Integrated Modeling Program and Total Cost of Ownership Calculator for Medium-Duty and Heavy-Duty Battery Electric Trucks in Regional Freight Use-Case Deployments

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A Research Report from the National Center for Sustainable Transportation

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16. Abstract
This report outlines the technical development and application of the Total Cost of Ownership Spreadsheet Tool (TCOST), a Microsoft Excel-based calculator that simplifies and integrates the main functions, data, and outputs of pre-existing models (MOVES-Matrix and the GREET Model) and other external sources of economic data. The tool accommodates twenty-one user-input variables to produce comparative total cost of ownership figures for diesel and battery-electric trucks within any use case, broken down by cost type (capital, operation, and maintenance), both as a gross number and on a per-mile basis. The tool also provides a series of visualizations comparing cost breakdowns, breakeven points, and expected tailpipe and fuel-cycle emissions for both technologies. A hypothetical regional container drayage use-case example was developed using quantitative and qualitative data, to which TCOST was applied to demonstrate the application of the tool and its value to fleet managers and policymakers in its ability to model the cost effects of minor parameter adjustments or the multiplicative effects of simultaneous parameter adjustments quickly and easily. TCOST may be used to help inform the decision-making process for fleet vehicle acquisition and planning, helping decision makers to visualize a variety of future scenarios and map those scenarios onto their fleet operations to assess risks and make informed choices about the future technological makeup of their fleets. TCOST will help policymakers quickly model the cost impacts of potential policy levers from a business perspective.

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EXECUTIVE SUMMARY

Over the past decade, battery-electric vehicle (BEV) technologies have made tremendous strides in technical performance and cost-effectiveness, compared to conventional combustion engines. The ability of BEVs to reduce emissions and operating costs has catapulted the technology to the forefront of conversations within sustainable transportation, especially with increasing downward pressure by an evolving policy landscape on fleet operators and original equipment manufacturers (OEMs) to reduce the on-road environmental footprint of their vehicles. So far, the vast majority of successful BEV deployments have occurred in light-duty market segments, but heavier vehicle classes are beginning to receive more attention for their electrification prospects.

Medium- and heavy-duty vehicles (MHDVs) represent significant opportunities for the deployment of BEV technologies. While some success has been achieved in electrifying transit buses, the vast majority of MHDV on-road activity is in freight transportation. Freight trucks are responsible for nearly 25% of emissions from the U.S. transportation system, or about 7% of national greenhouse gas (GHG) emissions. In addition to GHG emissions, diesel truck activity is currently a major source of criteria pollutant emissions, including fine particulate matter and oxides of nitrogen, which can be detrimental to human health and the environment. OEMs have identified MHDVs in freight applications as a potential market for BEV technology and have begun to advertise electric MHDVs to fleet operators as opportunities to reduce operating and maintenance costs. However, the benefits of electrification can be highly nuanced and may vary substantially depending on complex interactions between vehicle activity, duty cycle, payload, and the physical environment, including road topography and meteorology, as well as characteristics from the electrical power grid used to charge battery electric vehicles.

A central issue for BEV deployment in the freight sector is advancing the understanding of the specific vehicle use-cases and operational conditions for which electrification is a viable solution. Identifying the business activities and business economic environment, coupled with on-road operating activity conditions in which BEVs can successfully replace conventional vehicles, is complicated. However, achieving the highest impact reductions in emissions and reduced operating expenses is critical to ensuring that the most effective deployments of battery vehicle technology are implemented. This report outlines methods that can be used to quantify the lifecycle energy use, emissions, and economic implications of targeted deployments of electric trucks within freight use cases and optimal operating conditions for electrification. This report will demonstrate the quantification process for a hypothetical regional container drayage use-case example.

To aid in investigations of this nature, the research presented in this report outlines the technical development, and intended applications of a new tool dubbed the Total Cost of Ownership Spreadsheet Calculator (TCOST). The new TCOST model integrates a set of simplified functions with energy use and emission rate outputs from a group of preexisting models to produce comparative lifecycle emissions, energy consumption, and total cost of ownership figures for battery-electric and conventional diesel trucks performing the same on-road activity. The tool is intended to facilitate expedited and simplified inquiries into the technical and cost comparison between conventional trucks and comparable BEVs, to identify use-cases and conditions that should be prioritized for electrification so that ongoing electrification investment will maximize economic and environmental benefits over time. The tool's broad applicability, facilitated by its simple interface and customizable user-inputs that support the assessment of a vast array of possible modeling scenarios, will be of great value to a diverse range of fleet operators and policymakers, because the model provides a simple method for gaining quick insights into the economic and environmental implications of fleet management and regulatory decisions.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) concluded that only rapid, deep decarbonization, and implementation of climate change mitigation actions by the end of this decade can reduce disruptive and costly damage to human and natural systems [1]. Given the high risk of deleterious consequences of delayed implementation of greenhouse gas (GHG) abatement programs, given that transportation is the highest-emitting economic sector in the United States (responsible for more than 25% of total GHG emissions), and given the criticality of road transportation subsystems to higher order social and economic systems, the IPCC places great emphasis upon the accelerated maturation of alternative transportation fuels, low-emissions vehicle technologies, and reconfigured operational designs to pursue reduced energy consumption and GHG abatement. In recent years, accelerated rates of innovation have made alternative powertrains (parallel hybrid, plug-in hybrid (PHEV), battery-electric (BE)), and fuels (electricity, compressed/liquified natural gas (C/LNG), hydrogen (H_2)) much more competitive with traditional fossil fuel powered internal combustion engine (ICE) powertrains in the light-duty vehicle (LDV) market. LDV BEVs have made especially large strides in technological maturation, supported by multilateral policy encouraging research, development, adoption, and charging infrastructure network improvements.

While electrification prospects for LDVs are well established, those for medium- and heavy-duty vehicles (MHDVs) are less clear. MHDVs are essential to nearly all sectors of the economy and represent significant opportunities for BE technology deployments. In 2019, nearly 12 billion tons of freight were moved by MHD trucks, representing nearly 64% of national freight tonnage and value. Tonnage is expected to grow by about 1.4% per year until at least 2050 [2]. Additionally, 25% of fossil fuel consumption and GHG emissions from transportation in the United States come from MHDVs [3]. Because a typical MHDV consumes much more fuel than a LDV, each electric MHDV can yield greater environmental benefits than a single electric LDV. The scale and importance of trucks to the global economy and their corresponding energy consumption has given rise to a growing catalogue of BE MHDV models on the market for freight applications [4]. Original equipment manufacturers (OEMs) have identified an emerging market for BE MHDVs, advertising them to fleet operators as an opportunity to reduce operating and maintenance (OM) costs and their ecological footprint. While environmental benefits of BEVs are broadly appreciated, they can vary substantially depending on complex interactions between vehicle behavior (such as on-road driving cycle and payload), the physical environment (such as topography and meteorology), as well as characteristics of the electrical power grid used to charge these vehicles [5].

Due to the nuanced complexities of freight truck electrification, the MHDV market has focused BEV deployment strategies to target specific vocations that have operational characteristics that are the most conducive to electrification. Local small parcel delivery vehicles have received the most attention, due to the relatively low daily miles travelled (i.e., within the range of a single battery pack charge) and lower loads and less strenuous duty-cycles that do not require larger battery capacity. Signaling the attractiveness of BEV deployments in parcel delivery vocations, the United States Postal Service (USPS) awarded contracts for over nine thousand

BEVs and over fourteen thousand charging stations in early 2023 in support of the agency's stated goal to make 75% of its newly acquired vehicles electric, rising to 100% in 2026 and thereafter [6]. The United Parcel Service (UPS) has a similar goal of reaching 40% alternative fuel in the company's ground operations by 2025 and carbon neutrality by 2050. UPS currently boasts over one thousand BEVs and PHEVs on the road in support of that goal and has agreements in place to purchase thousands more [7]. Other vocations have also begun to reap the benefits of BE MHDVs in recent months as well. In late 2022, PepsiCo received the first order of Class 8 Tesla Semi electric trucks for deployment in their beverage delivery operation. Frito-Lay, a PepsiCo subsidiary, deployed 40 electric vans within their North American division last year [8]. PepsiCo's Class 8 heavy-duty trucks will operate on short and regional haul duty cycles. While the electrification of long-haul heavy-duty semitrucks has been studied closely, the significantly greater trip lengths, payloads, and subsequent greater energy demands and fuel consumption, necessitate larger and more powerful batteries for HDV electric powertrains than are provided by current technology in most cases. BEV models capable of long-haul operations are on the horizon, but existing BE MHDVs have operational ranges of less than 250 miles, with a few but growing number of exceptions [9].

Policy levers orchestrated by local, state, and national governments have also helped to accelerate much of the recent growth observed in truck freight electrification. In 2021, the California Air Resources Board (CARB) finalized their Advanced Clean Trucks rule, setting a standard requirement for 50% of new medium- and light heavy-duty vehicle (Class 4-6) and 30% of new heavy-duty tractor (Class 7-8) sales to be zero-emitting by 2030 as shown in Table 1 [10]. CARB is currently taking public comments on an updated clean trucks plan that is even more ambitious [11]. New York state adopted a similar rule, establishing a ratcheting standard for percentage of new electric MHDV sales as a share of total MHDV sales, culminating in 100% of new MHDVs registered in the state being zero-emitting by 2045 [12]. In addition, a coalition of 17 US states plus Washington D.C. and the province of Quebec, Canada signed a memorandum of understanding in 2022 committing to reaching 30% of new MHDV sales being zero-emitting by 2030, rising to 100% by 2050 [13]. This coalition estimates the potential net economic savings of the full electrification of the national MHDV fleet to be as much as $140 billion cumulatively, across the vehicles' lifetimes [14].

Table 1. BE truck sales percentage schedule (CA Code of Regulations 1963-1963.5) [10]

Model Year	Class 4-6	Class 7-8
2025	11%	7%
2030	50%	30%
2035 and beyond	75%	40%

At the Federal level, the United States Environmental Protection Agency (U.S. EPA) announced a proposed rule that applies more ambitious pollution standards to heavy-duty vocational vehicles, and CARB projects that the new rule will avoid 1.8 billion metric tons of GHG emissions between 2027 (the first model year subject to the rule) and 2055, and provide significant particulate matter and other criteria pollutant emission reductions. According to the U.S. EPA, the industry can meet the new standards by achieving 50% zero-emissions vehicles for vocational vehicles, 34% for day use tractors, and 25% for sleeper cab tractors in MY2032, with a mix of BE and fuel cell technologies. The U.S. EPA also projects significant savings for electric MHDV purchasers due to reduced operating costs, despite increased upfront costs and after accounting for available battery tax credits [15].

The regulatory focus on, and the consideration afforded to, electric trucks in present and future plans of players in the road freight industry signal an emerging alignment on the public and business benefits of electric MHDVs. There is widespread agreement in the freight industry that electrification can be a sound business choice, with operating mode savings surpassing higher MSRPs relatively early in the ZEV's useful lifetime. In support of their rulemaking, the U.S. EPA found that most zero-emitting MHDV purchasers would offset their increased upfront costs, including the cost of electric vehicle supplementary equipment (EVSE) like charging infrastructure, with operational savings within three years of ownership [15]. Elsewhere, Gao et al (2017) simulated energy consumption of a Class 7 local food delivery truck and found a battery electric or Power-GenSet PHEV (Power-GenSet implying the vehicle's downsized combustion engine is used only to generate electricity to recharge the PHEV battery when needed) can reduce the overall cost for energy by 29 to 44 percent, with the noted variability attributable to on-route charging availability, payload characteristics, and other factors [16]. However, these authors did not consider the increased cost of electric powertrain technology. Another study assumed a MSRP differential of around $100,000 between a conventional Class 8 diesel and battery-electric semi-truck and found a baseline payback period for the BEV of 3.24 years ±1.46 years [17].

The reality remains, however, that the magnitude of savings and payback periods are heavily dependent upon each vehicle's routes, on-road operating characteristics, and the design of the freight distribution system for each electrification application. A primary analytical goal of fleet electrification assessment is to identify what makes one use-case more attractive for BE technology deployment than another. This requires knowledge of the operational configurations of the fleet and availability of an analytical tool that can assess electrification benefits. A simple, standardized technoeconomic analytical framework can leverage preexisting economic and lifecycle models, while also reducing the modeling knowledge required to evaluate the electrification merits for specific conditions. The TCOST model is designed to help identify feasible use cases that can lead to the most efficient rollout of electrification within specific sectors/businesses in the MHDV fleet. The TCOST model implements an economic analysis framework that can be applied to any freight sectors wherein fleet composition, freight loads, and on-road activity can be quantified, and then calculates economic benefits and disbenefits of BEV deployment, as well as energy use and emission reduction benefits by applying existing energy use and air quality models (the U.S. Environmental Protection Agency's MOVES model, implemented in a matrix form known as MOVES-Matrix, and the U.S. Department of Energy's GREET model) within the economic analysis framework. As part of this research, an example short-range to-mid-range MHDV freight use-case is assessed using TCOST for the state of Georgia. The use-case example operating profiles presented in this report indicate how specific drayage freight flows can bring into focus the characteristics that help or hinder electrification potential.

The Total Cost of Ownership Spreadsheet Tool (TCOST) is provided as a Microsoft Excel®-based model (https://doi.org/10.5281/zenodo.14589111), distilling the framework utilized in the use-case evaluation down to a simple user interface with a series of inputs to customize calculations for user-defined use-cases. TCOST integrates primary data, functions, and assumptions of MOVES-Matrix for "Pump-to-Wheels" (PTW) energy consumption and emissions rates, and the DOE GREET model (for fuel pathway mixes and upstream "Well-to-Pump" (WTP) energy consumption) while also incorporating from the literature, additional information relevant to the simulations. TCOST expedites the analytical process and vastly reduces required modeling knowledge for MHDV electrification analyses, removing knowledge barriers and facilitating more efficient and effective decision-making for freight brokers and MHDV fleet managers.

Finally, TCOST is applied to the previously defined use-case to demonstrate its utility for fleet managers and planners as a simplified method for back-of-envelope calculations using a handful of user inputs to assess benefits and inform decision-making. The TCOST application to the use-case serves as an instructional model for future use of the tool.

Truck Freight Use-Case Study within Georgia's Freight System

Understanding the form, trends, and operational conditions of Georgia's freight system is important because it provides a context against which individual vocations can be evaluated. Handling over 850 million tons of freight flows annually, the state of Georgia boasts one of the most robust freight networks in the United States. The state is home to the nation's most significant airport for air cargo with Hartfield-Jackson International (HJIA), the fastest growing container port with the Port of Savannah (POS), and the southeast hub of operations for two Class I railroads in the eastern U.S. with Norfolk Southern (NS) and CSX. Georgia's Interstate system is in the top ten among states for interstate miles (1,243 miles), and Georgia has an extensive network of state highways and local roads providing enhanced connectivity. The state's logistic industry is a critical component of the state economy; in 2018 logistics was responsible for about 7% of Georgia's GDP ($46.6 billion) and nearly 500 thousand jobs, including 239 thousand direct jobs [18].

In Georgia, 75% of total 2018 freight flows by weight (excluding the pipeline mode) are carried by truck, with almost the entire remaining 25% of total tonnage carried by rail. An even larger share of freight value (about 88%) was carried by truck [18]. Truck freight is uniquely positioned to provide door-to-door service between almost any origin and destination, enabling highly flexible delivery scheduling at low cost and on short notice. For this reason, truck mode share and total volume in Georgia are forecasted to grow substantially, in line with the growth of same-day or next-day deliveries associated with e-commerce. Truck freight flows in Georgia are expected to grow anywhere from 1.5% per year (TRANSEARCH estimates) to 2.2% per year (American Trucking Association (ATA) and Economy.com estimates) through mid-century [19].

Georgia’s truck freight system activity is geospatially centered around the Metro Atlanta region as well as the Port of Savannah. Atlanta is the second largest population center in the southeast U.S. and is a major manufacturing and commercial hub. The Port of Savannah is the second busiest container port in terms of total throughput on the East Coast [20]. Figure 1 shows the convergence of multiple significant freight corridors in Georgia’s Atlanta region for both interstate (within state) and intrastate (between state) commodity flows. Figure 2 is from the Atlanta Regional Commission’s (ARC) latest regional freight mobility plan published in 2016 and depicts truck volumes on the Interstate system and state highways in the Atlanta region. The dense truck traffic on the I-285 perimeter is primarily due to interactions between through truck movements generated outside of the metro area with destinations also outside of the region (trucks may not enter the I-285 Perimeter without a permit to pick-up or drop-off freight), coupled with local delivery trucks transporting goods between warehouses and distribution centers and to locations within the region. The top twelve truck count locations in Georgia are in the Atlanta metropolitan region [19]. The restriction of activities on I-75 and I-85 inside the I-285 perimeter lead to comparatively low truck counts on those thoroughfares.

The Atlanta-Savannah corridor is especially significant to the economic wellbeing of Georgia as it connects the state’s regional economic and population center with the Southeast’s primary link to the international market at the Port of Savannah. Over 100 thousand loaded trucks complete trips between Atlanta and Savannah every year (averaging more than 400 trucks per day, assuming 250 workdays in a year), and three intermodal trains also depart every day [20]. These numbers have only grown since the Georgia Ports Authority completed a deepening project in Savannah harbor in 2022, which is estimated to allow a typical container ship to load an additional one thousand containers and increase import and export volumes at the Port of Savannah [21].

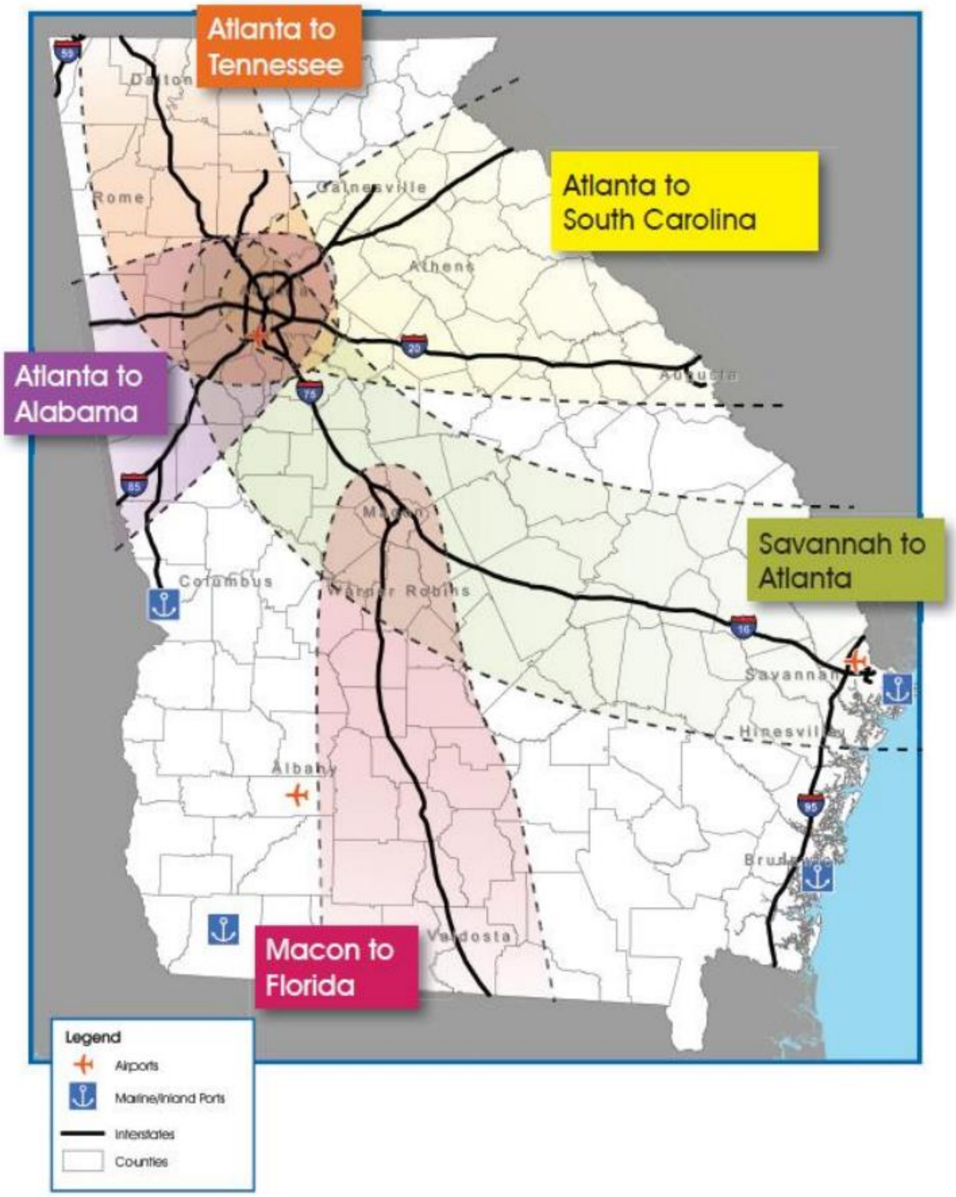


Figure 1. Significant freight corridors in Georgia [19]

Figure 2. Truck volumes in the Atlanta region [20]

The growth of the Port of Savannah has been accommodated by the maturation of intermodal drayage systems that provide more efficient container freight flows via inland ports in central Georgia, the Atlanta region, and beyond. For example, the Cordele Intermodal Facility (CIF) in Cordele, GA, is a prominent private truck-rail intermodal transfer facility located south of Macon, GA that boasts direct railroad service to the Port of Savannah. Incoming and outgoing containers can be moved by freight rail between CIF and Port of Savannah, being loaded and offloaded onto trucks further inland at CIF [22]. The inland, central location of CIF shortens the distance of required truck trips rather than relying entirely on direct truck service to POS; CIF is 64 miles from Macon, 147 miles from the Norfolk Southern Inman Yards intermodal complex in the Atlanta area, 121 miles from Tallahassee, Florida, and within much shorter distances to agricultural production centers in south-middle Georgia. Trucks need to travel less than two miles from CIF for I-75 access.

The Georgia Ports Authority (GPA) owns and operates inland ports of their own. Appalachian Regional Port (ARP) in northwest Georgia is operated in public-private partnership with CSX. ARP has direct CSX railway connection to the Port of Savannah and easy access to the I-75 corridor, providing inland intermodal transfers about 100 miles from both Atlanta and Knoxville, TN and 45 miles from Chattanooga, TN. GPA benchmarked the capacity of ARP at 50 thousand containers per year when it opened in 2018 and there are plans to double its capacity by 2028 [23]. GPA estimates each round-trip container moved by rail to and from ARP to offset 710 truck miles on Georgia's highways and the port diverts up to 40 thousand trucks from Atlanta area roadways each year [18, 24]. Bainbridge Terminal in southwest Georgia primarily handles intermodal transfers for containers traveling by barge on the Apalachicola-Chattahoochee-Flint waterway system in that part of the state. Construction plans for another inland port facility in Hall County, northeast of the Atlanta region, gained federal environmental approval in May 2023. GPA estimates construction to be completed in 2026 [25]. There are also five additional intermodal rail terminals located in the Atlanta region [20].

Expansion of intermodal and inland port capabilities can significantly lower transportation costs for commodity import and export flows, helping to make global markets more cost-competitive, accelerating regional economic development, and attracting business. By extending the gates of container ports inland, inland port systems enable shippers to efficiently serve new logistics pathways supporting online business divisions and e-commerce. Being able to serve customers with next-day, same-day, or even one-hour parcel deliveries is highly valuable to businesses, and many have reorganized their supply chains into multichannel configurations by replacing regional distribution centers with smaller, forward distribution centers in urban areas. Many of these warehouses need to be replenished with multiple incoming truckloads each day, in addition to generating many outgoing trips for local deliveries. Such fulfillment centers are increasingly co-located with manufacturing centers and intermodal ports, leading to more numerous and larger freight clusters around intermodal rail heads [20].

Three commodities, "mixed freight," "plastics and rubber," and "other foodstuffs," appear in the top ten commodities in Georgia for both ton-miles and value [26]. Mixed freight is a commodity group suggesting the cargo consists of a variety of different types of products. It is the most common commodity arriving at distribution centers as well as many retail businesses and restaurants because the commodity can include certain food items, hardware, office supplies, clothing, and much more [27]. Because distribution centers often handle a variety of goods to serve their customers, the generalized nature of the mixed freight commodity make it a useful classification and reduce administrative burden, compared with using multiple specific product classifications. While not all mixed freight movements can be unequivocally associated with distribution centers, freight flows for the commodity are more likely to be observed along intermodal freight systems in drayage movements between intermodal terminals and fulfillment centers, and beyond in delivery movements to customers and points of sale. Because of its expected on-road behavior, the commodity is more likely to be one that could technically achieve high penetration of BE truck technology.

The frequent proximity of forward distribution centers, intermodal ports, and population centers improve electrification prospects for vehicles on freight vocations connecting these locations by shortening typical trip distances and encouraging a "out-and-back" tour cycle, where trucks begin and end their routes at the same location, making charging equipment siting more straightforward. It is hypothesized that trips to and from intermodal ports could have a relatively high number of operational characteristics that make these flows high value opportunities for investment in BE deployments, especially as intermodal flows continue to grow. High utilization and miles traveled typically improve the economics of BEVs. Increasing trip frequencies could represent increasing electrification benefits, so long as BE technology can adequately fulfill service demands within the constraints of battery capacity and charging requirements. Exploring these parametric relationships and testing these hypotheses was central in the design of the use-case study.

Use-Case Selection

In the developing a use-case profile, national truck freight trends were first examined, to help inform assumptions about truck activity in Georgia where data gaps exist. National freight statistics provide a more comprehensive understanding of the broader freight system and trends, which can be scaled down to state-level systems. Many currently observed trends in the United States freight network have energy use implications that are important to consider as technical and economic electrification feasibility is studied. Doing so provides critical context for the activity of any specific use-case and helps to enable transferability of findings of electrification analyses such as these. That is, understanding overall trends makes it easier to identify patterns as well as outliers of system form and function that positively or negatively affect electrification potential, making identification of ideal use-cases simpler. This study considers several national truck freight trends that have a direct influence on use-case energy consumption and technoeconomic feasibility of BEV technology deployments:

- In 2022, 73.8% of weight and 55.5% of value of goods traveling by truck mode moved less than 250 miles between origin and destination, as depicted in Figure 3 [28]. Most of these freight flows, assuming payloads and driving conditions are reasonable, fall within the technically achievable operational range of current BE technologies.
- About 95.7% of MHDV fleets consist of ten or fewer trucks, and 99.7% of MHDV fleets operate with fewer than one hundred units [29]. Operational data for private fleets is not accessible to the public. However, understanding the typical fleet size is important for assessing the benefits of any economies of scale that arise from investing in multiple BEVs at once, such as those from charging equipment investments. It is also valuable for benchmarking charging demand and modeling different fleet charging schedules.

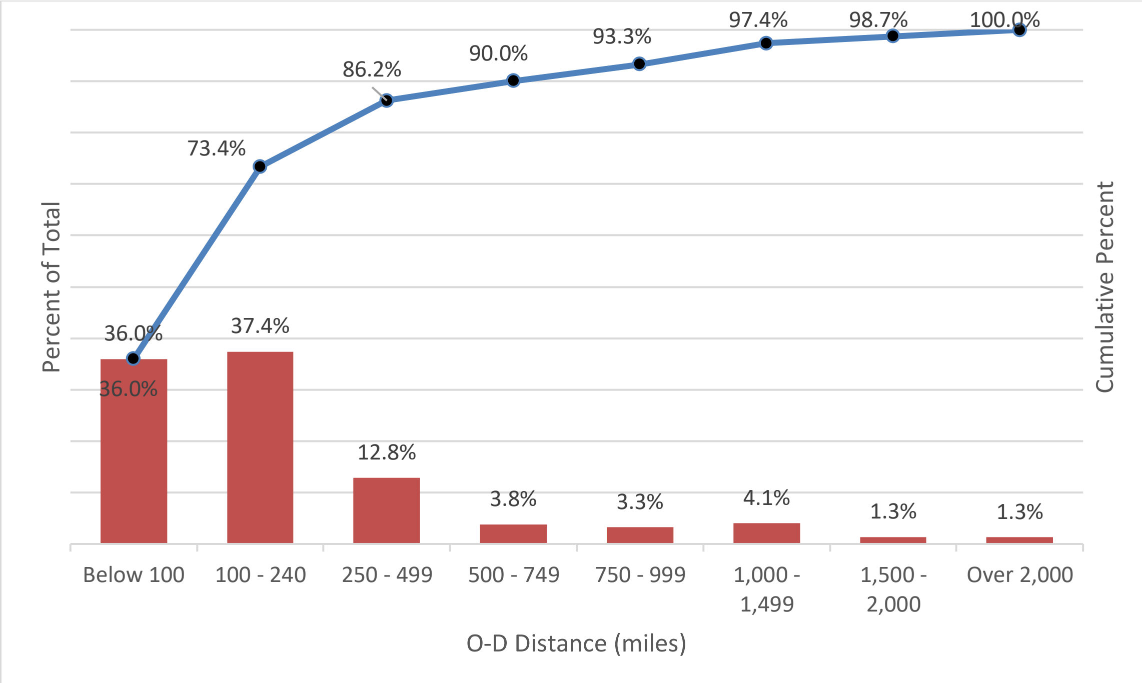


Figure 3. Total freight moved by distance in 2022 [28]

Keeping these national observations in mind, a MHDV use-case in Georgia was identified for further electrification analysis. Given the lack of access to proprietary operational data for private fleets, the use-case is largely reconstructed using assumptions to fill data gaps to create realistic hypotheticals. Relevant operational characteristics and model inputs cannot be known without private industry participation, so the analysis is supplemented by robust sensitivity analysis to evaluate a range of possible iterations of the same overall freight movement. For a fleet manager performing such an analysis, much of the missing data would be known and the analysis could be similarly executed but with much greater precision.

Appalachian Regional Port Drayage

The use-case designed for further analysis is a hypothetical mixed-freight drayage operation from ARP to a distribution center in Adairsville, Georgia, northwest of the Atlanta metropolitan area. ARP is in Murray County in central north Georgia and serves as an intermodal transfer facility, switching containers between rail and heavy truck. The facility is directly serviced by CSX, which offers rail service on a direct route of 388 miles to the Port of Savannah Garden City Terminal. Its capacity is over 50 thousand containers per year, and it is on target to grow to handle 100 thousand containers per year by the end of the decade [23]. The plans for the facility are shown in Figure 4.

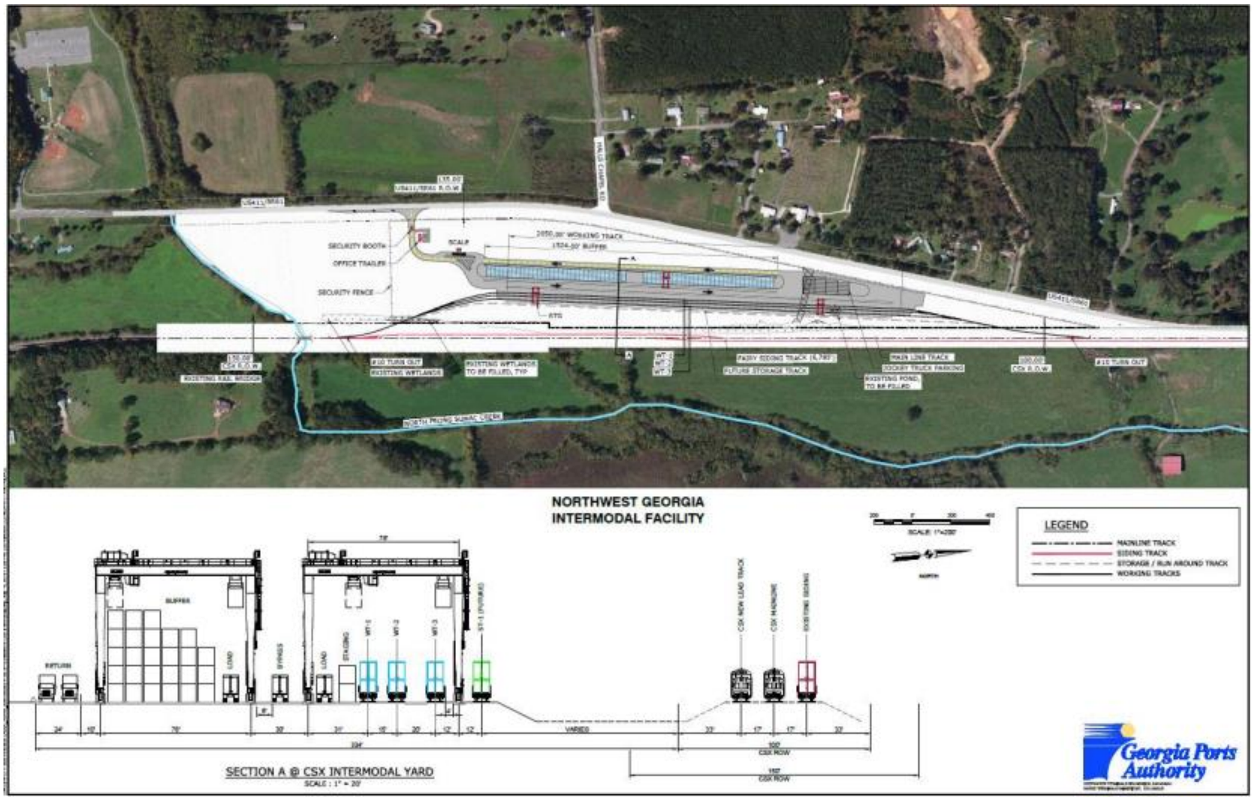


Figure 4. Appalachian Regional Port facility [30]

The distribution center is modeled on the 1.4 million square foot distribution center for a major hardware retailer that exists on the location [31]. This terminus is 61.1 miles from ARP using a truck-friendly route [32]. Figure 5 shows the route in Google Maps and Table 2 breaks each leg of the route into segments and portrays some of their roadway characteristics.

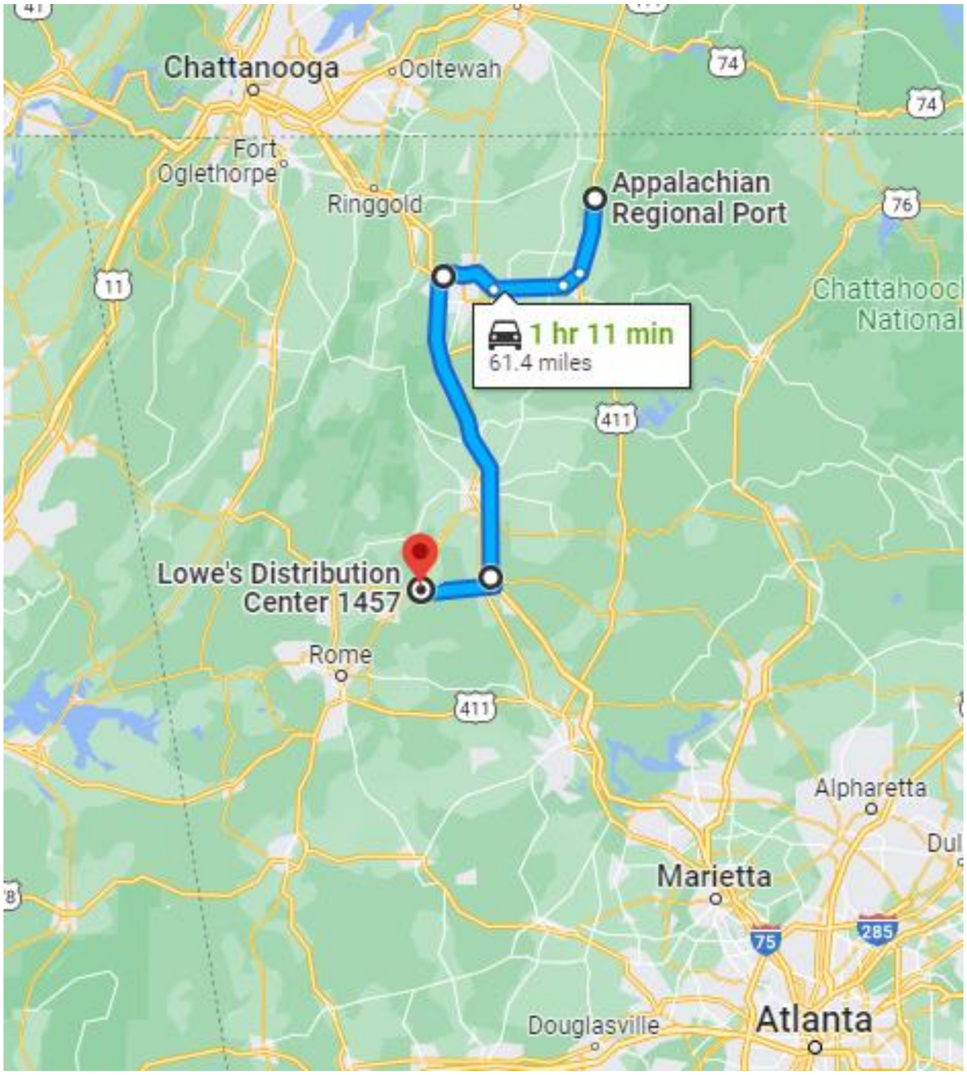


Figure 5. ARP to distribution center drayage use-case route [33]

Note: The discrepancy between the Google Maps portrayed distance and the actual on-road distance is due to a Google Maps routing error misprocessing the outbound alignment of the ARP to be right-turn only. The actual distance is 61.1 miles.

Table 2. Route segment attributes

No.	Road	Segment Length (miles)	Speed Limit (mph)	Road Class	Notes
1	**US 411/GA 2/ GA 61**	8.0	35/45	Major collector	2 lanes at ARP, growing to 4 on southbound approach to Eton, GA
2	**US 76/GA 52**	8.3	45	Principal Arterial	4 lanes
3	**US 41/US 76/GA 3**	6.1	45	Principal Arterial	4 lanes
4	**I-75**	30.2	70	Interstate	6 lanes
5	**GA 140**	7.6	50	Minor Arterial	4 lanes through Adairsville, 2 lanes from Adairsville to end of segment. Construction is ongoing to make 4 lanes for the entire segment.
6	**Prosperity Way**	0.3	Not posted	Local Road	2 lane access road. Distribution center is only business on alignment.

Container drayage is typically conducted using Class 8 combination tractor trailer day cab units. For this use-case, we assume that the fleet is a small privately owned and operated third-party logistics (3PL) operation consisting of three MY 2008 Class 8 combination trucks, all performing similar drive cycles on the same route. The trucks are assumed to travel from ARP to the distribution center with a full 20-foot shipping container of payload. Upon arrival, the full container is unloaded on-chassis at a staging area or delivery bay. The truck then picks up an empty container chassis and returns to ARP. The total distance of the tour on public roads (i.e., from gate to gate) is 122.2 miles. The vehicles have been operating on this vocation since their acquisition. The owner-operator is planning to evolve their fleet and is seeking to understand how the energy use and economic implications of fleet management decisions will affect their business. They have decided to replace their vehicles with new MY 2023 trucks and want to understand electrification potential for their operation. To quantify the pros and cons of fleet electrification compared to the purchase of new traditional diesel trucks, we analyze both on-road and upstream energy consumption and emissions for each technology and fuel type for this use-case. We also quantify fuel, maintenance, and capital costs of both purchasing scenarios.

MOVES is the federal regulatory model for quantifying on-road emissions and energy consumption for any use-case. MOVES essentially calculates the second-by-second power demand (kilowatts per metric ton) for a vehicle in units of vehicle specific power (VSP), or in the case of heavy-duty vehicles, scaled tractive power (STP). STP is essentially equivalent to VSP, except that STP integrates a large fixed mass factor to account for medium-duty and heavy-duty vehicle payload. VSP and STP are functions of vehicle speed, acceleration, and mass (see Equation 1):

$$VSP\ (STP)_t = \left(\frac{A}{M}\right) v_t + \left(\frac{B}{M}\right) {v_t}^2 + \left(\frac{C}{M}\right) {v_t}^3 + \frac{m}{M}(a_t + g \times sin\theta_t) v_t \qquad (1)$$

VPS is calculated at 1-hz resolution, where *A* is rolling resistance in kW-sec/meter, *B* is rotating resistance in kW-sec^2/m^2, *C* is aerodynamic drag in kW-sec^3/m^3, v_t is velocity in m/sec at time *t*, a_t is acceleration in m/sec^2 at time *t*, *g* is gravitational acceleration (9.81 m/sec^2), ϑ_t is road grade in degrees, *m* is vehicle mass in metric tons, and *M* is a scaling factor to relate VSP and STP ranges [35].

For this analysis, road grade impacts on energy consumption are not considered. This area of northern Georgia does possess considerable elevation changes and the presence of grade on truck routes could significantly improve or hinder electrification process. Route segments with high percentages of downgrade are opportunities for energy savings and charge regeneration via regenerative braking systems. Routes with steep upslopes increase energy demand on the driving cycle. Given that downgrades never recover all of the energy lost moving uphill, routes with significant grace can limit the feasibility of some routes for BE MHDV applications. Grade effects impact outcomes on a case-by-case basis and warrant inclusion in subsequent studies but are out of scope here. In the TCOST tool, which will be discussed in the next section, energy demand effects of road grade are captured by the fuel consumption user input which informs the model's energy use assumptions.

To calculate VSP for every second of the vehicle's driving cycle, a driving cycle with 1-hz speed and acceleration data is required. To capture the energy consumption effects of evolving driver behavior across different road types on this tour, a composite driving cycle was created using various standard regulatory cycles for heavy duty trucks with some modifications. In this manner, the generated driving cycle was crafted to be as realistic as possible until telematic device deployment can provide second-by-second data. The driving cycle is one-way between ARP and the distribution center. Its profile is depicted in Figure 6, which is color-coded to show how each segment of the trip was combined. The composite driving cycle was manufactured using various heavy heavy-duty truck cycles made available by Georgia Tech through the U.S. EPA and state regulatory agencies. The beginning of Segment 5, which is the leg of the trip on GA 140 between the I-75 exit ramp and the distribution center access road (Prosperity Way), is a modified version of a U.S. EPA HHD truck creep cycle used for characterization for truck emissions in California [36]. The total travel time for this one-way driving cycle is 104.3 minutes. For simplification, we assumed a truck on this use-case would execute this driving cycle with a full container load before executing it again in reverse with an empty container as the return trip.

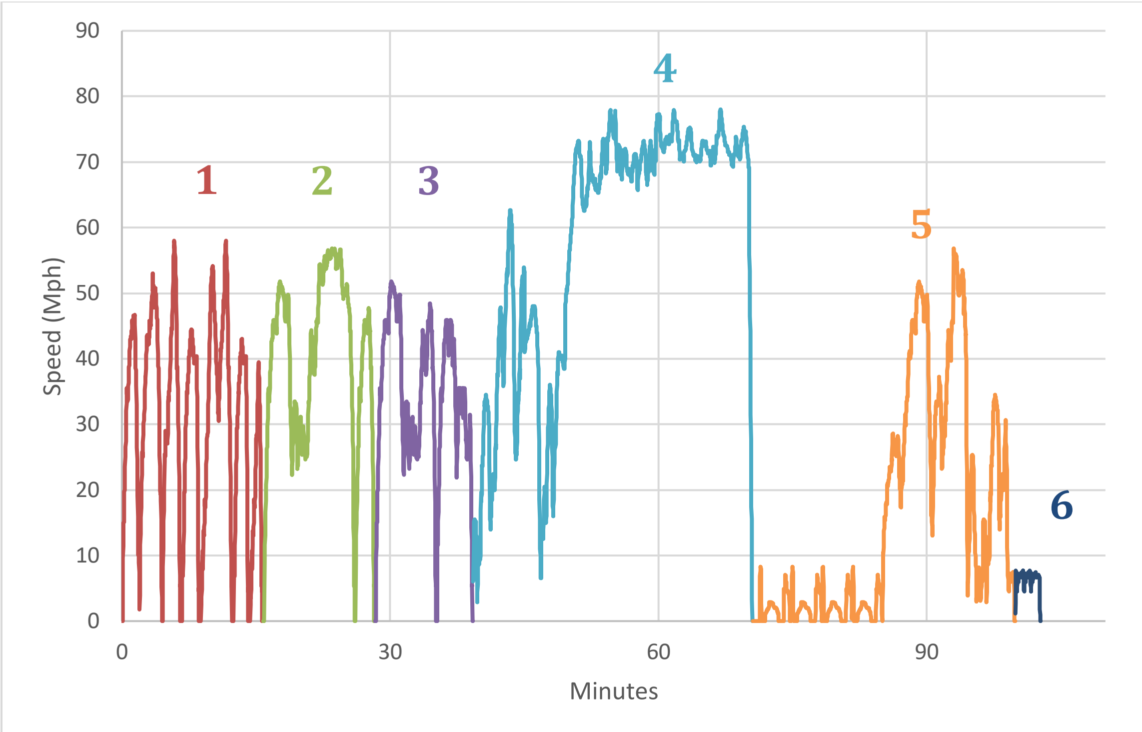


Figure 6. Composite driving cycle profile for ARP drayage use-case

MOVES-Matrix was developed at Georgia Tech to drastically reduce calculation times for MOVES runes by pre-processing hundreds of thousands of unique combinations of input variables and capturing outputs for lookup in a multidimensional array [37]. Here, the default physics parameters for a MY 2008 and a MY 2023 Class 8 combination long-haul truck (SourceTypeID 62 in MOVES-Matrix) were used for energy consumption calculations and are shown in Table 3. The default gross vehicle mass of 24.601 metric tons represents a curb weight of approximately fifteen metric tons and a payload on the order of ten metric tons. Figure 7 shows that this weight is in good agreement with available data [38-39]. Speed and acceleration rates were derived from the composite driving cycle.

Table 3. MOVES-Matrix default inputs (SourceType 62, MY2008)

A ***(kW-sec/m)***	**B** **(kW-sec^2/m$^{2)}$**	**C** **(kW-sec^3/m^3)**	***m*** ***(metric tons)***	***M*** ***(metric tons)***
1.63	0	0.004188	24.601	17.1

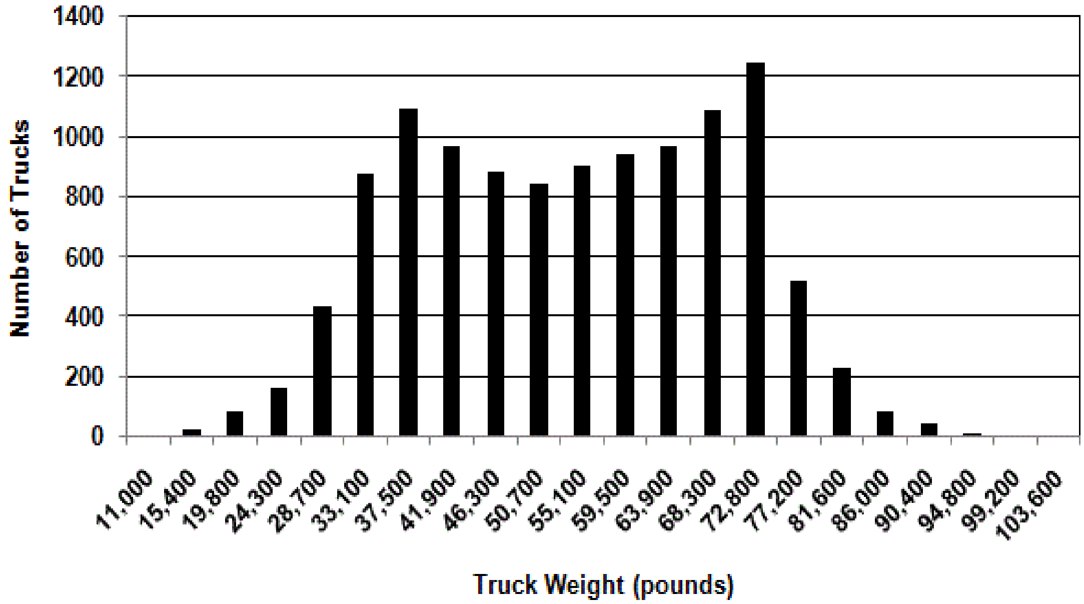


Figure 7. Heavy truck gross weight distribution [40]

STP was calculated for each second of the composite drive cycle for both MY trucks operating in 2022 and each second of operation was sorted into one of 23 operating mode (OpMode) bins. OpMode bin definitions are shown in Table 4. OpMode bin distribution for the composite cycle is shown by the histogram in Figure 8. Each OpMode bin has associated emissions and energy consumption rates from MOVES that are multiplied by the number of seconds in each bin. The sum of these products is the total energy consumed and emissions produced by the vehicle as it completes the driving cycle.

Table 4. OpMode bin definitions in MOVES

Speed bin	VSP bin (KW/tonne)	OpMode ID
0-25 mph	Braking	0
	Idle	1
	VSP < 0	11
	0 < VSP ≤ 3	12
	3 < VSP ≤ 6	13
	6 < VSP ≤ 9	14
	9 < VSP ≤ 12	15
	VSP ≥ 12	16
25-50 mph	VSP < 0	21
	0 < VSP ≤ 3	22
	3 < VSP ≤ 6	23
	6 < VSP ≤ 9	24
	9 < VSP ≤ 12	25
	12 < VSP ≤ 18	27
	18 < VSP ≤ 24	28
	24 < VSP ≤ 30	29
	VSP ≥ 30	30
>50 mph	VSP < 6	33
	6 < VSP ≤ 12	35
	12 < VSP ≤ 18	37
	18 < VSP ≤ 24	38
	24 < VSP ≤ 30	39
	VSP ≥ 30	40

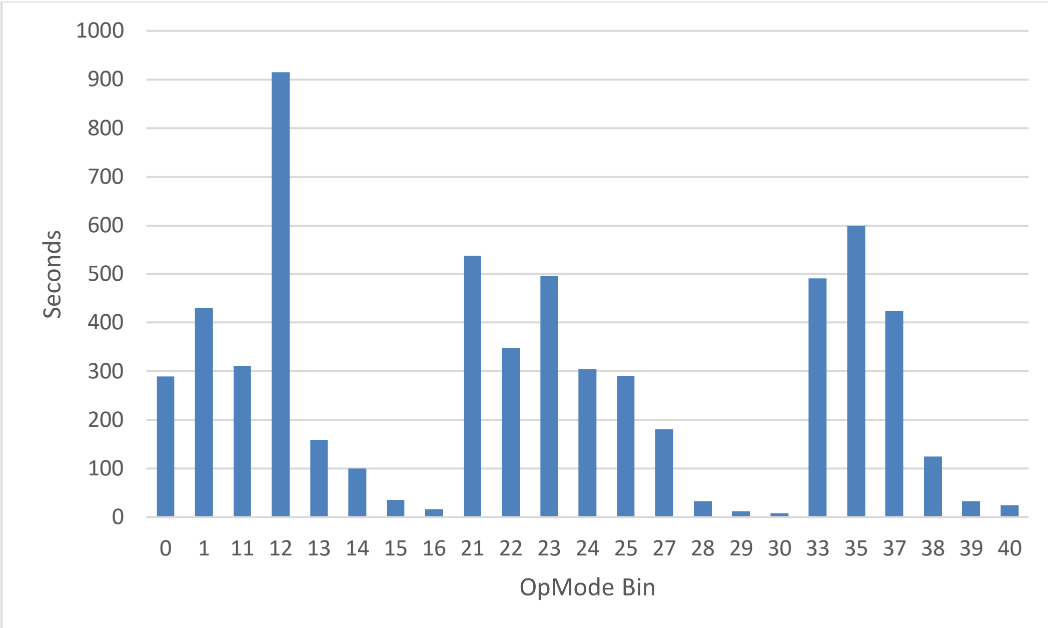


Figure 8. Distribution center drayage OpMode bin distribution

MOVES-Matrix outputs were collected using the OpMode bin distribution, default physics parameters, and default meteorology inputs for the Atlanta region in July (temperature 85°F; relative humidity 70%) [40-41]. The analysis year t=0 for the analysis was 2022, where existing MY 2008 trucks are fifteen years old. MOVES-Matrix was also run for a brand new MY 2023 diesel combination truck to compare abatement and energy savings of purchasing new trucks compared to the existing baseline fleet composition. The improvements seen in the new trucks are mainly due to efficiency improvements in vehicle design in response to significantly strengthened federal standards for tailpipe emissions and fuel economy since MY 2008 [42-43]. Resulting on-road emissions rates are shown in Table 5.

Table 5. Use-case on-road emissions rates (grams per mile) in 2022

Model Year	CO	NOx	VOC	Atmospheric CO2	PM10	PM2.5
2008	3.29	11.22	0.89	2,133.98	0.97	0.89
2023	0.36	1.27	0.05	2,003.30	0.02	0.02

Energy consumption for the driving cycle was 461.58 kWh for the MY 2023 truck in 2022. Assuming a ten metric ton payload, this equates to 1.324 ton-miles per kWh for the MY 2023 truck. Fuel consumption was 11.34 gallons.

BEVs have higher curb weights than vehicles with traditional powertrains because of the added weight of their battery packs. For weight-constrained shipments, studies have found electrification of freight trucks will require a maximum payload reduction anywhere from 1.25 to 2.0 or more tons to accommodate the increased weight of the electric powertrain [44].

Reducing the tonnage of cargo per truckload can negatively affect profit margins and potentially disrupt supply chains and the effects of electrification on the ton-mile capabilities of a fleet must be considered for comprehensive analysis. In this example, we assume the payload is constrained by volume rather than tonnage such that an increased curb weight will not necessitate a decreased payload and should not have any effect on the quantity of goods delivered. More refined analyses can be performed if actual payload data (volumes and weights) can be collected for individual use cases.

Electrification of this use-case is technically achievable. Many new electric Class 8 combination tractors on the market have battery capacities of 500 kWh or more [45-47]. However, nameplate capacity is not representative of available charge, as BEV systems will typically prevent batteries from depleting below a certain threshold of total capacity to preserve battery health and longevity. Assuming a 550-kWh battery, the driving cycle could be completed so long as at least 84% of capacity was actually available. The primary implementation challenge is operational. Designing charging schedules that are symbiotic with delivery schedules and do not cause unacceptable amounts of downtime is critical to the success of BE technology on this vocation. To be able to transition to BE trucks entirely, the vehicles would need to have an opportunity to charge after each one-way trip on the route, which might necessitate the acquisition of multiple chargers and garage locations near each terminus.

To evaluate the financial aspect of BE truck purchases as compared to traditional ICE truck purchases, a series of assumptions guided by real-world conditions observed today and projected into the future were constructed. Purchase prices for Class 8 BE MHDVs were collected from PG&E's vehicle catalogue [48]. Diesel truck purchase prices were collected from OEM specification sheets and websites, as well as from California HVIP [49]. For this use-case example, a new MY 2023 Class 8 diesel truck was estimated to cost $107,433 and a comparable BE option was estimated to cost $300,000. In Georgia, new vehicle purchases are subject to a 6.6% title ad-valorem tax [50]. Additionally, all new Class 8 vehicles are subject to a 12% federal excise tax at the time of purchase [51]. Diesel and electricity price projections were collected from EIA and are shown in Figure 9 and Figure 10 [52]. Maintenance costs per mile were gathered from AFLEET and California HVIP [49, 53]**.** All financial assumptions are displayed in Table 6.

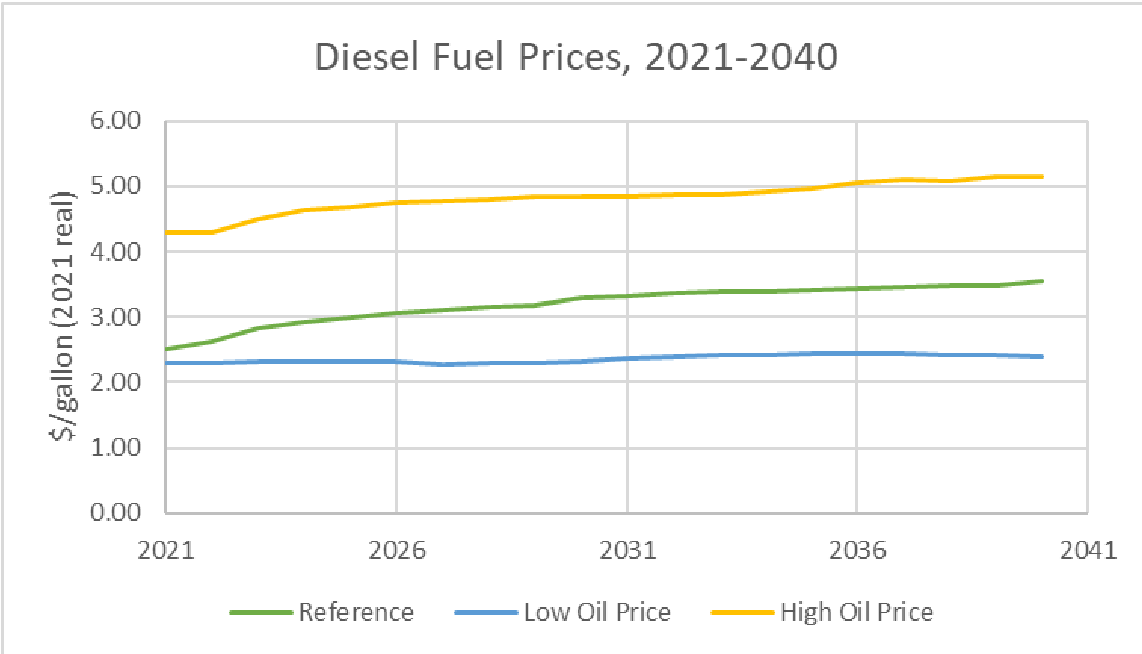


Figure 9. Predicted diesel price through 2040 [53].

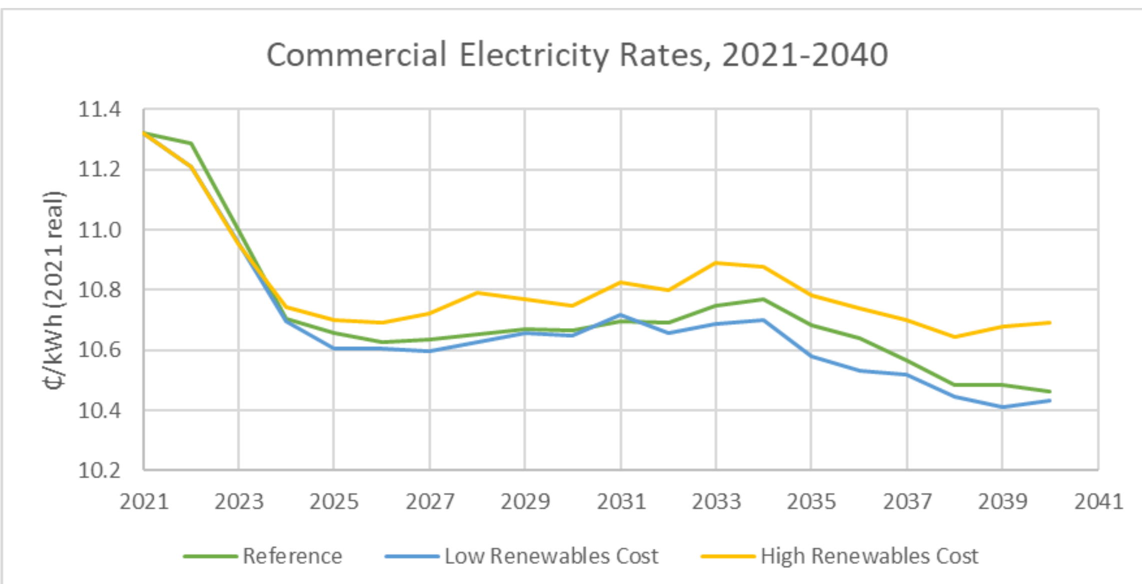


Figure 10. Predicted commercial electricity rates through 2040 [53].

Table 6. Financial parameters

Vehicle Type	Purchase Price	Sales and Local Tax	Federal Excise Tax	Maintenance Cost	Starting Diesel Price	Starting Electricity Price	Discount Rate
Diesel	$107,433	6.6%	12%	$0.44/mile	$2.51	$0.1132	5%
BEV	$300,000	6.6%	12%	$0.23/mile	$2.51	$0.1132	5%

Using the parameter values in Table 6, the total cost of ownership of purchasing new BE trucks is compared to that of new diesel trucks. It was assumed the fleet manager would opt to pay a 10% down payment at the point of sale for the new vehicles and that they would finance the capital cost of the vehicles over a 72-month period at a 5% interest rate.

Based on the composite driving cycle constructed for this use case, we assumed that a typical day's operation would be about 140 miles round trip (to account for first- and last-mile trips from the garage to the ARP or distribution center) for 250 workdays per year, and that the average fuel economy was 5.38 miles per gallon. The new vehicles were assumed to have a 20-year lifespan, and retired vehicles were assumed to have no real resale or salvage value. With these assumptions, the total cost of ownership was modeled, including purchase price and financing, operation cost, and maintenance cost. All future cash flows were discounted using a 5% discount rate.

BE powertrains are more efficient than ICE powertrains. CARB has found that heavy duty electric trucks have energy efficiency ratios ranging from 3.5 to more than 7 when compared to diesel trucks, depending on operational speed. The efficiency ratio curve produced by CARB is reproduced in Figure 11 [54]. The average speed on the composite driving cycle is 32.8 mph. By using the regression equation provided by CARB, the average speed equates to an efficiency ratio of 3.73. Based on the ICE efficiency calculated at 5.38 mpg, the BE efficiency is found to be 20.05 mpge, or 0.52 miles per kWh.

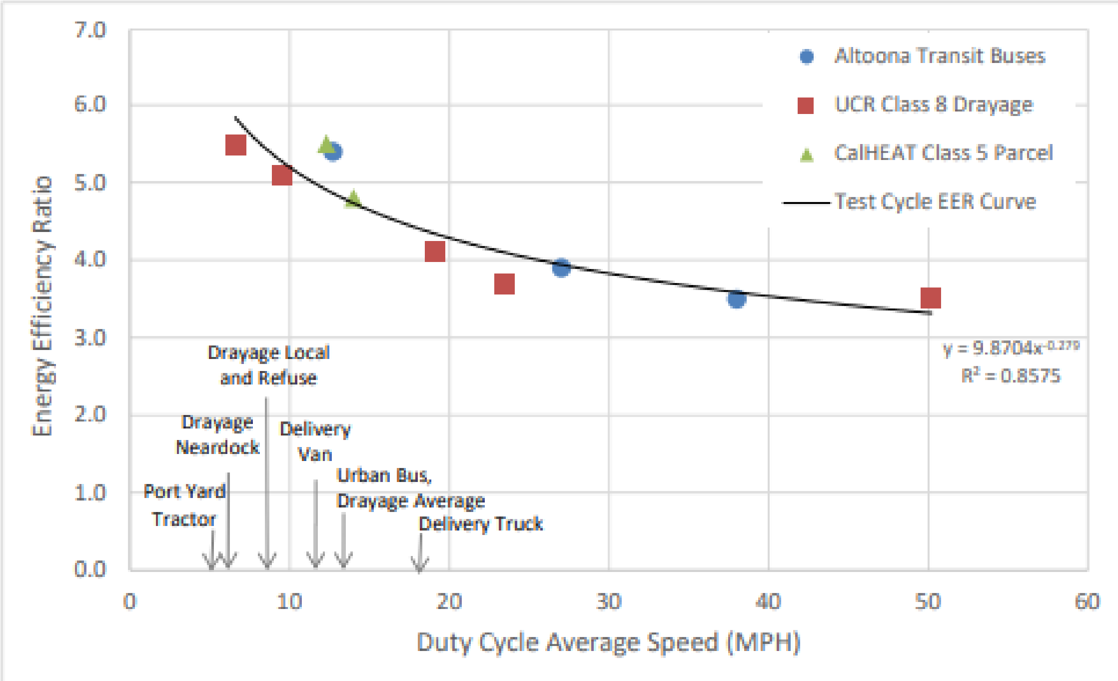


Figure 11. Vehicle energy efficiency ratio by average speed from CARB [54]

The down payment due at time of purchase is $12,741 for each diesel truck and $35,580 for each BE truck. The cost comparison between the two technologies for one vehicle is broken down in Table 7. The BE truck, for this use-case, works out to be about $0.02 cheaper per mile than the diesel truck, before accounting for any electric vehicle supplementary equipment costs. Adding the cost of 2 level 2 charger systems ($5,000 each) makes the BE truck almost level in cost with the diesel ($0.005 cheaper per mile).

Table 7. Total cost of ownership breakdown (with charging systems)

	Capital	Operation	Maintenance	Total Cost	Cost per Mile
Diesel	$145,070.91	$265,472,82	$220,171.56	$630,715.29	$0.901
BEV	$416,485.91	$94,853.72	$115,643.25	$626,982.88	$0.896

Electrifying this use-case would save the fleet $3,732.41 per vehicle, if operations could be designed to accommodate the technology. This includes the cost of two Level 2 charging systems, which could in theory be deployed near either end point of the route to allow for charging as needed after each one-way trip. Of course, other real-world considerations, like acquiring property for a second depot to install the charger on, may also increase costs for the BE truck pathway. Overall, the breakeven point for the BE truck would not be until its 20th year of operation. Performing more than one round trip per day, leading to a greater number of miles travelled, would improve the economics of electrification on this route because the bulk of the savings are in per-mile operating cost and maintenance cost. If charging schedules can be designed to accommodate delivery needs, and the demand for deliveries is adequate, increasing the freight activity in this freight operation would make electrification much more attractive.

Finally, BEVs do not have tailpipe emissions. To accurately compare emissions of a BE truck with that of a diesel truck, it is important to consider the upstream emissions associated with the fuel cycle in addition to the tailpipe emissions, to capture the emissions associated with generation of the electricity used to charge the BE vehicles. The on-road emissions rates calculated via MOVES and shown in Table 5 were combined with upstream "well-to-pump" fuel cycle emissions from GREET Model. Fuel cycle emissions rates for diesel and electricity production are shown in Table 8. Figure 12 and Figure 13 show the total emissions for both the diesel and BEV options. As expected, the BEV option yields fewer emissions over the vehicle's lifetime than the ICE option.

Table 8. Upstream emissions from fuel cycle from GREET

	CO	NOx	VOC	Atmospheric CO2	PM10	PM2.5
Diesel (grams/gallon)	1.609	2.47	0.9707	1707.1	0.1762	0.1482
Electricity (US Mix) (grams/kWh)	0.176	0.319	0.4913	414.9	0.048	0.0263

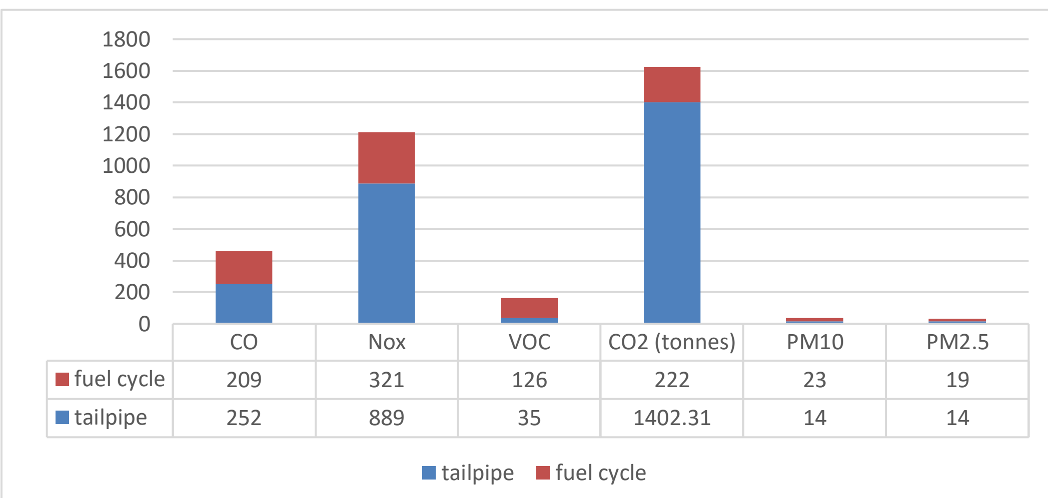
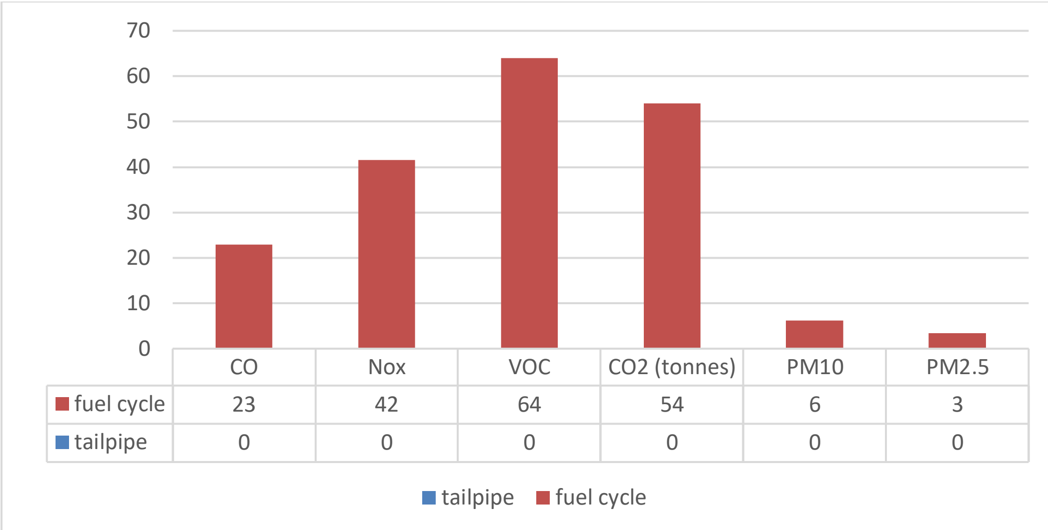


Figure 12. Total ICE lifetime emissions (kgs)



	CO	Nox	VOC	CO2 (tonnes)	PM10	PM2.5
fuel cycle	23	42	64	54	6	3
tailpipe	0	0	0	0	0	0

Figure 13. Total BEV lifetime emissions (kg)

The economic, business case for BEVs versus diesel trucks in this use-case example is very similar, with the BEV being about half a cent cheaper per mile. However, the breakeven point is not until the very end of the vehicle's useful lifetime. If the fleet plans to operate the vehicles for their entire 20-year lifetime on this use-case, then in the long run the BEVs are the better choice. However, there are lots of external factors to consider. Finding locations suitable for installation of private EV chargers will add additional costs for this example, and current operations will need to evolve to accommodate the technology switch. Minor changes of other parameters, such as fuel prices and fuel economy, VMT, interest and discount rate and other financial terms, incentives, pollution taxes, and maintenance costs may be enough to swing the economic comparison in favor of one technology over another. Being able to analyze a wide variety of parameter adjustments, tailored to a specific scenario, quickly and easily is of high value to fleet managers. TCOST, the tool discussed in the following section, was designed to enable fleet managers to model their scenario as well as alternative scenarios with adjusted parameters more quickly and easily by removing knowledge barriers while simultaneously leveraging the power of preexisting models utilized in this use-case example.

Total Cost of Ownership Spreadsheet Tool

This section will familiarize the reader with the concepts, functions, and data used in TCOST before presenting a sensitivity analysis exploring the effects of parameter adjustments in the context of the use-case example from the previous section to demonstrate how the tool can be used by fleet owners to explore the effectiveness of ICE and BE technology for their business and generate insightful comparative data to make informative decisions about the future purchases of their fleet.

TCOST is a parametric spreadsheet-based tool intended to assist fleet managers seeking to quantitatively evaluate the increased costs or savings of opting to acquire BE MHDV units compared to diesel MHDVs projected into the future for the duration of the vehicle's useful life, assumed to be 20 years. The model uses a series of 21 input variables defined by the user to produce total cost of ownership for a diesel truck versus a BE truck in the same use case. The input page of the spreadsheet model is shown in Figure 14.

TCOST is intended to serve a simplified model distilling the functions of several preexisting models into an easy-to-use tool that can help perform electrification analysis and allow users to vary input values to evaluate how each parameter can affect electrification potential in each scenario. The main outputs of TCOST are comparative total cost of ownership figures broken down by cost category (capital, on-road operation, maintenance), both as a gross number and on a per-mile basis, as well as a series of visualizations comparing cost breakdowns, breakeven points, and the expected tailpipe and fuel cycle emissions for both technologies.

Total Cost of Ownership Spreadsheet Tool		
State	GA	
Vehicle Class	8	
Number of Vehicles	1	
Miles per Day per Vehicle	140	miles
Days per Year per Vehicle	250	days
Annual VMT	35000	miles
Finance Length	72	months
Down Payment	10%	
ICE Purchase Price	$ 107,433	
BEV Purchase Price	$ 300,000	
Charging Equipment	Level 2	
Number of Chargers	2	
Interest Rate	0.05	
Sales Tax Rate	0.066	
Federal Excise Tax	0.12	
BEV Incentive	0%	of MSRP
ICE Maintenance Cost	$ 0.44	
BEV Maintenance Cost	$ 0.23	
Maintenance CAGR	1%	
Discount Rate	0.05	
ICE Fuel Economy	5.38	mpg (diesel)
BEV Fuel Economy	0.52	miles per kWh
Custom Diesel Price		$/gallon
Custom Electricity Price		$/kWh

Figure 14. TCOST input cells

The primary economic function employed by TCOST is adapted from [55-57]. It calculates a TCO figure for each powertrain and takes the difference of their net present values (NPV) as the potential cost or savings of transitioning to BE trucks. This function is shown by Equation 2.

$$NPV = \sum_{i=0}^{n} \frac{(TCO_{diesel,i} - TCO_{electric,i})}{(1+r)^{i}} \qquad (2)$$

Where *NPV* is the net present value, *n* is the vehicle lifetime, *i* is the i_{th} year, *r* is the discount rate, and *TCO* is the total cost of ownership of each powertrain type in year *i*. The model receives inputs for location, vehicle class, purchase prices, diesel fuel price and electricity rate, vehicle miles, financing terms (down payment, financing length, interest rate), available BEV incentives, maintenance costs, and more. The spreadsheet has default values based on vehicle class and location for most inputs in the case no user input is available for a particular parameter.

Default purchase prices for diesel and BE vehicles were taken from PG&E, California HVIP, and OEMs [48-49]. State and local sales tax are automatically calculated based on the state selection input. While local tax varies depending on exact position, a statewide average can be reasonably estimated by weighting their values by population size [58]. The 12% federal excise tax is automatically applied if the user selects a Class 8 vehicle from the vehicle class dropdown menu. Maintenance costs for diesel and BE vehicles were taken from AFLEET and California HVIP [49, 53]. Maintenance costs are set to grow by 1% compounded annually by default to reflect the aging and deterioration of vehicle components. Default fuel economy figures for each technology type and vehicle regulatory class are taken from CARB [59].

TCOST uses EIA national average fuel price projections for diesel fuel and commercial electricity. If desired, users can enter their local fuel prices and the tool will project the EIA national trends onto the input starting prices provided by the user and use those in the calculations instead. Table 9 shows the default vehicle parameters in the tool. The model includes parameters for modeling the economic implications of the acquisition of levels 1, 2, and 3 chargers. The purchase prices for each level of charger were based on chargers for sale and listed in CALSTART's EVSE catalogue (prices appeared reasonably representative of the typical price for each level of charging equipment). As a caveat, charger installation often comes with additional expenses for utility service upgrades and other necessary investments upstream on the electrical power system. That is, not all fleets can immediately install chargers if the grid conditions are not ready for such installations. These expenses can vary depending on current infrastructure status at the specific location and must be considered independently as part of the decision-making procedure.

Table 9. TCOST default vehicle parameters

		Class 3	Class 4/5	Class 6	Class 7	Class 8	Source
Diesel	**Purchase price**	$50,000	$55,000	$66,546	$73,805	$107,433	[48-49]
	Fuel economy (mpg)	14	10	9	8	6.5	[59]
	Maintenance (per mile)	$0.20	$0.30	$0.44	$0.44	$0.44	[49, 53]
BEV	**Purchase price**	$120,000	$188,542	$197,238	$247,860	$300,000	[48-49]
	Fuel economy (miles/kWh)	1.5	1.5	1.5	1.5	1.5	[59]
	Maintenance (per mile)	$0.10	$0.16	$0.23	$0.23	$0.23	[49, 53]

TCOST calculates WTP and PTW emissions of both technology types to compare the environmental impacts of each option. WTP emissions for diesel fuel were sourced from the "conventional diesel from crude oil for U.S. refineries" fuel pathway within the GREET model. This fuel pathway includes emissions from the extraction, transportation, refinement, and delivery of the finished diesel fuel product. For electricity, WTP emissions were taken from the "distributed – U.S. mix" pathway in GREET. This includes the generation and transmission of electrical power, including transmission losses, for a national average generation resource portfolio. Future versions of the model will include state-specific or FERC region-specific WTP electricity emissions.

PTW energy use and emissions were calculated using per-mile emissions rates by regulatory class calculated using MOVES for diesel vehicles. PTW emissions for BEVs were assumed to be null. The on-road estimates of energy use (gallons of diesel and kWh for BEVs) were multiplied by GREET energy use and emissions rates to estimate upstream emissions and energy use associated with fuel and electricity production [37, 53, 60]. Emissions are reported by TCOST for CO_2, VOCs, CO, NOx, CH_4, PM10, and PM2.5. Emissions rates are depicted in a table in Appendix A of this report. Upstream vehicle cycle emissions associated with vehicle manufacturing and retirement were excluded in this version of TCOST due to insufficient data coverage for every regulatory class in GREET. In future versions, these will be calculated through a simulated reconstruction of vehicle components in a vehicle-cycle simulation model like Autonomie® to expand the available inventory of vehicle cycle data [61].

Inputs are set by the user and TCOST calculates the corresponding economic comparison of both technology types, reporting lifetime savings (or increased costs, as indicated by a negative savings value) and generating four comparative visualizations: cost schedules for the diesel and BE truck (as a column chart with one column for each year of the vehicle's useful life, with each column segmented to show the breakdown of capital, operation, and maintenance costs), a cost of ownership comparison line graph (showing the breakeven point in the vehicle's useful life, if a breakeven exists), and a clustered column chart showing the emissions difference between each technology.

Critically, TCOST allows users to override all default parameters with custom values which makes the tool useful for modeling a huge variety of operational and economic scenarios. Users of the tool need only type directly into the input cells to tailor the tool to their fleet conditions and drastically improve model precision for their scenario. Using their conditions as a baseline, they can evaluate the effects of minor parameter changes on cost comparisons between the two technologies.

TCOST Application in the Use-Case Example

TCOST inputs were set to reflect the conditions described by the use-case example. The example inputs are shown in Appendix B of the report. Where input values were not known, default values were assumed to be reasonable estimates of conditions and were left unchanged. The fuel economy values were taken directly from the results of the MOVES-Matrix simulation and are reflective of the on-road conditions for the use-case. The total cost of ownership reported by TCOST was $630,715.29 for the diesel option and $626,982.88 for the BE option, resulting in a lifetime savings of $3,732.41 for the BE option with a breakeven point in the 20th and final year of operational life. While the BE option costs over twice as much for the initial acquisition of the vehicle, the operation and maintenance costs combined are less than half that of the diesel option over the vehicle lifespan. These cost savings come with the caveat of charger citing and utility upgrade costs, as well as any potential alterations to the drayage operation that might incur additional costs or lost revenue (i.e., if payloads are not volume-constrained and the BEV cannot handle the cargo weight of all of the trips within actual payload variability). The visualizations produced by TCOST are shown in Figure 15 through Figure 18. These visuals show the large influence of purchase capital cost and taxes during the first six years of vehicle ownership, and the large difference in on-road operating costs and maintenance costs that show up in the cumulative cost curves across the diesel and BEV alternatives. By comparing these charts, fleet owners and operators can quickly gain insight into the economics and environmental impacts of each potential fleet procurement decision.

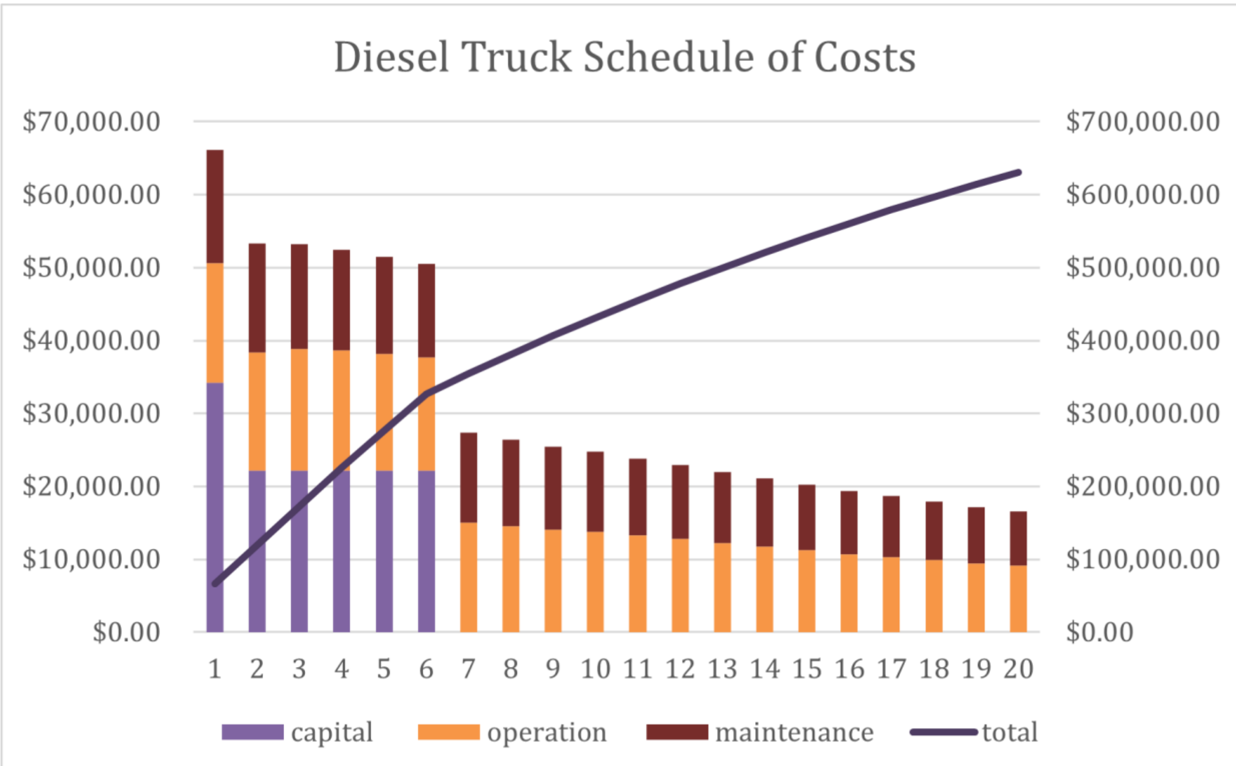


Figure 15. Diesel truck schedule of costs from TCOST

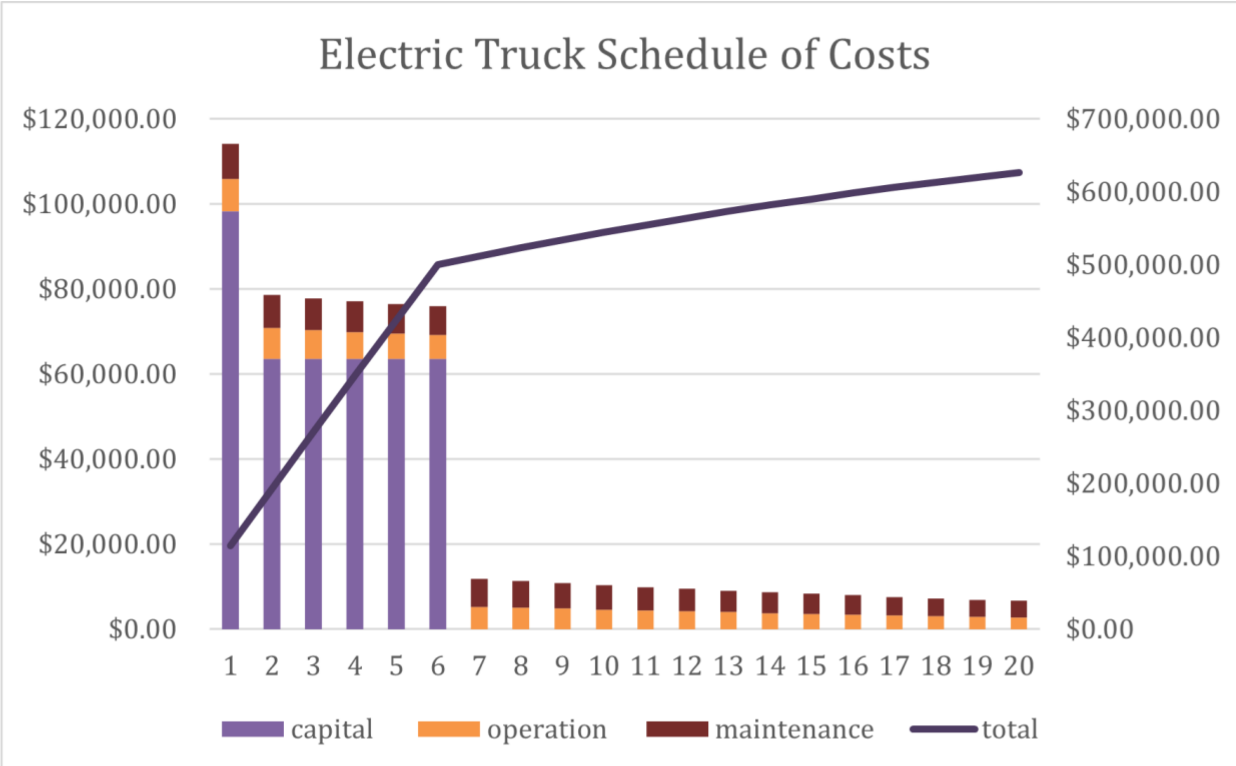


Figure 16. BE truck schedule of costs from TCOST

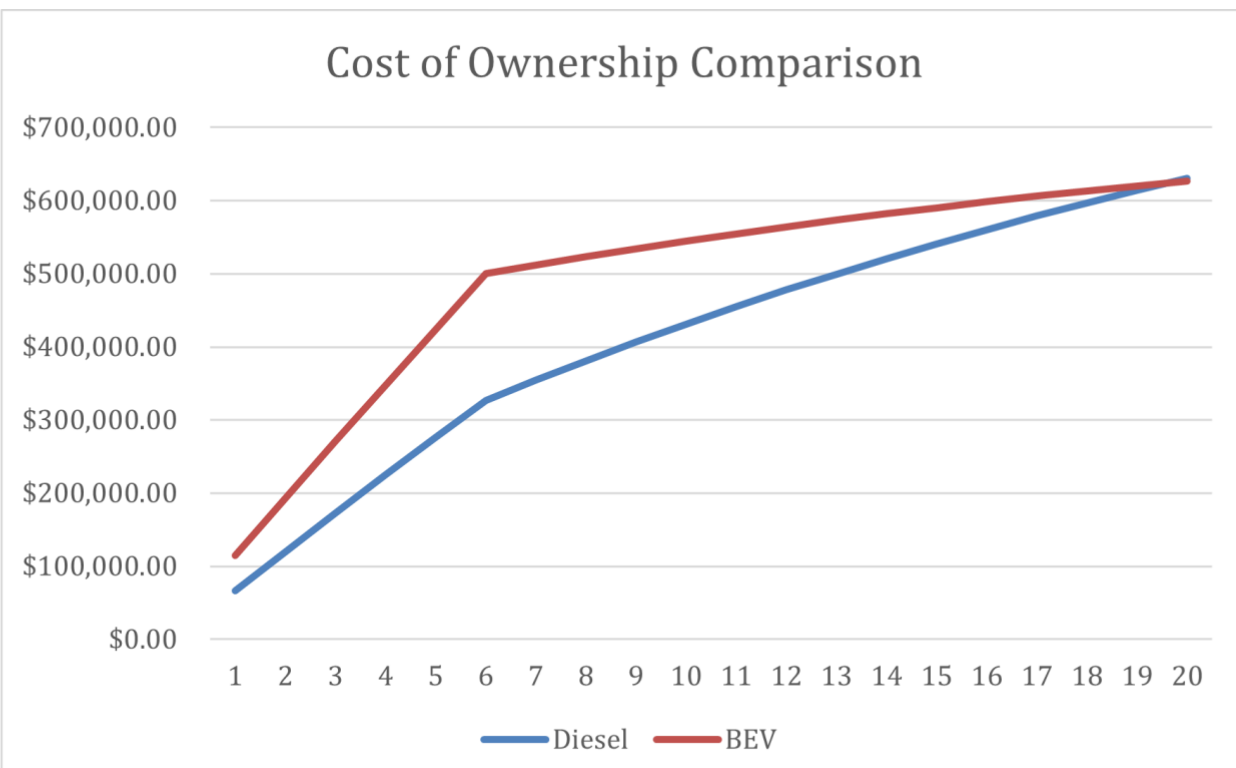


Figure 17. TCO comparison from TCOST

NCST

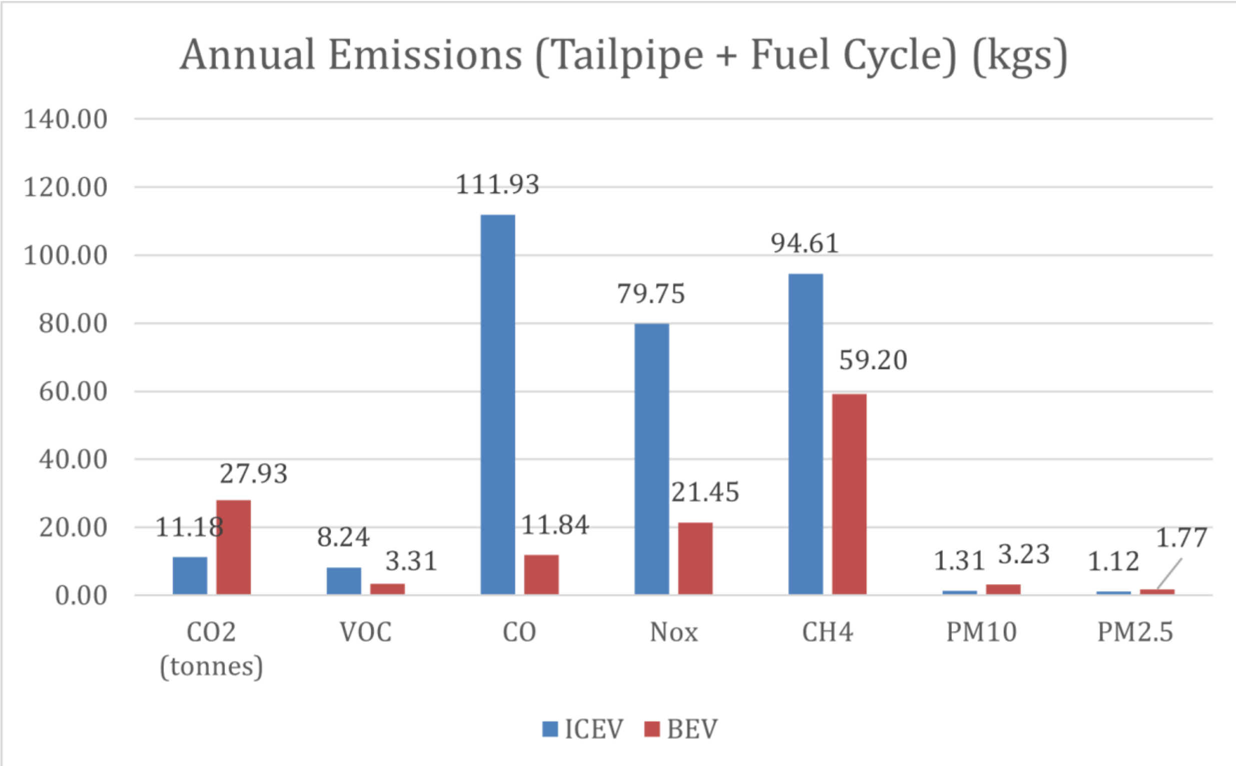


Figure 18. Emissions comparison from TCOST

The use case example presented above for Appalachian Regional Port Drayage results in very small savings that take almost the entire life of the vehicle to realize, compared to some use-case examples in the literature that appear to take less than five years to reach payback [17]. Fortunately, TCOST can be customized to specific use cases, allowing fleet owners to easily adjust parameters to identify sub-fleets that make more sense to electrify and to perform sensitivity analysis, helping to assess specific deployment scenario risk and make informed investment decisions. A selection of parameters was adjusted, one at a time, to isolate their effects on the TCO difference between the two technologies. Each parameter was adjusted up and down by 5% and the effects of each parameter was observed. The results of the sensitivity analysis are shown in Figure 19 and are discussed in more detail below.

The parameters with the highest sensitivities are BEV purchase price and ICE fuel economy (increasing these two parameter values decreases savings), followed by miles per day, diesel price, and ICE maintenance cost (increasing these three parameter values increases savings). The sensitivity analysis indicates that a high amount of risk involved in the investment decision, as altering these parameters even slightly can affect total cost savings by over 100%. However, this percentage difference in savings is somewhen misleading, because the savings were so small to begin with. That is, the high percentage changes observed here do not equate to high absolute values. But, the model sensitivity analysis does indicate that assumed future conditions does have a large impact on the simulation.

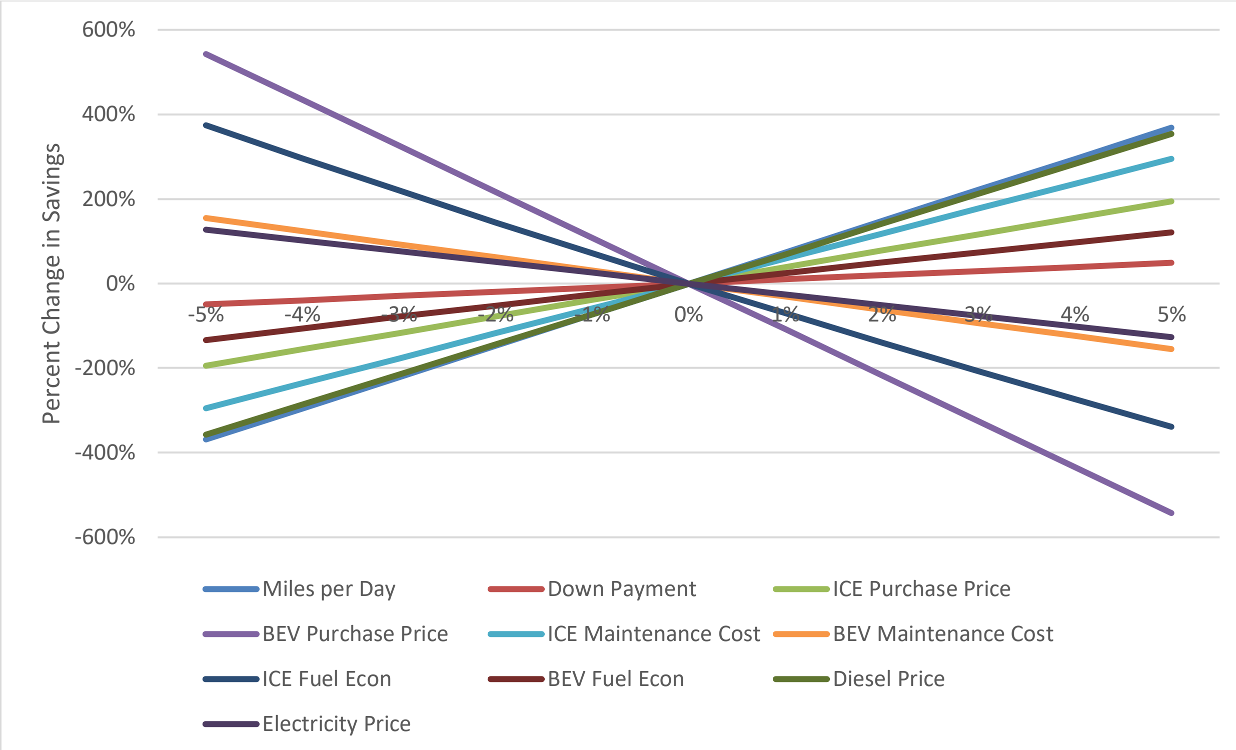


Figure 19. Sensitivities of selected input parameters in use-case example

Because diesel fuel economy won't change very much over time, due to the consistent on-road conditions of the vocation, the most critical parameter in play is the purchase prices of the BEVs. If there are any incentives available to the fleet for investing in BE trucks, a simple reduction of purchase price by only 1% would almost double expected savings under these conditions. Much recent regulatory focus has been on monetary incentives for BE technology because purchase price represents the largest expense occurred by an electrifying fleet.

Fuel prices are notoriously hard to project. If diesel becomes more expensive in the long-term, it would improve the savings of BE investments. Even if diesel fuel prices in the operational area are notably higher than the national average used in TCOST, it would have a large impact on savings. If the fleet is expected to travel more daily miles in the future, additional miles travelled would also have significant impact on the fleet's savings (provided the mileage remains within practical BEV recharge range). Finally, under a diesel option, if future retrofits are required to keep the vehicle and fleet compliant with evolving emissions standards, diesel maintenance costs might increase, positively impacting fleet savings under the BE option.

TCOST enables fleet managers to quickly and accurately adjust parameters to model a variety of possible scenarios to produce sensitivity analyses like this. TCOST customizability and parametric design allow the tool to quickly model case-specific conditions or a variety of alternative futures. Its spreadsheet-based nature is accessible, reducing modeling knowledge and information barriers, and allowing fleets of all shapes and sizes to gather data to make informed decisions about the futures of their fleets.

Conclusion

This report explored an example regional drayage freight use-case potentially attractive for deployment of Class 8 BE combination tractor trailers. TCOST employs the MOVES model (operationalized in MOVES-Matrix) for "pump-to-wheels" energy consumption and emissions, the GREET Model for "well-to-pump" fuel cycle energy use and emissions, and various economic data from the literature to simulate and compare the deployment of new BE and diesel trucks. The simulation of BE trucks on the Appalachian Regional Port Drayage use-case found the clean technology to be about a half-cent cheaper per mile than new diesel trucks, leading to a savings around $3,731.97 per truck over their lifetimes. However, the breakeven point for the two technologies under the use-case scenario is not expected until the 20th year of operation. The long payback period and limited savings led to an exploration of how minor parameter adjustments are likely to affect anticipated savings. The results of the sensitivity analysis were informative, showing the dominant factor affecting cost savings is the up-front procurement cost of the BEV, but also that the impacts of daily operations (miles per day and payloads), fuel prices, and maintenance costs, are also important elements of the decision-making process for fleet procurement. Resulting model output visualizations can also help decision makers to visualize a variety of future scenarios, map those scenarios onto their fleet operations, and assess risks to make informed choices about the future technological makeup of their fleets.

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Data Summary

Products of Research

No original data were created for this study. Rather, this research presents and combines existing data from independent sources in new ways. Several data sources were relied upon in the development of the Total Cost of Ownership Spreadsheet Tool, including:

- Pre-set vehicle purchase price estimations from CALSTART, California HVIP, and PG&E, accessible here: https://calstart.org/zero-emission-component-cost-study/; https://californiahvip.org/tco/; https://fleets.pge.com/vehicle-catalog/
- Electricity prices from U.S. Energy Information Administration, available here: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=8-AEO2023&cases=ref2023&sourcekey=0
- Liquid fuel prices from U.S. Energy Information Administration, available here: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=12-AEO2023&cases=ref2023&sourcekey=0
- Pre-set EVSE costs from CALSTART's Infrastructure Insite tool: https://insitetool.org/equipment_catalog
- Pre-set maintenance costs for battery-electric and combustion engine vehicles from Argonne National Laboratory's AFLEET Model: https://greet.es.anl.gov/afleet
- Pre-set vehicle fuel efficiency, tailpipe emissions factors, and electrical power grid emissions factors from Argonne National Laboratory's GREET Model: https://greet.es.anl.gov/greet_excel_model.models

Data Format and Content

All data used in this report are open source and stored within the TCOST Microsoft Excel® file, which can be found at https://doi.org/10.5281/zenodo.14589111.

Data Access and Sharing

All data employed in the research are publicly accessible through the hyperlinks provided above. All data and parameters contained in the TCOST Microsoft Excel® file can be freely accessed and shared.

Reuse and Redistribution

There are no restrictions on reuse or redistribution, provided that proper citations are employed to credit the primary (i.e., original) data sources.

Appendix A: TCOST Emissions Rates

Table 10. Well-to-pump

	CO2 (g/gallon)	VOC (g/gallon)	CO (g/gallon)	NOx (g/gallon)	CH4 (g/gallon)	PM10 (g/gallon)	PM2.5 (g/gallon)
Diesel	1.7071	0.0009707	0.001609	0.00247	0.014467	0.0001762	0.0001482
Electricity	0.4149	4.91E-05	0.000176	0.000319	0.00088	4.80E-05	2.64E-05

Table 11. Pump-to-wheels

Truck Class	CO2 (g/gallon)	VOC (g/mile)	CO (g/mile)	NOx (g/mile)	CH4 (g/mile)	PM10 (g/mile)	PM2.5 (g/mile)
Class 3	10705.35	0.071301	1.4264	0.4323	18.6012	2.2889	2.1058
Class 4/5	10705.35	0.1655	1.7803	0.5724	39.852	2.9624	2.7254
Class 6	10705.35	0.1763	1.6239	1.1054	42.2231	10.9293	10.0549
Class 7	10705.35	0.2126	4.4451	2.3863	49.3941	4.866	4.4767
Class 8	10705.35	0.055066	2.899	1.8195	14.28	4.7258	4.3477

Appendix B: Use-Case Example Inputs to TCOST

Table 12. Use-Case Example Inputs to TCOST

Parameter	Value	Parameter	Value
State	GA	Number of chargers	2
Vehicle class	8	Interest rate	0.05
Number of vehicles	1	Sales tax rate	0.066
Miles/day/vehicle	140	Federal excise tax	0.12
Days/year/vehicle	250	BEV incentive	0%
Annual VMT	35000	ICE maintenance cost	$0.44
Finance length	72 months	BEV maintenance cost	$0.23
Down payment	10%	Maintenance CAGR	1%
ICE purchase price	$107,433	Discount rate	0.05
BEV purchase price	$300,000	ICE fuel economy	5.38 mpg
Charging equipment	Level 2	BEV fuel economy	0.52 miles/kWh