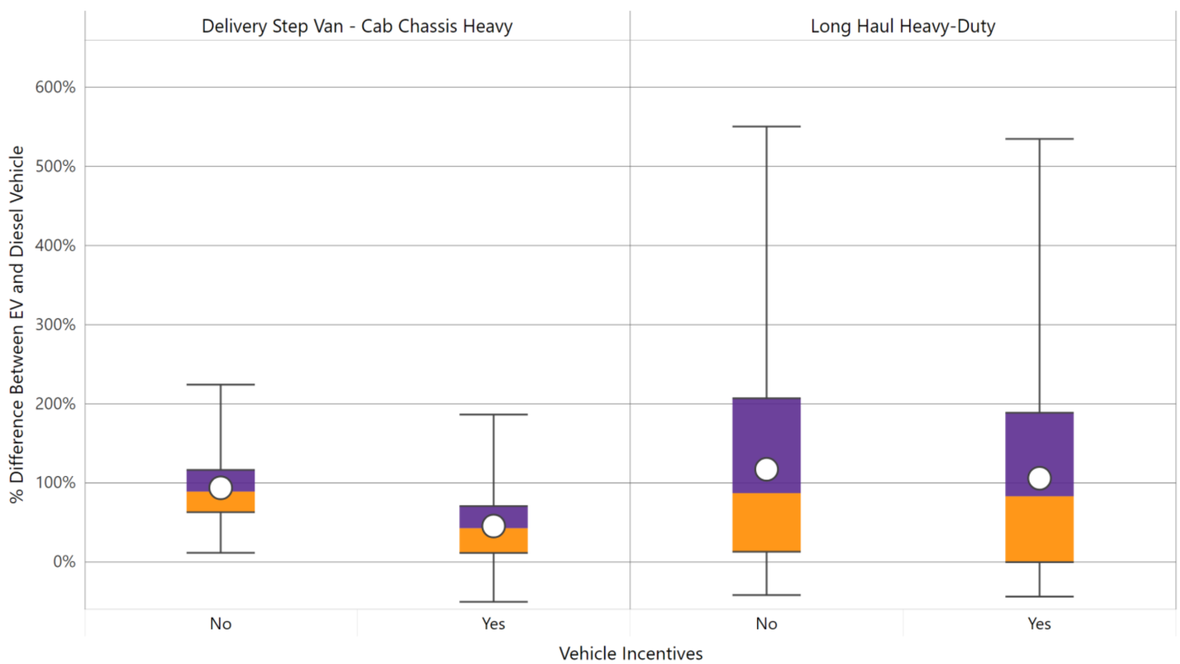
VEHICLE INCENTIVES

Vehicle incentives are typically cited as a key factor in the decision for companies interested in electrifying their shipping fleets [28]. Considering that the EVs included in this analysis were two to five times more expensive than their diesel equivalents, it is conceivable why overcoming differences in upfront cost are such a heavy focus of policymakers. However, the results of this analysis show that, while important, the presence of state incentives for medium and heavy-duty EVs may not be the largest factor affecting EV cost competitiveness. Of all the scenarios identified as cost competitive in the analysis, 98 percent included depot charging while 69 percent included vehicle incentives. This was the second most important factor for determining EV cost competitiveness, but the results of the analysis indicate that state EV incentives may not be necessary for achieving a lower total cost of ownership in all cases.

The distribution of costs between upfront capital expenses and ongoing operating expenses greatly affects the importance of vehicle incentives. For example, the incentive for the BYD T9, a Long Haul Heavy-Duty EV, in this analysis is $150,000 which is half of the vehicle MSRP. For scenarios that rely on depot charging, the difference in average TCO between scenarios which do or do not include this incentive is just under 15 percent. This is primarily because the high utilization of Long Haul Heavy-Duty EVs in this analysis causes operating costs to overwhelm the fixed upfront costs, so any changes in the latter have a relatively small effect. In scenarios which do not include any charging infrastructure (public charging only), the effect of vehicle incentives in scenarios is even smaller, achieving a less than three percent reduction in TCO for the BYD T9. In this analysis, the savings from not procuring charging infrastructure were always outweighed by the increased cost of charging at public charging stations and the additional cost of lost productivity; the relatively higher savings on upfront costs from vehicle incentives were irrelevant.

In the case of a Delivery Step Van – Cab Chassis Heavy EV, a vehicle with low utilization, the average fixed upfront costs make up the majority of the TCO. In scenarios that rely only on depot charging, including an incentive for 50 percent of the vehicle cost achieves a 27 percent reduction in average TCO for scenarios that rely on depot charging. This savings is similar to the cost savings achieved by reducing the number of charging stations for this vehicle in a depot charging scenario from 10 to five, which would also net a 27 percent reduction in average TCO. For scenarios which only include public charging, the effect of vehicle incentives on EV TCO is slightly less pronounced, achieving only a 25 percent reduction in TCO for the Delivery Step Van – Cab Chassis Heavy EV.

FIGURE 17: EFFECT OF VEHICLE INCENTIVES ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This figure shows the percentage difference in TCO between an EV and an equivalent diesel vehicle for procurements that either include or do not include state EV incentives. Incentive figures are from the New York Vehicle Incentive Program and cover between 35 and 50 percent of the vehicle price. (Scenarios Shown: 14,256)

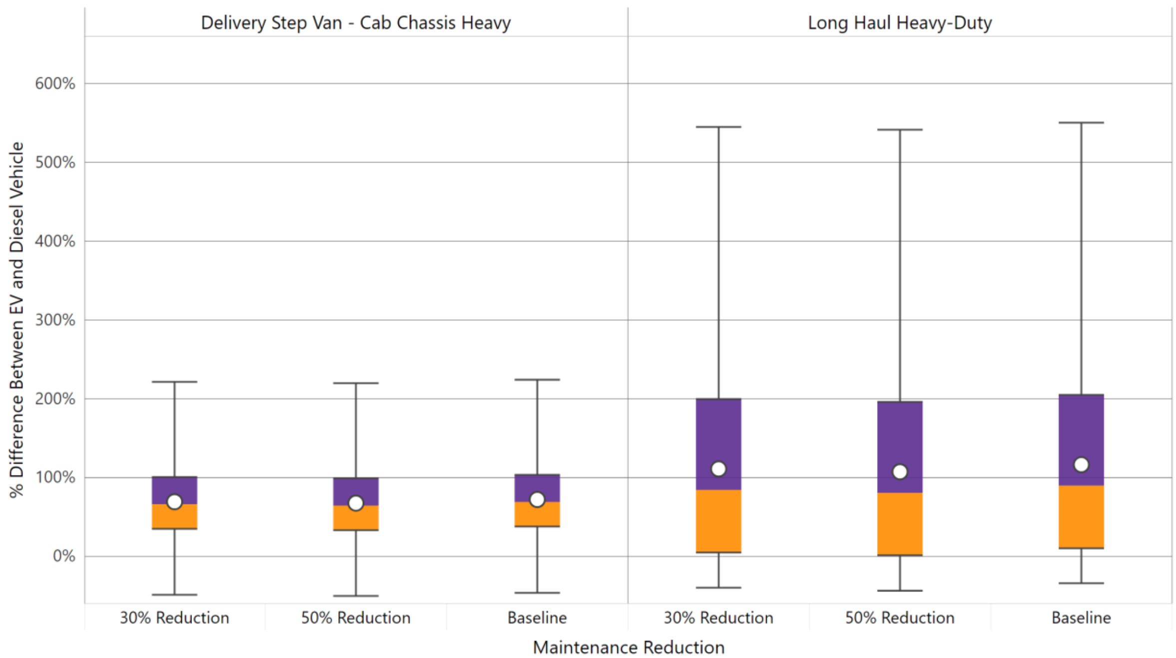
Figure 17 shows the effect of the vehicle incentives on the average percentage difference in TCO between electric and diesel vehicles for the Delivery Step Van – Cab Chassis Heavy use case, which had the lowest rate of utilization of all use cases, and the Long Haul Heavy-Duty use case, which had the highest rate of utilization of all use cases.

MAINTENANCE COST REDUCTIONS

The total costs for maintenance over the life of a vehicle were a small portion of the total cost of ownership in this analysis, accounting for roughly four percent of the total CPM across all EV scenarios, and thus reductions in maintenance costs had a minor effect on the cost competitiveness of EVs. Even when maintenance costs for EVs were reduced by 50 percent compared to diesel vehicles, the effect on the TCO for EVs was relatively small in comparison to other factors in the analysis. The gap in average TCO between scenarios with a 50 percent and no reduction in maintenance costs was only eight percent for Long Haul Heavy-Duty EVs, the use case with the highest total maintenance cost. The reduction in average TCO for a Delivery Step Van – Cab Chassis Heavy EV, a use case with much lower utilization and maintenance costs, was only three percent.

Figure 18 shows the effect of maintenance cost reductions on the average difference in TCO between electric and diesel vehicles for the Delivery Step Van – Cab Chassis Heavy and Long Haul Heavy-Duty use cases.

FIGURE 18: EFFECT OF MAINTENANCE COST REDUCTIONS ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This figure shows the percentage difference in TCO between an EV and an equivalent diesel vehicle for procurements that include maintenance cost reductions for EVs of 0, 30, and 50 percent. (Scenarios Shown: 14,256)

VEHICLE TECHNOLOGY PROGRESS

Technological advancements or increases in production efficiencies were the next most important factor for determining the cost competitiveness of EVs after the charging strategy and vehicle incentives. As production costs or the price of EV components fall, competition will drive down the purchase price of EVs. For the purposes of this analysis, all cost reductions relating to any technological breakthrough or production efficiency were combined into the sensitivity variable of MSRP reductions and the effect of changes in EV MSRP on EV TCO is discussed below.

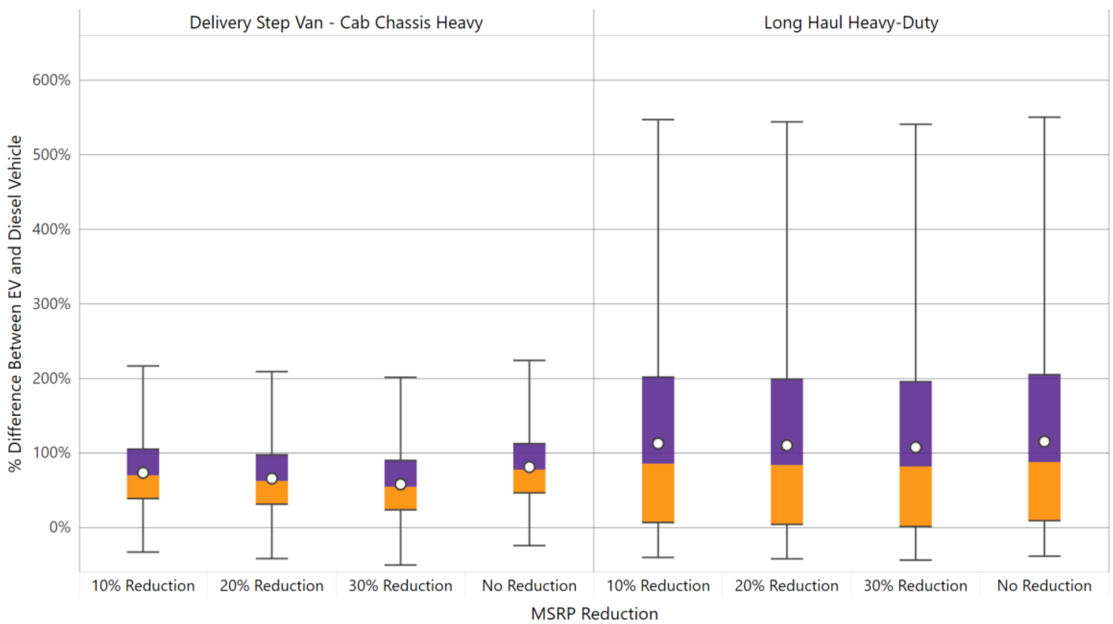
MANUFACTURER SUGGESTED RETAIL PRICE (MSRP) REDUCTIONS

The analysis results on EV MSRP reductions indicate that EV incentives may not be necessary in the long term for EVs to achieve mass adoption. If medium- and heavy-duty EVs can achieve a 30 percent cost reduction, a scenario which is expected by 2025 or sooner according to a report from consulting firm ICF [13], then the effect will be similar to a nationwide EV incentive program. This would nearly negate the need to limit EV procurements to states with incentive programs and open up previously cost-prohibitive regional markets.

MSRP reductions had a similar effect on the TCO of an EV as the vehicle incentives included in the analysis, only to a lesser degree. Also, like vehicle incentives, reductions in EV MSRP had a more significant effect on the TCO of vehicles with lower rates of utilization. For every 10 percent reduction in EV MSRP, the average TCO for Delivery Step Van – Cab Chassis Heavy EVs fell by four percent. Long Haul Heavy-Duty EVs saw a one percent drop in TCO under the same conditions. For MSRP reductions to achieve the drop in average TCO seen when decreasing the number of charging stations by two in a Delivery Step Van – Cab Chassis Heavy EV procurement, the vehicle MSRP would need to drop by over 30 percent.

It should be noted that this analysis did not include any variations on the price of charging infrastructure due to the relative maturity of the market for electrical equipment. The effect of varying levels of MSRP reductions on the average difference in TCO between electric and diesel vehicles for the Delivery Step Van – Cab Chassis Heavy and Long Haul Heavy-Duty use cases is demonstrated in Figure 19.

FIGURE 19: EFFECT OF MSRP REDUCTIONS ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This figure shows the percentage difference in TCO between an EV and an equivalent diesel vehicle for procurements that include EV MSRP reductions of 0, 10, 20, and 30 percent. (Scenarios Shown: 14,256)

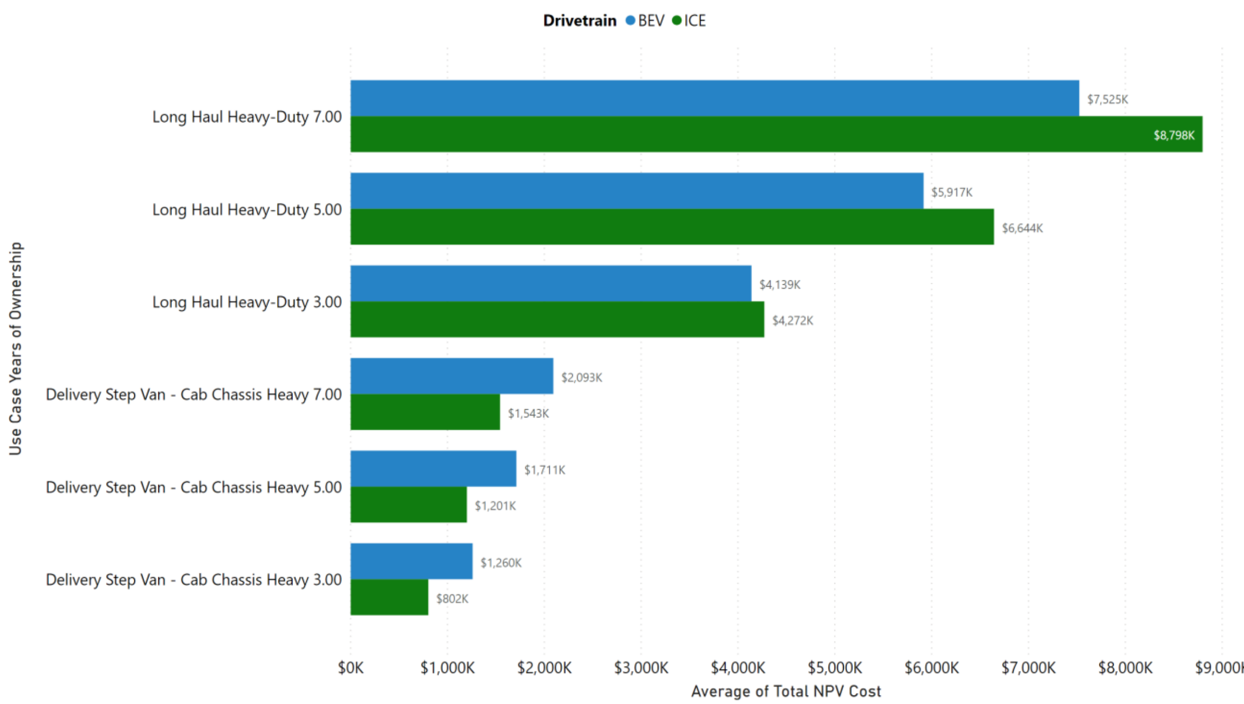
VEHICLE PROCUREMENT STRATEGY

When entering into a vehicle procurement, either for an electric or diesel vehicle, two key decisions are the intended years of ownership and the method of procurement. Depending on factors such as vehicle resale value, reliability, and payback period, fleet managers may choose shorter or longer terms of ownership for their vehicles. Fleet managers also have a multitude of financing options at their disposal for procuring new vehicles and must decide on an option which best fits their financial situation. These sensitivity variables were the only two that were held constant across both EV and diesel scenarios; when comparing the TCO of an EV and diesel vehicle, only vehicles with the same length of procurement and procurement method were compared. In this section of the paper, the focus will be on the effect of variations in these variables on the TCO of an EV relative to a diesel vehicle that is experiencing the *same variation*. The results of the analysis for these variables are discussed below.

YEARS OF OWNERSHIP

Increasing the term of ownership will be beneficial when operating costs are lower or when resale value of a vehicle is low. The importance of extending the term of ownership will be dependent on the magnitude of these operational cost savings or residual values. Under the assumptions of this analysis, years of ownership had the smallest incremental effect on the cost competitiveness of EVs of all the sensitivity variables analyzed. Increasing the years of ownership by two increased the number of cost competitive scenarios by just over 10 percent on average. In comparison, increasing the savings on maintenance cost by 30 percent, a change which had a little significance on TCO, increased the number of cost competitive scenarios by nearly 14 percent.

FIGURE 20: AVERAGE TCO OF ELECTRIC AND DIESEL VEHICLES UNDER DIFFERENT TERMS OF OWNERSHIP

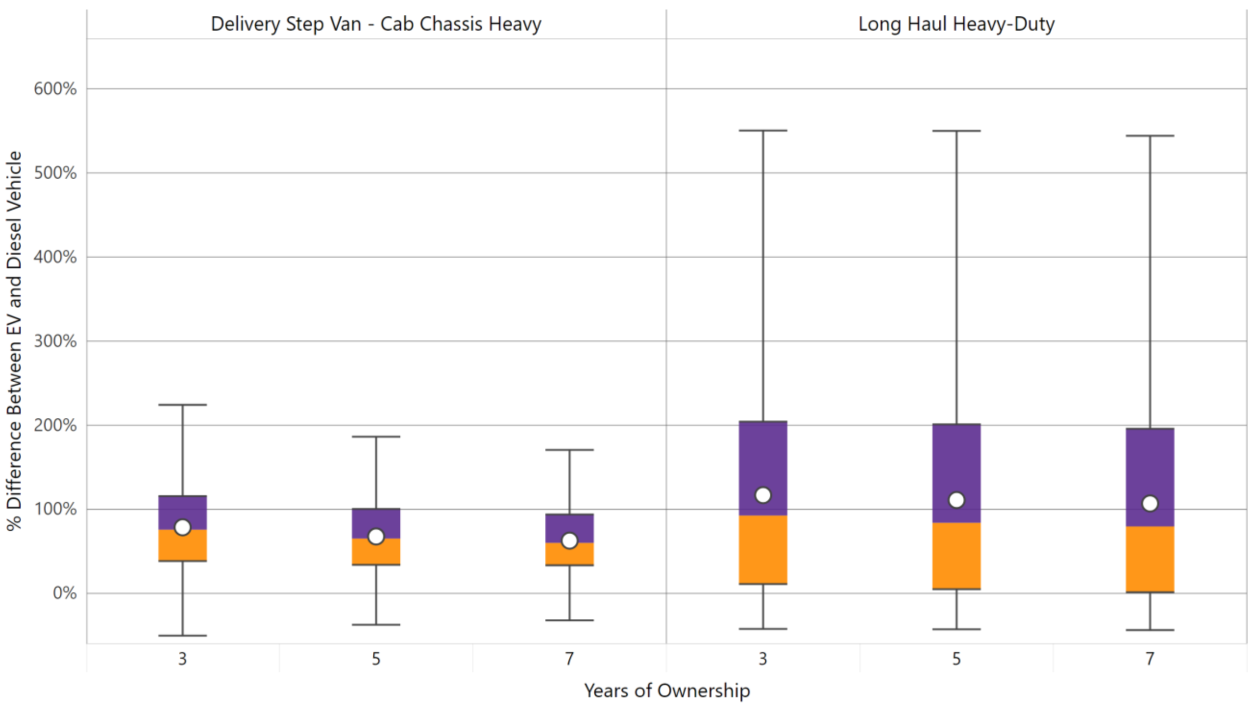


This figure shows the change in average TCO for both and EV and an equivalent diesel Long Haul Heavy-Duty vehicle under 3, 5, and 7 year terms of ownership. The EV scenarios in the figure above were limited to only those with exclusively depot charging and reduced cost of electricity. (Scenarios Shown: 2,214)

The primary takeaway from the results is that if EVs were cost competitive with diesel vehicles, then they were largely cost competitive regardless of length of ownership. Under the assumptions of the analysis, the savings from reduced operating costs did not accrue fast enough to substantially increase the number of cost competitive EVs over even a seven year timeframe. Figure 20 shows the difference between the average TCO of electric and diesel Long Haul Heavy-Duty vehicle when the scenario includes depot charging and reduced electricity – factors which cause the EV to have lower operating costs. Even under these favorable conditions, the gap between the average TCO of the two vehicle types grows at a moderate pace, increasing from three to 11 to 14 percent. The most telling of these jumps is from five to seven years at which point any upfront costs have been largely diluted and the variations in TCO are primarily related to operating costs. Here the gap in TCO increases by only three and a half percent, or 1.75 percent per year. Unless the TCO of an EV was within a few percent of a diesel vehicle, additional years of ownership was unlikely to be an important factor in determining EV cost competitiveness.

One important factor to note in considering years of ownership that is not immediately apparent is that if the life cycle of charging infrastructure is expected to outlast that of the vehicle, then any subsequent electric vehicles would be unburdened by the capital investment necessary for charging infrastructure. For instance, if a three year EV procurement includes charging infrastructure which lasts for 10 years, then any EVs purchased after that initial 3 year period would be substantially more cost competitive. Figure 21 demonstrates the impact of varying the term of ownership on the difference in TCO between EV and diesel vehicles.

FIGURE 21: EFFECT OF YEARS OF OWNERSHIP ON DIFFERENCE BETWEEN EV AND DIESEL TCO



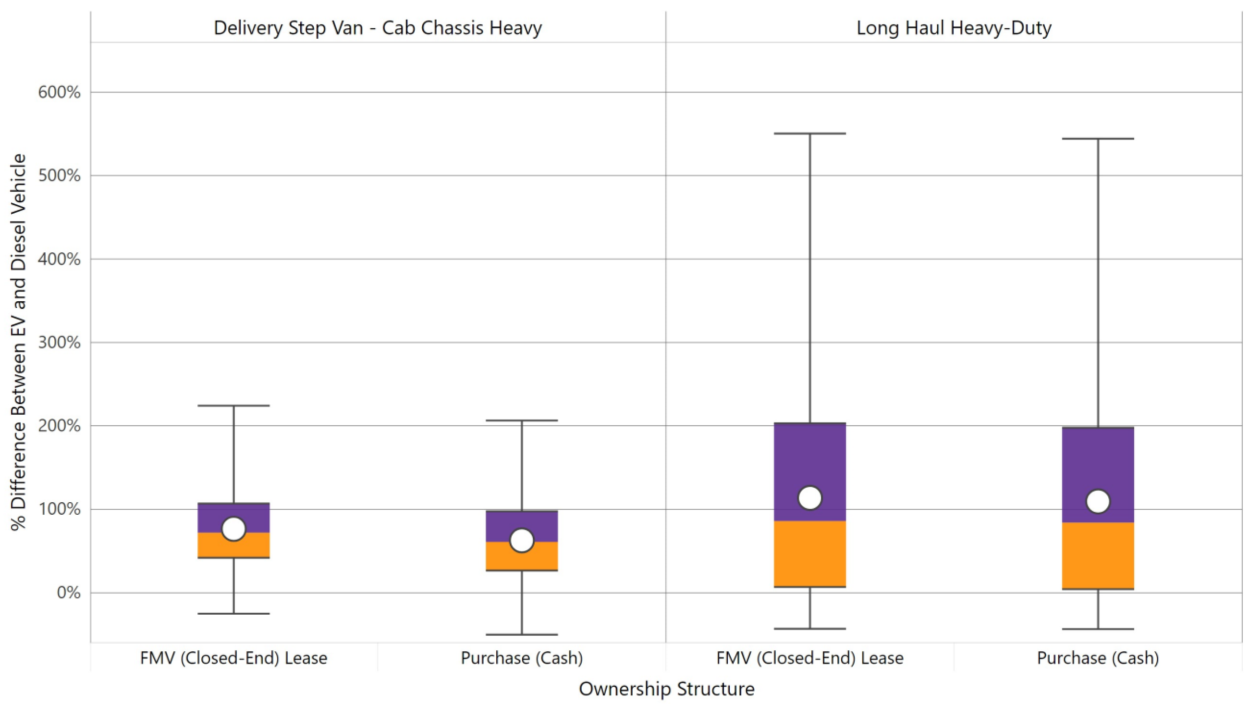
This figure shows the percentage difference in TCO between an EV and an equivalent diesel vehicle for procurements that are 3, 5, and 7 years in length. (Scenarios Shown: 14,256)

PROCUREMENT METHOD

Despite small differences in average TCO between the two procurement methods of cash purchase and closed end lease, cash purchases conferred a relative benefit to EVs when compared to diesel vehicles. Although the average change in TCO was less than three percent for all use cases, choosing a cash purchase increased the number of cost competitive scenarios for EVs by 25 percent. This finding is a result of the parameters of the closed end lease assumed in the analysis wherein the residual value of vehicles was set at $1, meaning all vehicles would be fully depreciated at the end of the lease term. This resulted in considerably higher depreciation costs for EVs due to higher upfront costs, increasing average CPM for depreciation by nearly 150 percent for EVs compared to 89 percent for diesel vehicles. Financing costs accounted for less than five percent of CPM across both diesel and EV procurement scenarios so any variations in costs between the two types of vehicles were insignificant.

Although the change in the number of cost competitive scenarios between the two procurement methods was relatively minor in comparison to the differences seen by varying other factors, the result does provide some insight into the relative importance of the upfront costs of vehicles. The depreciation calculation used in the analysis is based on estimates from Argonne National Laboratory; actual rates of depreciation and residual values may vary. Under the closed lease option, all vehicles are fully depreciated and the effect of any differences in upfront cost are fully realized. Although this circumstance is unrealistic, particularly for shorter term leases, the results of the analysis are instructive for understanding the importance of disparity in vehicle residual value. Even under these harsher parameters, the cost competitiveness of EVs was not dramatically dulled. Figure 22 shows the effect of the two procurement methods on the average difference in TCO between an EV and an equivalent diesel vehicle.

FIGURE 22: EFFECT OF PROCUREMENT METHOD ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This figure shows the percentage difference in TCO between EVs and equivalent diesel vehicles when procured via a cash purchase or fair market value (closed-end) lease with a set residual value of $1. (Scenarios Shown: 14,256)

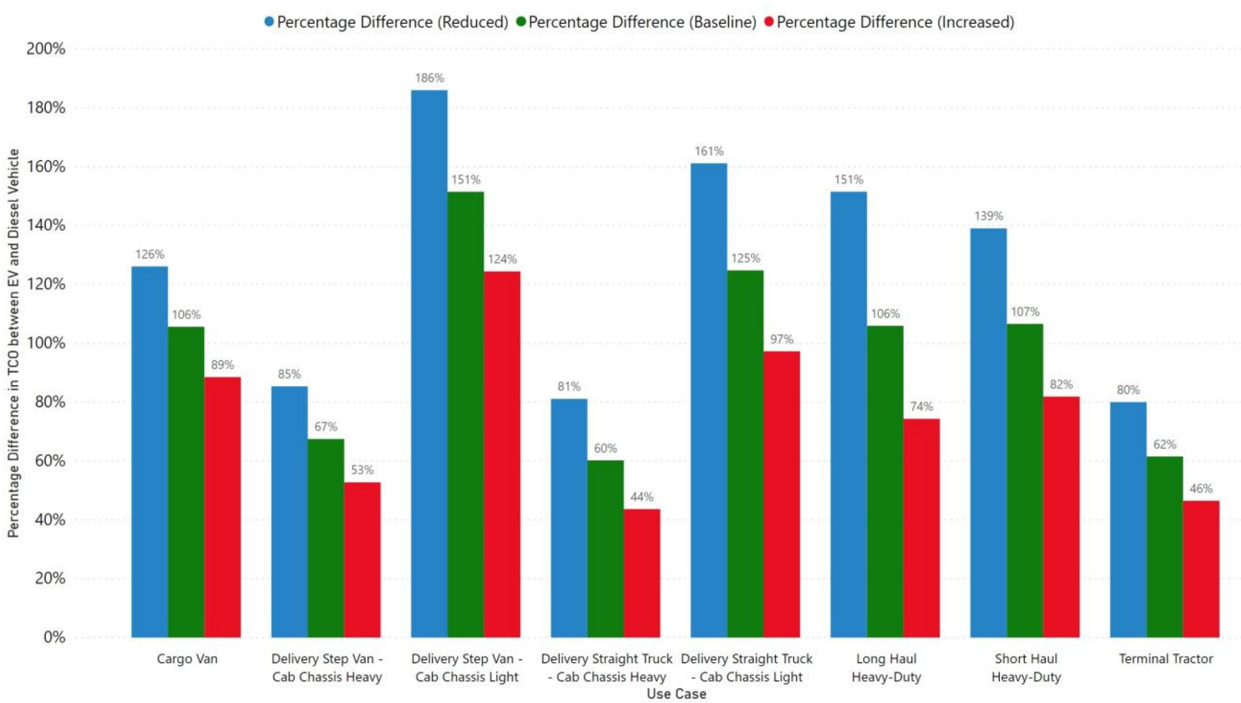
DIESEL PRICE

While the analysis focused primarily on factors related to EVs, the factors for diesel vehicles were also varied to demonstrate the effect of realistic changes in equivalent diesel procurements on the cost competitiveness of EVs. For this analysis, the variable exclusively used to alter the cost of diesel vehicle procurements was the price of diesel fuel.

The TCO for every scenario involving a diesel vehicle was calculated when the price of diesel was plus or minus 33 percent of the 2018 U.S. average price. Similar to variations in charging cost, the effect of changes in diesel price on EV cost competitiveness were more pronounced for vehicles with higher utilization. However, diesel vehicles were more sensitive to changes in diesel price as fuel costs accounted for nearly 35 percent of average CPM across all scenarios compared to just 20 percent for EVs. For Long Haul Heavy-Duty diesel vehicles, increasing the price of diesel by 33 percent caused the average TCO to rise by 18 percent, 5 percent more than for EVs under the corresponding scenario. The change in average TCO differences for use cases with either better diesel fuel economy or lower utilization was noticeably smaller with a 9 percent increase in average TCO for the Cargo Van use case.

Although diesel price was not the most important factor when comparing electric and diesel vehicle procurements, expectations around the price of diesel should be taken into account when deciding between the two vehicles types. Diesel prices have historically been highly volatile in comparison to electricity prices [29], and, all else being equal, there is more risk of operational cost increases in a diesel vehicle procurement. It should be noted that this analysis did not explicitly model variations in potential carbon taxes which could disproportionately effect diesel vehicles, choosing instead to have the effect of carbon taxes modeled by changes in diesel price. Figure 23 shows the average difference in TCO between an EV and equivalent diesel vehicle when the price of diesel is the current U.S. average, 33 percent lower, and 33 percent higher.

FIGURE 23: EFFECT OF DIESEL PRICE ON DIFFERENCE BETWEEN EV AND DIESEL TCO



This figure shows the average percentage difference in TCO between an EV and an equivalent diesel vehicle when the price of diesel is plus or minus 33 percent (labeled as Increased and Reduced, respectively) from the baseline cost. The baseline in this analysis was the average price of diesel in the U.S. in 2018. (Scenarios Shown: 41,148)

CONCLUSION

Achieving a cost competitive EV procurement in the current market is a difficult but achievable goal based on the results of this analysis. In meeting the primary goal of this paper, assessing the financial barriers to adoption of medium- and heavy-duty electric vehicles, the analysis modeled 41,148 procurement scenarios which covered a broad range of procurement possibilities across vehicle types and uses as well as factors related to vehicle charging, market conditions, vehicle technology, and vehicle procurement.

Although the overall picture may not appear promising, including just two key elements in a procurement scenario, depot charging and vehicle incentives, substantially improved the cost competitiveness of EVs. Eliminating all scenarios that rely on any public charging more than doubled the share of scenarios where an EV was cost competitive with a diesel vehicle. If both depot charging and vehicle incentives were included, then nearly half of all scenarios became cost competitive.

Among scenarios that relied exclusively on depot charging, nearly 60 percent of Long Haul Heavy-Duty EV procurement scenarios were cost competitive. EVs often cost less to operate than conventional vehicles because of lower fuel costs and the fact that electric motors have fewer moving parts, requiring significantly less maintenance than internal combustion engines. Put simply, the more an owner uses an EV, the more benefit they can derive from it. This was borne out in the analysis results. Long and Short Haul Heavy-Duty EVs along with Terminal Tractors had considerably higher rates of cost competitiveness compared to vehicles that had lower rates of utilization.

In general, however, the results of this analysis indicate that achieving a lower total cost of ownership for EVs remains difficult. Even after the public charging scenarios were eliminated, there were a significant number of procurement scenarios were EVs were projected to have a higher total cost of ownership than their diesel counterparts. In some cases, the difference in cost between the two vehicle types was substantial and highlights the risk of entering into an EV procurement without careful consideration of the relevant procurement elements and market conditions. Procurement scenarios that included use cases with low utilization, excessively high upfront vehicle costs, significant charging infrastructure requirements, no vehicle incentives, or expensive electricity all ran considerably higher risk of not being cost competitive with their diesel counterparts. Procurement scenarios that included any public charging, representing over 55 percent of all scenarios, were almost all non-competitive.

The analysis results indicate that EV procurements should be designed to maximize the advantages of EVs, primarily through lower operating costs. Specifically, efficient depot charging can complement state EV incentive programs that lower the upfront cost of vehicles and result in a competitive EV procurement in today’s market.

The scenario analyses also drew the following specific conclusions:

- The choice of charging strategy was the most important decision when procuring a medium- or heavy-duty EV. Including depot charging in a procurement opened up cost saving options for an EV procurement such as allowing for cheaper vehicle charging and avoiding lost productivity by charging during normal downtime. When using depot charging, the number and type of charging stations played a critical role in maximizing these cost savings; over 98 percent of all cost competitive scenarios used only depot charging. Conversely, fewer than one percent of EV procurement scenarios which included public charging were cost-competitive with a diesel equivalent.

- Purchasing an EV in a state with a medium- and heavy-duty EV incentive program increased the likelihood that an EV will be cost competitive with an equivalent diesel vehicle and was the second most important factor behind the decision to pursue depot charging.
- Under the conditions explored in this analysis, Long Range Heavy-Duty EVs offered the highest likelihood of at cost savings compared with an equivalent diesel vehicle with more than 60 percent of scenarios that included depot charging being identified as cost competitive.
- In general, vehicles with higher rates of utilization had a greater likelihood of being cost competitive with the uses cases with the top three yearly VMT accounting for over 85 percent of all cost competitive scenarios.
- Cost savings from reduced maintenance costs for EVs were not a significant determinant of EV cost competitiveness since it represented a relatively small portion of the total cost of ownership for both electric and diesel vehicles compared to other costs elements.
- The impact of variations in electricity prices was only significant for vehicles with extremely high utilization with a 33 percent reduction in electricity cost equating to just a two percent drop in the average TCO for a medium-duty EV traveling 16,500 miles per year. This drop in TCO jumps to 13 percent for a heavy-duty EV traveling 170,000 miles per year under the same conditions.
- Reductions in EV MSRP from predicted technological advancements provide smaller TCO reductions than vehicle incentives, but do offer the potential of achieving nationwide impact whereas vehicle incentives are currently limited to a few states. An MSRP reduction of 30 percent, a scenario which could occur within a few years according to the consulting firm ICF, would achieve nearly the same effect as a nationwide incentive program.
- Choice of procurement method did not have an appreciable effect on the TCO for EVs, but did provide a relative advantage when compared to diesel vehicles for cash procurements. The closed-end lease used in the analysis assumed a residual value of $1 at the end of the lease, so the full effect of any differences in upfront cost were realized.
- Diesel vehicles were more sensitive than EVs to comparable variations in fuel prices (diesel or electricity). Given the historical volatility of diesel prices compared to electricity prices, fluctuations in the cost of fuel represent a greater source of risk for diesel procurements.

While the analysis demonstrated that cost competitive EV procurements are achievable, it can be challenging and depends on careful and well-thought out procurement strategies. The savings, however, can be substantial with more than 700 scenarios achieving TCO reductions of more than 25 percent compared to equivalent diesel vehicles. The focus for any EV procurement should be on careful planning to both maximize the advantages of EVs via lower operating costs and minimize the additional upfront investment required. For retailers, third party logistics providers, and any other interested parties, this can lead to cost savings, achieving environmental and health benefits, staying ahead of increasingly stringent emissions regulations, and industry leadership.

APPENDIX A: TOOL INPUTS

FLEET PROCUREMENT ANALYSIS TOOL INPUTS

Input Field	Values	Source
Market Inputs		
Market	U.S.	Atlas estimate used to calculate public benefits.
Zip Code	0000	U.S. Average
Diesel Price ($/Gallon)	$2.24 to $4.48	+/- 30% of national average diesel price for 2018 (https://www.eia.gov/petroleum/gasdiesel/)
Electricity Cost ($/kWh)	$0.078 to $0.156	+/- 30% of national average electricity price for 2018 (https://www.eia.gov/electricity/)
Public Charging Price ($/kWh)	$0.33 to $0.67	+/- 30% going rate of public charging in 2018
En Route Charging Price ($/kWh)	$0.078 to $0.156	+/- 30% of national average electricity price for 2018 (Not used for this analysis)
Inflation Rate (Excluding Fuel) (%/Year)	2.20%	Federal Reserve’s medium-term target
Cost of Downtime from Public Charging ($/Hour)	$35.00	The Economic Costs of Freight Transportation
Include Cost of Carbon?	No	Atlas assumption
Cost of Carbon ($/Ton)	$42.00	https://www.epa.gov/climatechange/social-cost-carbon , Not applicable to this analysis
Vehicle Inputs		

Input Field	Values	Source
Vehicle Drivetrain Type	See Use Case Table	N/A
Vehicle Class	See Use Case Table	N/A
Vehicle Year	See Use Case Table	N/A
Vehicle Make	See Use Case Table	N/A
Vehicle Model	See Use Case Table	N/A
Fuel Economy Gasoline/Diesel City (MPG)	Model dependent	Argonne AFLEET tool (converted to diesel equivalent and rounded to nearest whole number)
Fuel Economy Gasoline/Diesel Highway (MPG)	Model dependent	Argonne AFLEET tool (converted to diesel equivalent and rounded to nearest whole number)
Fuel Economy Electric City (MPGe)	Model dependent	Published figures or calculated value based on: (Vehicle Range/Battery Size)*33.7 (https://www.edmunds.com/fuel-economy/decoding-electric-car-mpg.html)
Fuel Economy Electric Hwy (MPGe)	Model dependent	Published figures or calculated value based on: (Vehicle Range/Battery Size)*33.7 (https://www.edmunds.com/fuel-economy/decoding-electric-car-mpg.html)
Expected Years of Use/Ownership (Years)	3 - 7	Atlas assumption
Annual Vehicle Mileage (VMT/Year)	16,500 – 170,000	Argonne AFLEET tool
% of Annual Miles on Gasoline/Diesel	Model dependent	N/A
% of Annual Miles City Driving	50%	Atlas Assumption

Input Field	Values	Source
Cost to Insure ($/Year)	4,000 to 10,000	https://www.boxtruckinsurancehq.com/box-truck-insurance-tips/how-much-does-box-truck-insurance-cost/ https://www.commercialtruckinsurancehq.com/
Use Drivetrain Default Maintenance and Repair Costs?	No	N/A
Maintenance and Repair Cost - Years 1 - 5 ($/Mile)	$0.08 to $0.16	50%, 30%, and 0% reductions from maintenance figures included in Argonne AFLEET tool; figures for reduced percentages from National Renewable Energy Laboratory - Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050
Maintenance and Repair Cost - Years 5+ ($/Mile)	$0.104 to $0.21	Atlas assumption of 30% increased repair costs after 5 years
Recurring Taxes and Fees ($/Year)	$10	Atlas assumption
Vehicle Procurement Inputs		
Discount Rate for NPV Calculations (%)	8.00%	http://people.stern.nyu.edu/adamodar/New_Home_Page/datacurrent.html#discrate Rounded average cost of capital for the Trucking industry sector from 2015 -2019
Number of Vehicles to Procure (#)	10	Atlas assumption
Pricing Approach (select one)	MSRP Less Discounts	Atlas assumption
MSRP ($/Vehicle)	$42,185 - $300,000	Prices for vehicles derived from manufacturer websites or the average cost of new listings on commercialtrucktrader.com (rounded to the nearest $5,000), and price listings from the New York Vehicle Incentive Program (https://truck-vip.ny.gov/NYSEV-VIF-vehicle-list.php)
Value of Negotiated Discounts off MSRP ($/Vehicle)	$0	Atlas assumption
Value of Federal Tax Incentives ($/Vehicle)	$0	Atlas assumption

Input Field	Values	Source
Value of State Tax Incentives ($/Vehicle)	$0	Atlas assumption
State Tax Incentive Cap ($)	$0	Atlas assumption
Value of Non-tax Incentives ($/Vehicle)	$16,000 - $150,000	Incentives taken from the New York Vehicle Incentive Program (https://truck-vip.ny.gov/NYSEV-VIF-vehicle-list.php) where applicable. Incentive for the Tesla Semi is based upon the standard incentive for Heavy-Duty EVs in Colorado.
Initial Tax, Title, and Registration Cost ($/Vehicle)	$1,000	Atlas assumption
Initial Fee as Percent of Vehicle Base Price (%)	0%	Atlas assumption
Ownership Structure	Purchase (cash) or FMV (Closed – End) Lease	Atlas assumption
Tax Credits Can Be Monetized? (Y/N)	Yes	Atlas assumption
Down Payment ($/Vehicle)	$0	Atlas assumption
Lease Term (Years)	3 - 7	Atlas assumption
Lease Interest Rate (APR - %)	4.00%	Atlas assumption
Money Factor (#)	0.0017	Atlas assumption
Acquisition Fee ($/Vehicle)	$0	Atlas assumption
Disposition Charge ($/Vehicle)	$0	Atlas assumption
Negotiated Residual Value ($/Vehicle)	$1	Atlas assumption

Input Field	Values	Source
Mileage Included (Closed-End Only)	0	Atlas assumption
Excess Mileage Cost ($/Mile)	$0	Atlas assumption
EV Charging and Installation Inputs		
% Depot/Home Charging	0 – 100%	Atlas assumption based on survey data
% Public Charging	0 – 100%	Atlas assumption based on survey data
% En Route Charging	0%	Atlas assumption
Charging Level	DC Fast Charging	
Maximum Power for Public Charging Only (kW)	350.0	Atlas assumption
Procurement Includes EV Charging?	Yes/No	Atlas assumption, value depends on scenario
Number of EV Charging Stations Needed (#)	3 – 10	Atlas assumption
Charging Equipment Cost ($/Station)	$25,000 - $150,000	Idaho National Labs: Considerations for Corridor and Community DC Fast Charging Complex System Design and interviews with industry personnel
Construction & Equipment Installation Cost ($/Station)	$25,000 - $50,000	Idaho National Labs: Considerations for Corridor and Community DC Fast Charging Complex System Design and interviews with industry personnel
Electric Utility Upgrades and Grid Interconnection Cost ($/Site)	$30,000 - $60,000	Idaho National Labs: Considerations for Corridor and Community DC Fast Charging Complex System Design and interviews with industry personnel
Maintenance Cost ($/Station/Year)	$14,800	Idaho National Labs: Considerations for Corridor and Community DC Fast Charging Complex System Design (includes estimate of demand charges)
Ownership Structure	Purchase (Cash)	

SENSITIVITY VARIABLES

Variable Category	Values	Number of Scenarios
Charging Strategy	50/50	18,144
	Depot Charging	18,144
	Public Charging	4,320
	N/A (for diesel vehicles)	540
Number of Charging Stations	10	12,096
	3	12,096
	5	12,096
Charging Station Power	50kW	25,920
	350kW	10,368
Charging Cost - Depot	$0.078 (Baseline)	12,096
	$0.117 (Increased)	12,096
	$0.156 (Reduced)	12,096
Charging Cost – Public	$0.33 (Baseline)	7,488
	$0.50 (Increased)	7,488
	$0.67 (Reduced)	7,488
Vehicle Incentives	No (includes diesel vehicles)	20,844
	Yes	20,304
Maintenance Cost Reductions	50% Reduction	13,536
	30% Reduction	13,536
	Baseline (No Reduction)	13,536

Variable Category	Values	Number of Scenarios
	N/A (for diesel vehicles)	540
MSRP Reductions	10% Reduction	10,152
	20% Reduction	10,152
	30% Reduction	10,152
	No Reduction	10,152
	N/A (for diesel vehicles)	540
Years of Ownership	3	13,716
	5	13,716
	7	13,716
Procurement Method	Cash Purchase	20,574
	FMV Closed-End Lease	20,574
Diesel Price	$3.36 (Baseline)	180
	$4.48 (Increased)	180
	$2.24 (Reduced)	180

APPENDIX B: EV SURVEY

RESPONDENT INFORMATION

1) Is your organization a:

( ) Shipper

( ) Carrier/3PL

( ) EV Manufacturer

( ) EV Charger Supplier

( ) Other- Write In: ____

PRICE OF ELECTRIC VEHICLES

2) What price range would you estimate for a Class 8 electric truck?

( ) $150,000-$200,000

( ) $200,000-$250,000

( ) $250,000-$300,000

( ) $300,000-$350,000

( ) Unsure

3) What price range would you estimate for a Class 6 electric truck?

( ) $150,000-$175,000

( ) $175,000-$250,000

( ) $200,000-$225,000

( ) $225,000-$300,000

( ) Unsure

4) What price range would you estimate for a Class 5 electric truck?

( ) $130,000-$150,000

( ) $150,000-$170,000

( ) $170,000-$190,000

( ) $190,000-$210,000

( ) Unsure

5) What price range would you estimate for a Class 4 electric truck?

( ) $130,000-$150,000

( ) $150,000-$170,000

( ) $170,000-$190,000

( ) $190,000-$210,000

( ) Unsure

6) What price range would you estimate for a Class 3 electric truck?

( ) $70,000-$90,000

( ) $90,000-$110,000

( ) $110,000-$130,000

( ) $130,000-$150,000

( ) Unsure

7) What is your estimation for the above based on (check all that apply):

[ ] Quotes received from manufacturers

[ ] Publications on Electric Vehicles

[ ] Information from other companies

[ ] Rough guess based on knowledge of diesel truck prices

MAINTENANCE COSTS PER MILE

Electric vehicles are expected to have reduced maintenance costs compared to conventional vehicles due to having fewer moving parts and using regenerative braking which reduces wear on brake pads. Even in the case where these reductions in costs are delayed by slow introduction of charging infrastructure and maintenance training, electric vehicles should still achieve cost-parity with conventional vehicles for maintenance according to the National Renewable Energy Laboratory. Early survey data from adopters of electric trucks have already indicated a decrease in maintenance costs compared to conventional vehicles.

8) Based on your experience with the deployment of new technologies for conventional vehicles maintenance, which of the below scenarios would you rate as the most likely for the widespread implementation of heavy-duty (Class 7-8) electric vehicle maintenance technology and training?

( ) Slow advancement. In this scenario, EV repair infrastructure and training for proper EV maintenance does not achieve widespread adoption.

( ) Moderate Advancement. In this scenario, EV repair infrastructure and training for proper EV maintenance is adopted but is not as widespread as that of conventional heavy-duty vehicles.

( ) Rapid Advancement. In this scenario, EV repair infrastructure and training for proper EV maintenance is rapidly adopted and is comparable to conventional heavy-duty vehicles.

9) Based on your experience with the deployment of new technologies for conventional vehicle maintenance, which of the below scenarios would you rate as most likely for the widespread implementation of medium-duty (Class 3-6) electric vehicle maintenance technology and training?

( ) Slow advancement. In this scenario, EV repair infrastructure and training for proper EV maintenance does not achieve widespread adoption.

( ) Moderate Advancement. In this scenario, EV repair infrastructure and training for proper EV maintenance is adopted but is not as widespread as that of conventional heavy-duty vehicles.

( ) Rapid Advancement. In this scenario, EV repair infrastructure and training for proper EV maintenance is rapidly adopted and is comparable to conventional heavy-duty vehicles.

AVERAGE DAILY MILES TRAVELED PER VEHICLE

10) Which range of daily miles traveled per vehicle is most representative of your current retail-related operations with Heavy-Duty Vehicles (Class 7-8)

Average Daily Miles Traveled per Vehicle

	No Vehicles	Some Vehicles	Most Vehicles	All Vehicles
0-50 Miles	( )	( )	( )	( )
51-150 Miles	( )	( )	( )	( )
151-250 Miles	( )	( )	( )	( )
251-500 Miles	( )	( )	( )	( )
500+ Miles	( )	( )	( )	( )

11) Which range of daily miles traveled per vehicle is most representative of your current retail-related operations with Medium-Duty Vehicles (Class 3-6)

Average Daily Miles Traveled per Vehicle

	No Vehicles	Some Vehicles	Most Vehicles	All Vehicles

0-40 Miles	( )	( )	( )	( )
41-70 Miles	( )	( )	( )	( )
71-100 Miles	( )	( )	( )	( )
101-130 Miles	( )	( )	( )	( )
131-250 Miles	( )	( )	( )	( )
250+	( )	( )	( )	( )

FUELING BREAKDOWN

We are interested in understanding how you fuel your fleets and using that information to inform our estimates of where electric vehicles will refuel. We'll ask you how often you refuel different types of vehicles on-site, at another hub-site, or a publicly available fueling site.

12) For vehicles performing short hauls (100 or fewer miles traveled per day, on average) how are various fueling options typically leveraged? Please indicate using approximate percentages (0 if not used).

_____% On-Site Fueling

_____% Another Hub-Site

_____% Publicly Available Stations

13) For vehicles performing intermediate range (100-250 miles traveled per day, on average) how are various fueling options typically leveraged? Please indicate using approximate percentages (0 if not used).

_____% On-Site Fueling

_____% Another Hub-Site

_____% Publicly Available Stations

14) For vehicles performing long hauls (250 or more miles traveled per day, on average) how are various fueling options typically leveraged? Please indicate using approximate percentages (0 if not used).

_____% On-Site Fueling

_____% Another Hub-Site

_____% Publicly Available Stations

15) If on-site fueling is used, is refueling typically done overnight during downtime?

( ) Yes

( ) No

( ) Not Applicable

16) Based on your staffing history and if you were to purchase a fleet or part of a fleet of electric truck vehicles, would hiring an additional staff-member or members to manage overnight recharging of electric vehicles be a viable consideration for your company?

( ) Yes

( ) No

17) Installing electric vehicle charging stations, also known as electric vehicle supply equipment (EVSE), will likely be a key component of integrating electric vehicles into commercial operations. What is the price range you would estimate for charger installation at a depot?

( ) $15,000-$30,000

( ) $30,000-$90,000

( ) $90,000-$200,000

( ) $200,000-$550,000

( ) Unsure

21) Which of the following is/are part of the basis for your estimation for the above (check all that apply):

[ ] Quotes received from manufacturers

[ ] Publications on Electric Vehicles

[ ] Information from other companies

[ ] Rough guess based on knowledge of alternative fueling installation cost

APPENDIX C: SCENARIOS BY LIKELIHOOD AND SENSITIVITY VARIABLE

Variable Category	Variable Choice	Very Likely	Likely	Neither Likely nor Unlikely	Unlikely	Very Unlikely	Nearly Impossible
Charging Strategy	50/50	-	6	66	156	13,253	4,663
	Depot Charging	738	1,852	3,236	2,332	9,595	391
	Public Charging	-	8	37	77	3,011	1,187
Number of Charging Stations	10	17	192	564	648	7,979	2,696
	3	528	1,047	1,432	1,024	7,042	1,023
	5	193	619	1,306	816	7,827	1,335
Charging Station	50kW	646	1,425	2,235	1,594	17,104	2,916
	350kW	92	433	1,067	894	5,744	2,138
Charging Cost	Baseline	167	639	1,138	922	8,371	2,299
	Increased	49	354	993	792	8,661	2,687
	Reduced	522	873	1,208	851	8,827	1,255
Vehicle Incentives	No	200	566	1,113	991	13,560	3,874
	Yes	538	1,300	2,226	1,574	12,299	2,367
Maintenance Cost Reductions	50% Reduction	349	711	1,120	862	8,729	2,185
	30% Reduction	246	646	1,114	856	8,612	2,065
	Baseline	143	509	1,105	847	8,518	1,991
MSRP Reductions	10% Reduction	139	425	814	598	6,553	1,623
	20% Reduction	209	510	844	668	6,453	1,468
	30% Reduction	301	586	906	745	6,265	1,349
	No Reduction	89	345	775	554	6,588	1,801
Years of Ownership	3	257	728	1,201	944	8,683	2,509
	5	252	646	1,101	896	8,660	1,981
	7	229	492	1,037	725	8,516	1,751
Procurement Method	Cash Purchase	244	817	1,581	1,232	13,146	3,284
	FMV Closed-End	494	1,049	1,758	1,333	12,713	2,957
Total		738	1,866	3,339	2,565	25,859	6,241

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