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The Current and Future Performance and Costs of Battery Electric Trucks: Review of Key Studies and A Detailed Comparison of Their Cost Modeling Scope and Coverage

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The Current and Future Performance and Costs of Battery Electric Trucks: Review of Key Studies and A Detailed Comparison of Their Cost Modeling Scope and Coverage

June 2022

A White Paper from the National Center for Sustainable Transportation

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16. Abstract

This project aims to assess the current and future performance and costs of battery electric trucking, through reviewing key recent studies in the U.S. and presenting a detailed comparison of their cost modeling scope and coverage. This white paper presents a review of 10 recent studies of the total cost of ownership (TCO) of battery electric trucks (BET), now and in the future, compared to a baseline diesel truck, for the following 3 important types of truck: heavy-duty long-haul trucks, medium-duty delivery trucks, and heavy-duty drayage/short-haul trucks. The researchers break down the studies into their estimates for a range of important cost and operating factors, such as vehicle purchase cost, efficiency, fuel cost, maintenance cost, required range and thus battery pack sizing, and other factors. Of note are differences in major assumptions of studies and variables that are included or excluded from consideration. The authors do not judge these studies against each other but attempt to derive general findings that are robust across studies, areas of significant difference, and areas for further research. Overall, TCO estimates across the studies, for a given truck type, can vary dramatically, though often several studies cluster together. But as this study explores, the differences in TCO link directly to differences in assumptions, parameters and other differences across the studies. The studies vary in important ways that should be taken into account when comparing TCO estimates. Policy makers should consider the context of truck type, truck use and other factors when reading such studies, and pay attention to assumptions. Policies should reflect the wide range of situations that trucks may encounter and avoid assuming a simple average TCO across all situations.

17. Key Words Battery Electric Trucks; Total Cost of Ownership (TCO); Medium and Heavy Duty Trucks; Battery Cost; Zero Emission Vehicles	**18. Distribution Statement** No restrictions.

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Disclaimer

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The Current and Future Performance and Costs of Battery Electric Trucks: Review of Key Studies and A Detailed Comparison of Their Cost Modeling Scope and Coverage

A National Center for Sustainable Transportation White Paper

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The Current and Future Performance and Costs of Battery Electric Trucks: Review of Key Studies and A Detailed Comparison of Their Cost Modeling Scope and Coverage

EXECUTIVE SUMMARY

This project aims to assess the current and future performance and costs of battery electric trucking, through reviewing key recent studies in the U.S. and presenting a detailed comparison of their cost modeling scope and coverage. This report presents a review of 10 recent studies of the total cost of ownership (TCO) of battery electric trucks (BET), now and in the future, compared to a baseline diesel truck, for the following 3 important types of truck: heavy-duty long-haul trucks, medium-duty delivery trucks, and heavy-duty drayage/short-haul trucks. We break down the studies into their estimates for a range of important cost and operating factors, such as vehicle purchase cost, efficiency, fuel cost, maintenance cost, required range and thus battery pack sizing, and other factors. We note differences in major assumptions of studies and variables that are included or excluded from consideration. We do not judge these studies against each other but attempt to derive general findings that are robust across studies, areas of significant difference, and areas for further research.

Overall, TCO estimates across the studies, for a given truck type, can vary dramatically, though often several studies cluster together. But as this study explores, the differences in TCO link directly to differences in assumptions, parameters and other differences across the studies. The studies vary in important ways that should be taken into account when comparing TCO estimates. we have compiled a list of significant findings in this regard, across these studies:

1. As shown in all the studies, the most important factors affecting TCO, and the relative TCO of BETs vs. diesel trucks, include vehicle price, fuel prices, vehicle efficiency, and miles driven.
2. Across all the studies, for all three truck classes covered, BETs become cost effective from a TCO point of view at some point in the future, with the specific point varying between 2025 and 2035 depending on study and type of BET.
3. While some factors affecting TCO appear to have broad agreement across studies (such as diesel truck fuel economy), others show a wide variation (such as fuel prices). Some of this is unavoidable since there really is wide uncertainty, but in some cases these variations can probably be narrowed through discussion and cooperation on future research.
4. The range of estimates for purchase and operating cost of BETs can be quite wide, and this typically has a major effect on TCO. Attributes also affect each other, such as efficiency and required range affecting the assumed required battery capacity, which in turn affects both vehicle cost and fuel cost.

5. Fuel economy differences between diesel and battery electric trucks is large and generally reflected in all studies, but the magnitude of the difference can vary significantly. Some studies use lab tested rather than on-road efficiency (which takes into consideration the real-world driving conditions such as road grade and climate), which has a big impact.
6. Few studies have explicitly considered non-cost factors such as charging time penalties on vehicle use and payload impacts of the extra weight penalty caused by the battery system. These do not typically directly affect TCO calculations but could have strong impacts on vehicle purchase choice behavior by fleets.
7. There are significant differences in the assumed current and future prices of both diesel and electricity to the end user. Most studies include taxes on diesel which may skew the comparison, since taxes on electricity are much lower at this time. Including taxes can thus skew the comparison, and scenarios with levelized taxes across studies would be useful to see how this affects results.
8. The role of charger cost and "make-ready" charging infrastructure cost are not clearly elaborated in most studies or are difficult to estimate. Some studies appear to ignore these costs, while some amortize them and include them in either the retail price of electricity or the cost of the vehicle.
9. Vehicle maintenance costs appear important but remain uncertain, and while some empirical estimates suggest that current BET maintenance costs are not substantially lower than diesel, these costs may drop significantly in the future as systems and vehicles are optimized. The UCD study considers current and future different maintenance costs, while almost all other studies do not take into consideration the cost decline potential of BEV maintenance.
10. The role of policies and incentives, particularly the credit system under the Low Carbon Fuel Standard (LCFS), appear very important in determining final TCOs and the relative TCOs between BETs and diesel trucks. Few of the studies account for this, or the possibility of future policy changes to make BETs more competitive at an earlier date.

This report was circulated to all study authors with request for verification and review, but not all have provided this. We also received reviews from several other experts, as listed in the acknowledgements. We take full responsibility for any errors in representing the results of the different studies.

Future work of this type could include an analysis comparing fuel cell trucks to electric and diesel trucks in this manner, and comparisons including non-cost attributes (such as range and refueling time) of the different truck types, if more studies included such analysis.

Introduction

California and other states and countries are focused on transitioning to zero emission vehicles, and trucks will play an important part in this transition. The potential for pure battery electric trucking across different truck types, its viability and its cost, are important questions going forward. This applies both to current technology options and the potential for these to improve in the future, and to become more competitive with diesel trucks.

There have been a number of studies of battery-electric truck “total cost of ownership” (TCO) undertaken in the U.S. over the past 3-4 years, with differing numeric estimates and findings about the current and future competitiveness of battery electric trucks (BET) or battery electric vehicles (BEV) interchangeably in this study. There is a strong need to investigate these studies and compare them, to identify what makes estimates similar and different and to see if a more common set of estimates could be achieved. This report compares 10 such studies and lays out their estimates and assumptions across 3 important truck classes: heavy-duty long-haul trucks, medium-duty delivery trucks, and heavy-duty drayage/short-haul trucks.

Among the various estimates made of key attributes of trucks that affect their performance and TCO are vehicle purchase price, weight, payload capacity, driving range, operating and energy costs. These can vary significantly for different types of trucks or even the same trucks in different applications. Depending on the specific estimates and the class of truck, various findings are possible, from BETs being highly cost effective compared to diesel, to being relatively non-cost-effective; from being quite capable of performing in various conditions and duty cycles, to being inadequate. There is a notable lack of agreement in certain key areas such as weight/payload compromises and real-world driving range. This paper reviews the key literature and estimates (including those of this research group and others), attempts to understand the reason for differences and resolve them, and undertake a “final” robust analysis with conclusions about the best applications of BETs and where they may be very challenged to replace diesel trucks. We consider a range of truck types and both near term (e.g., 2020-23) and long term (e.g., 2030-35) sets of estimates. The results and findings are intended to Californian and other policymakers in prioritizing how and when to deploy BETs and the needed policy support.

Recent TCO Studies and Their Major Results

In this section, the reviewed reports are briefly described and key findings are presented. Then in the following section the estimates and values for key attributes are compared.

The key studies are listed and summarized in Table 1.

Table 1. Reports covered in this comparison (LH = Long Haul; SH/D = Short Haul/Drayage; Del. = Delivery)

Study Author	Date	Truck types covered			Years covered	Notes
		LH	SH/D	Del.		
CARB	2019		X		2018/24/30	2019 is a draft report that is to some degree superseded by 2021 report, but they are different and have some different findings.
CARB	2021	X	X	X	2025/30/35	
ICF	2019	X	X	X	2020/30	Detailed analysis of current policy (e.g., LCFS) impacts on TCOs
ICCT	2019	X	X	X	2020/25/30	Particular emphasis on recharging infrastructure costs
UCLA	2019		X			Focus on drayage applications at the ports in LA region
LBL	2021	X	X		2025	Focus on near term potential for long-haul BETs vs diesel
ANL	2021	X	X	X	2020	Includes a wide range of cost factors beyond technology, such as driver, insurance, etc.
NREL	2021	X	X	X	2020, 2025, "ultimate"	Includes analysis of indirect costs such as dwell time for recharging
CALSTART	2021	X	X	X	2020/25/30	On-line calculator, no report at this time
UC Davis	2022	X	X	X	2020-2040	Focus on 2020 and "future" Post 2030; final report due out in June 2022.

The studies are briefly reviewed below with major TCO results shown in figures copied directly from reports.

CARB ACT TCO study (2019)

> CARB, 2019. Advanced Clean Trucks Total Cost of Ownership Discussion Document. Preliminary Draft for Comment. California Air Resources Board (CARB). February 22, 2019.

This report was aimed at developing the Advanced Clean Trucks (ACT) regulation by California Air Resources Board (CARB). CARB modeled more than just 3 vehicle applications for the ACT regulatory analysis, but this report only covers 3 types of vehicles, with three technologies for each type and three different years for the estimates (and projections). They consider diesel, EV and fuel cell vehicle for each truck type and the years 2018, 2024, and 2030.

Note that this 2019 CARB study and the other 2021 CARB study (to be discussed in the subsequent section) are closely related but targeting for different policy makings, and their vehicle coverage and scope are quite different as well. Therefore, both studies are considered in the review.

The basic TCO results for the regional tractor are shown below. Detailed assumptions are summarized in a big table in the following section below.

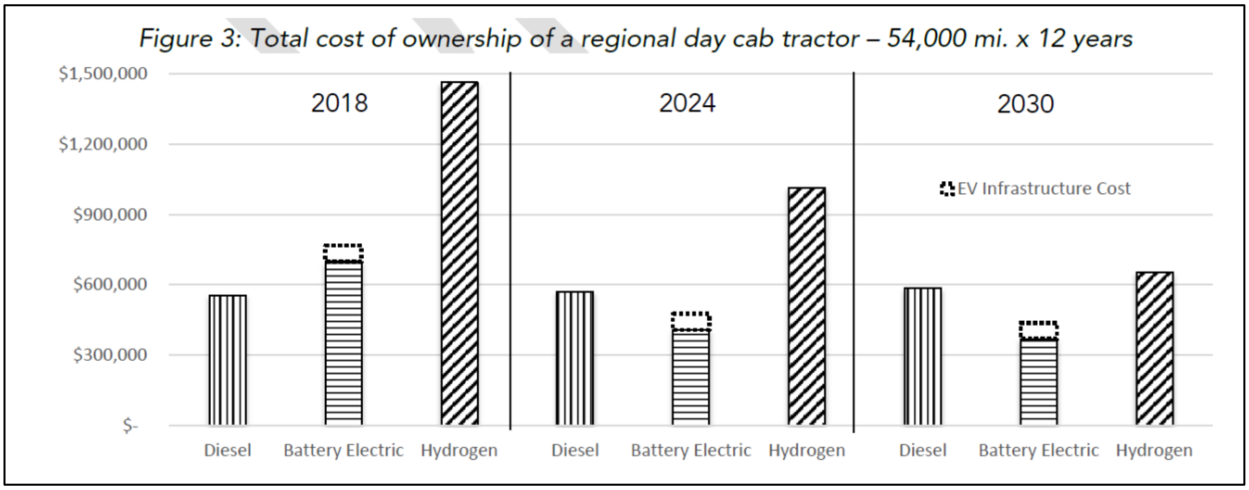

Figure 1. TCO of a regional day cab tractor (source: CARB, 2019)

CARB ACF TCO study (2021)

> CARB, 2021. Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document. California Air Resources Board (CARB). September 9, 2021.

As reported in the document, this analysis was prepared by California Air Resources Board staff to document the preliminary cost inputs and assumptions to be used for the economic analysis of the Advanced Clean Fleets (ACF) regulation under development, as well as display the TCO of selected vehicles. TCOs are assessed for the four basic drivetrain technology types and include vehicle costs, fuel costs, maintenance costs, infrastructure investments, Low Carbon Fuel Standard (LCFS) revenue, and other costs. Six vehicle types were modeled in this analysis – a Class 2b cargo van, a Class 5 walk-in van, a Class 6 bucket truck, a Class 8 refuse packer, a Class 8 day cab tractor for use in drayage operations, and a Class 8 sleeper cab tractor. Apart from the LCFS, the analysis does not include any rebates, incentives, or grants to show how costs compare without the effect of subsidies.

Key findings included:

- BETs appear cost competitive with the established combustion technologies by 2025 in a variety of use cases (taking into account LCFS credit values).
- Significant savings are shown for battery-electric in the walk-in van, refuse truck, and day cab categories, even in the early years.
- The TCO for zero emission trucks (ZETs) is expected to improve over time as costs continue to decline.

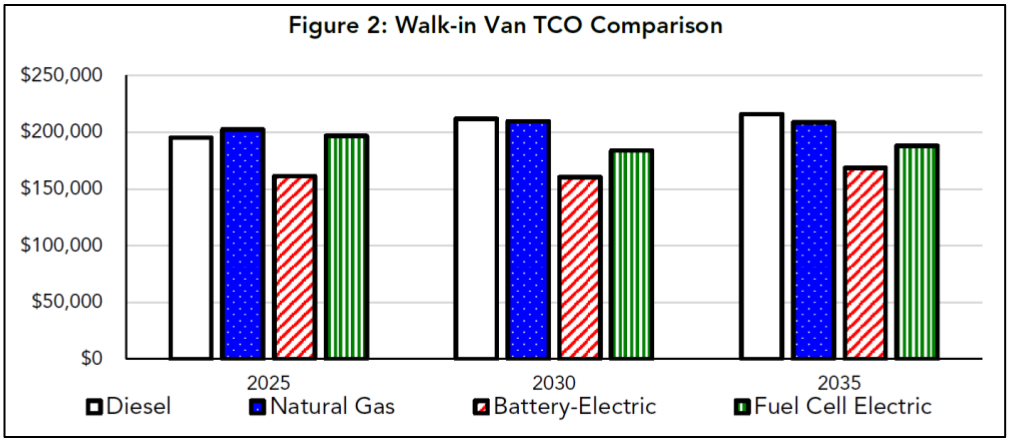

Figure 2. Walk-in van TCO comparison (source: CARB, 2021)

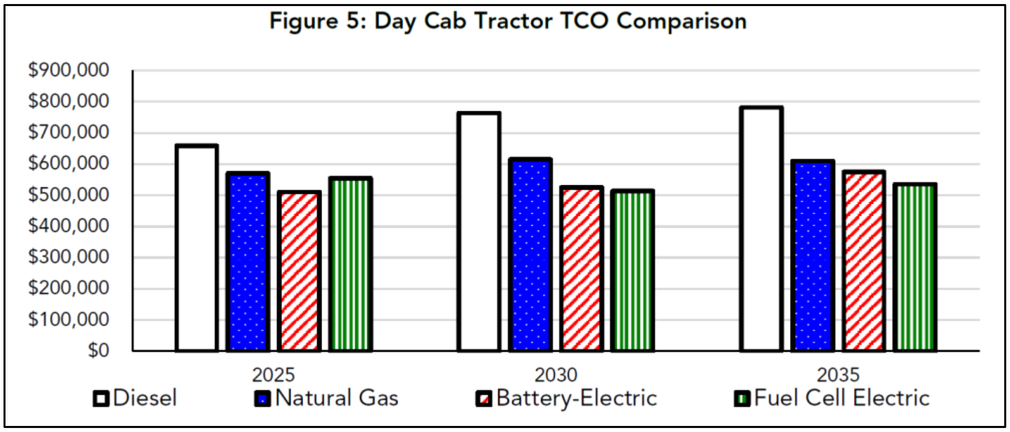

Figure 3. Day cab tractor TCO comparison (source: CARB, 2021)

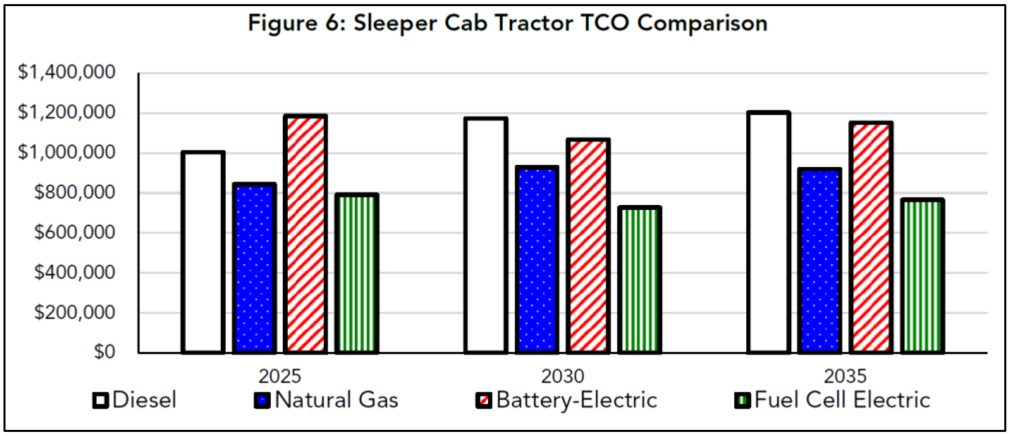

Figure 4. Sleeper cab tractor TCO comparison (source: CARB, 2021)

ICF MD/HD report (2019)

ICF, 2019. Comparison of Medium- and Heavy-Duty Technologies in California. December 2019. https://caletc.com/assets/files/ICF-Truck-Report_Final_December-2019.pdf

ICF produced a TCO report covering Class 8 Tractors, drayage trucks and two classes of delivery trucks (class 6 and class 4/5), among others. In each case they compared across four drive-train technologies. The TCO is calculated as the cumulative cost to the first owner of a vehicle, including vehicle capital (purchase price minus residual value), operation and maintenance (which includes the cost of fuel), and any necessary infrastructure, minus applicable incentives and regulatory requirements. The ICF analysis considers the effect of the three policy incentives, including the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), the Low Carbon Fuel Standard (LCFS), and the California Investor Owned Utility (IOU) Programs for charging infrastructure. The TCO calculation was performed for fourteen vehicle sizes and applications from Class 2b to Class 8 trucks and buses, and across fuels including diesel, natural gas and renewable natural gas (including landfill gas (LFG)), electricity, and hydrogen. Some key findings from this analysis include:

Key findings included:

- Costs for electric MD and HD vehicles are falling, largely due to the rapidly declining cost of batteries.
- While the value of LCFS credits, along with direct vehicle incentives such as HVIP, make the economics attractive for fleet operators and owners now, by 2030 battery electric trucks and buses are projected to achieve favorable TCO across almost all classes evaluated, even absent incentives.
- Utility programs providing low- and off-peak rate periods and mitigating demand charges for MD and HD technologies are critical for electric vehicle and fleet owners. Current programs offered by utilities in California are allowing fleet owners to take advantage of the potentially lower fuel costs compared to diesel or natural gas vehicles.

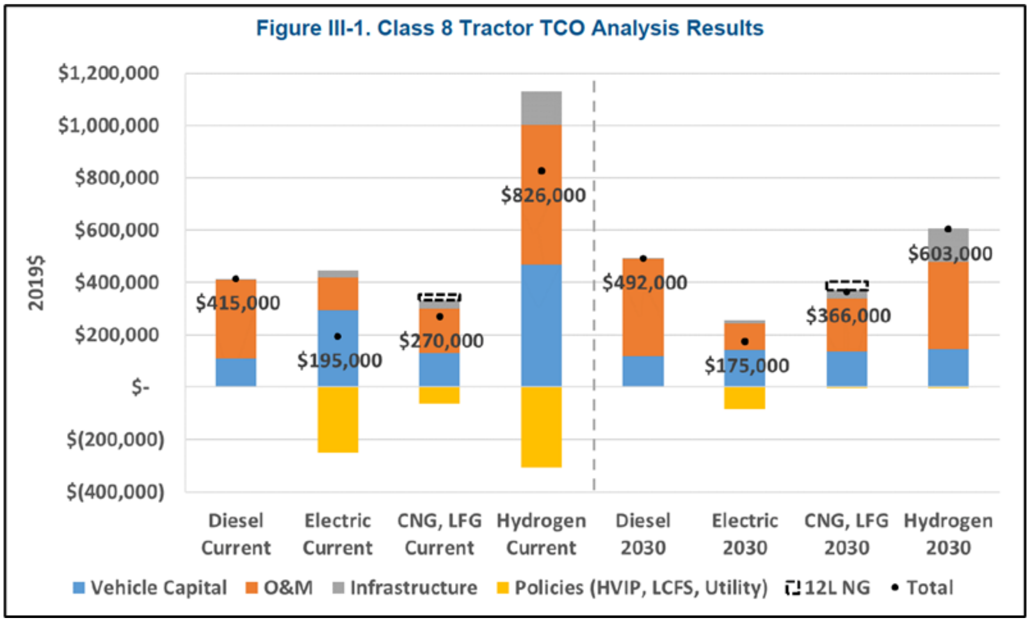

Figure 5. Class 8 tractor TCO analysis results (source: ICF, 2019)

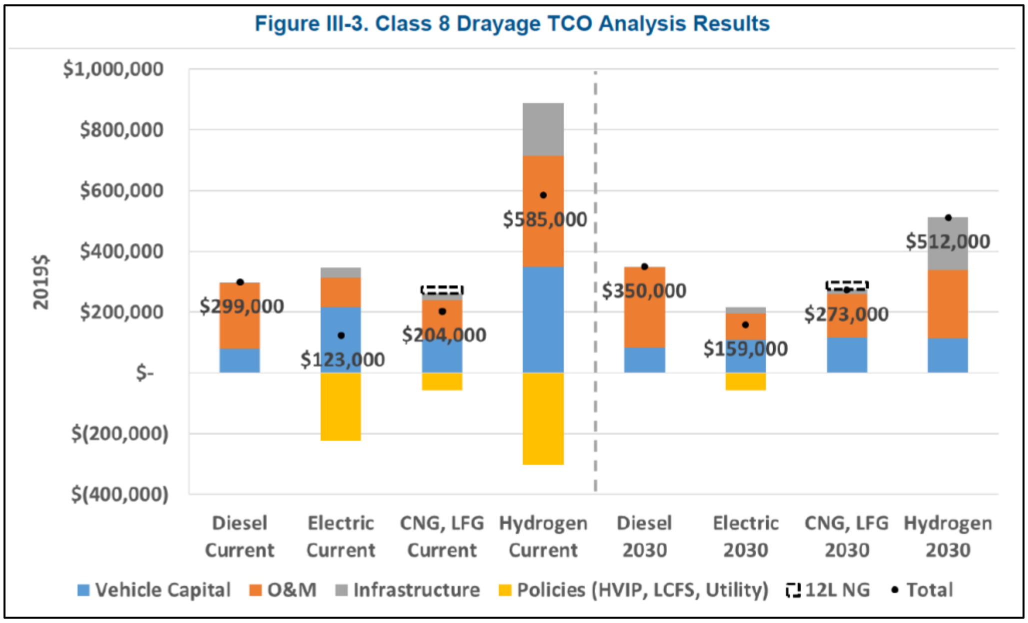

Figure 6. Class 8 drayage TCO analysis results (source: ICF, 2019)

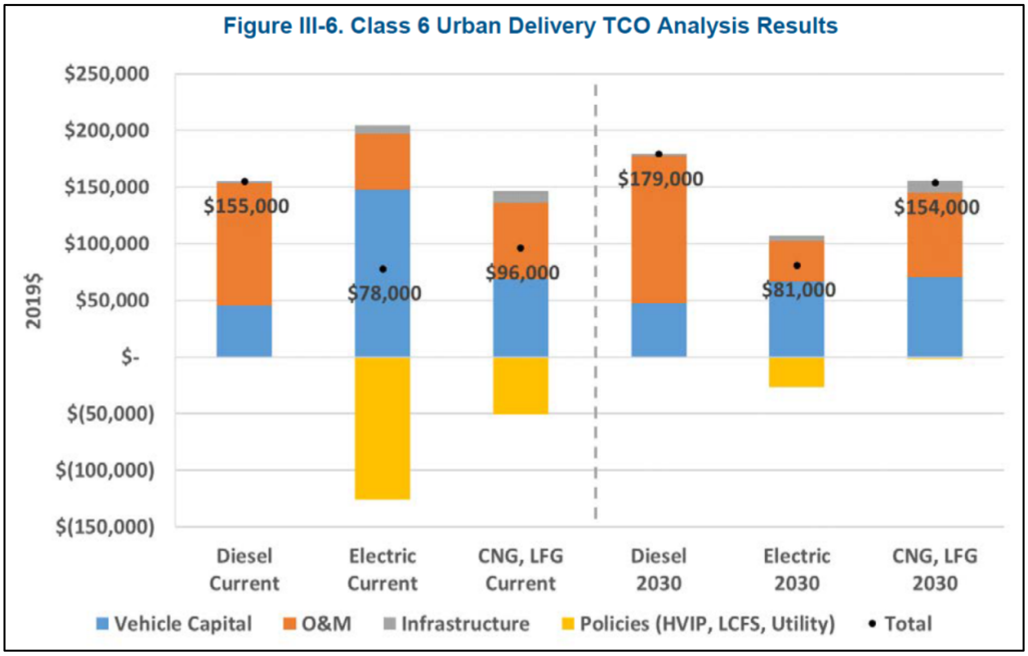

Figure 7. Class 6 urban delivery TCO analysis results (source: ICF, 2019)

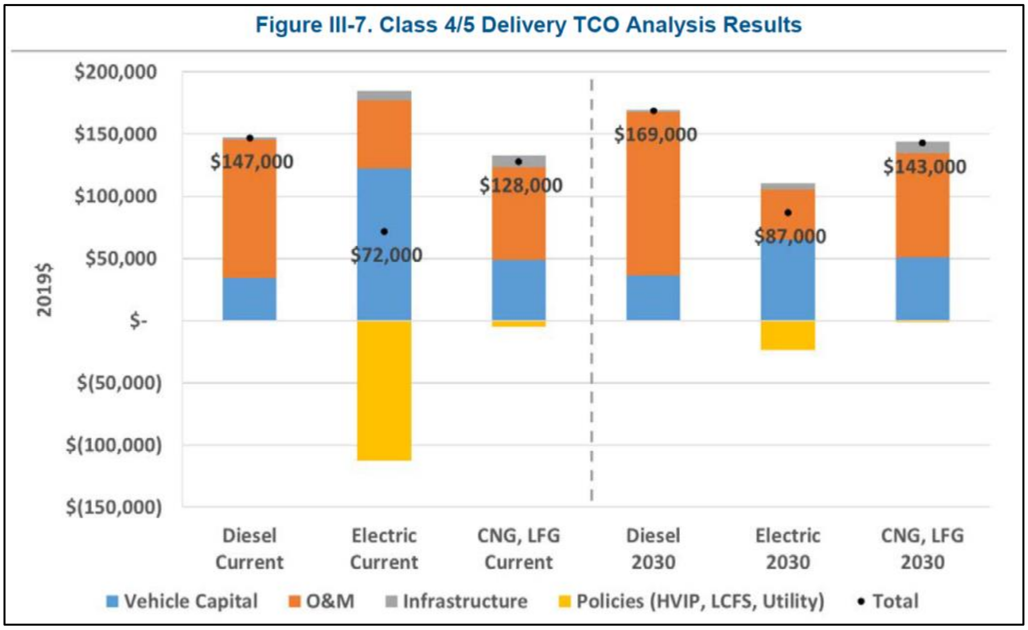

Figure 8. Class 4/5 delivery TCO analysis results (source: ICF, 2019)

ICCT truck Infrastructure report (2019)

Hall, Dale, Nic Lutsey, 2019. Estimating the infrastructure needs and costs for the launch of zero-emission trucks. August 2019.

This ICCT study is focused primarily on the recharging and refueling infrastructure costs associated with different truck types and technologies, in the context over the overall TCOs of these options. It considers the years 2020, 2025 and 2030. The study finds that:

- Charging infrastructure for BETs (and other zero-emission trucks) will require significant funding, particularly for long-haul tractor-trailers and in early phases of deployment.
- However, it is important to place these expenses in the context of the TCO of these powertrain options. Falling technology costs are making zero-emission trucks increasingly cost-competitive. Cost declines in batteries and electric motors in particular make battery electric trucks less expensive than diesel trucks in purchase price between 2025 and 2030.
- Obstacles such as charging time and reduced cargo capacity could add complications and costs for electric fleets beginning the transition.
- The per-tractor charging infrastructure costs for electric long-haul tractor-trailers range from $113,000 at lower volumes in the 2025 timeframe, to $70,000 at higher volumes in the 2030 timeframe. As scale increases, infrastructure represents a decreasing portion of total operating expenses.

The ICCT study presents combined figures to illustrate how battery electric trucks compare with conventional diesel in terms of TCO. In addition to the four primary cost drivers: vehicle capital cost, maintenance, fuel or energy, and the infrastructure per vehicle, the ICCT study also includes weight penalty and time penalty costs. Weight penalty costs reflect the cost of additional trucks due to the "weight penalty” from batteries, which means that fleets would have to be approximately 1% larger to carry the same cargo, for the long-haul tractor-trailers. Time penalty costs reflect an added “time penalty” representing increased fleet size required to make up for lost driving time spent charging. That is based on the assumption that if a fleet loses driving time due to charging (compared with the diesel truck refueling), additional trucks must be purchased, which increases fleetwide costs. The “time penalty” is assumed to equal the percentage of the day dedicated to fast charging (compared with an assumed 5 minutes spent fueling).

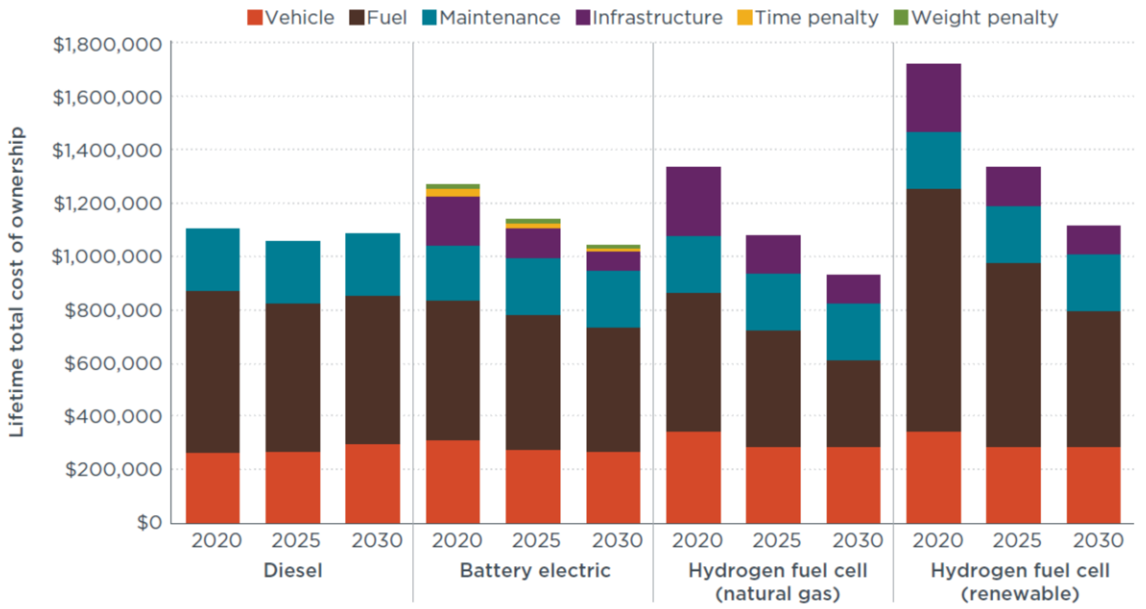

Figure 8. Total cost of ownership for diesel, electric, and hydrogen fuel cell long-haul tractor-trailers

Figure 9. TCO for long-haul tractor-trailers (source: ICCT, 2019)

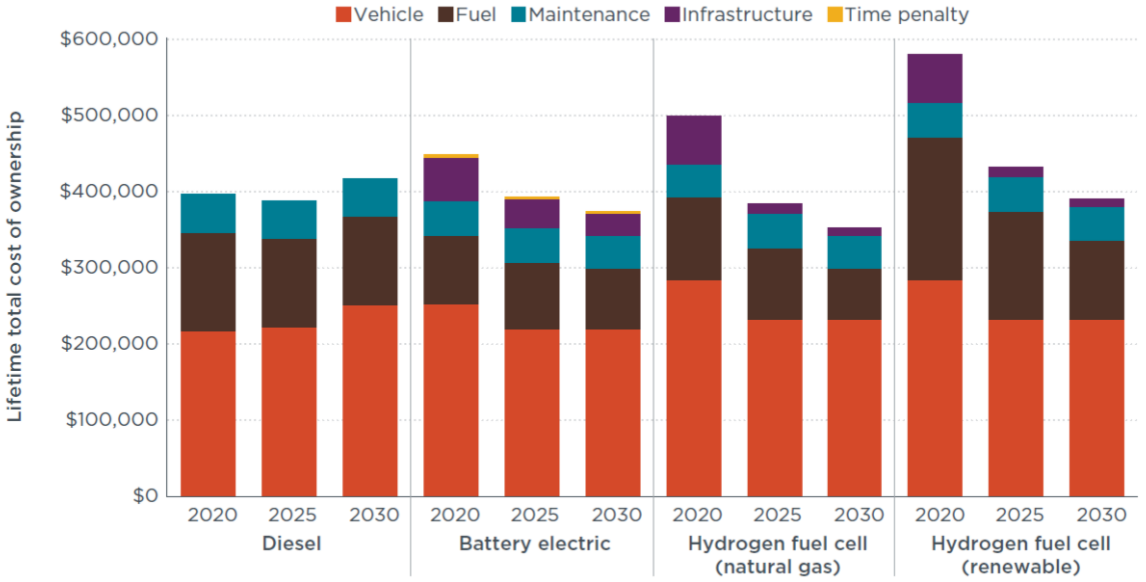

Figure 9. Total cost of ownership for diesel, electric, and hydrogen fuel cell Class 8 drayage trucks

Figure 10. TCO for class 8 drayage trucks (source: ICCT, 2019)

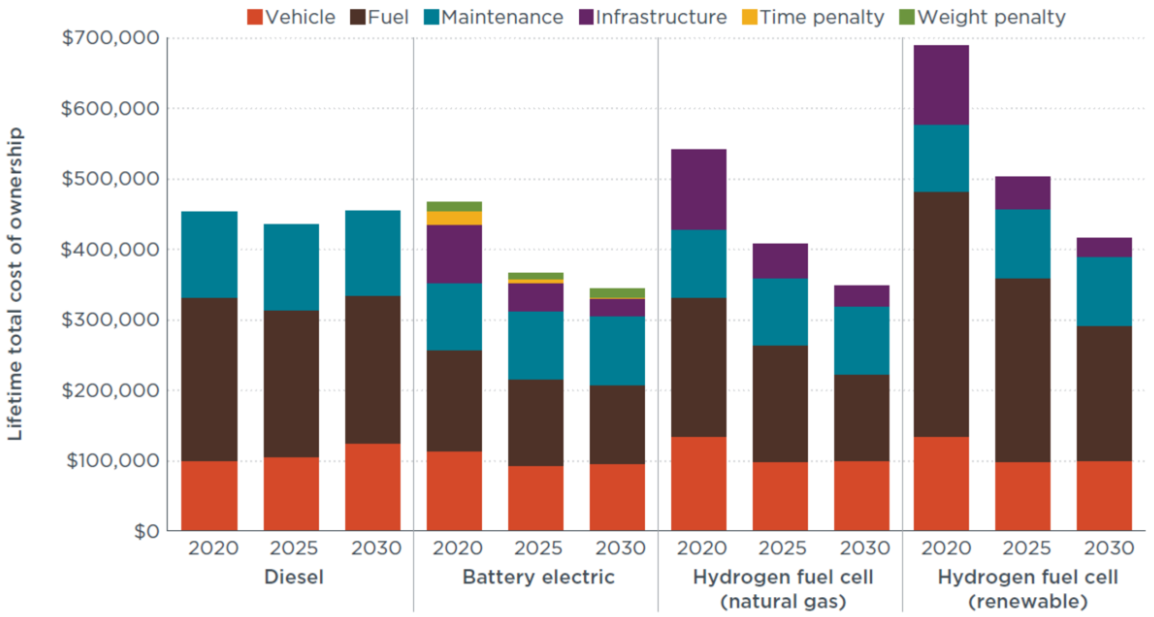

Figure 10. Total cost of ownership for diesel, electric, and hydrogen fuel cell Class 6 delivery trucks

Figure 11. TCO for class 6 delivery trucks (source: ICCT, 2019)

UCLA drayage report (2019)

Filippo, James Di, Colleen Callahan, Naseem Golestani, 2019. Zero-Emission Drayage Trucks: Challenges and Opportunities for the San Pedro Bay Ports.

This study examined the potential and cost of BETs in drayage applications, considering costs of the vehicles now and in the future, and the different costs for electricity in the Southern California Edison (SCE) territory and in the Los Angeles Department of Water and Power (LADWP) territory.

The report finds:

- Without incentives, as of 2019, BETs are still considerably more expensive on a TCO basis than all other alternatives on all scenarios. However, when the value of LCFS credits is applied, BETs in SCE territory become less expensive than natural gas trucks and competitive with diesel for different drayage usage scenarios (such as the “two-shift limited” and “average daily mileage” scenarios).
- The authors point out that though the cost model relies on a reasonable set of assumptions about operations and potential costs, future truck purchase costs are uncertain and charging infrastructure costs can be extremely variable.
- The paper provides a set of potential policies and measures to incentivize BETs in drayage applications specifically at the ports in Los Angeles, though these could be generally applied in port/drayage situations.

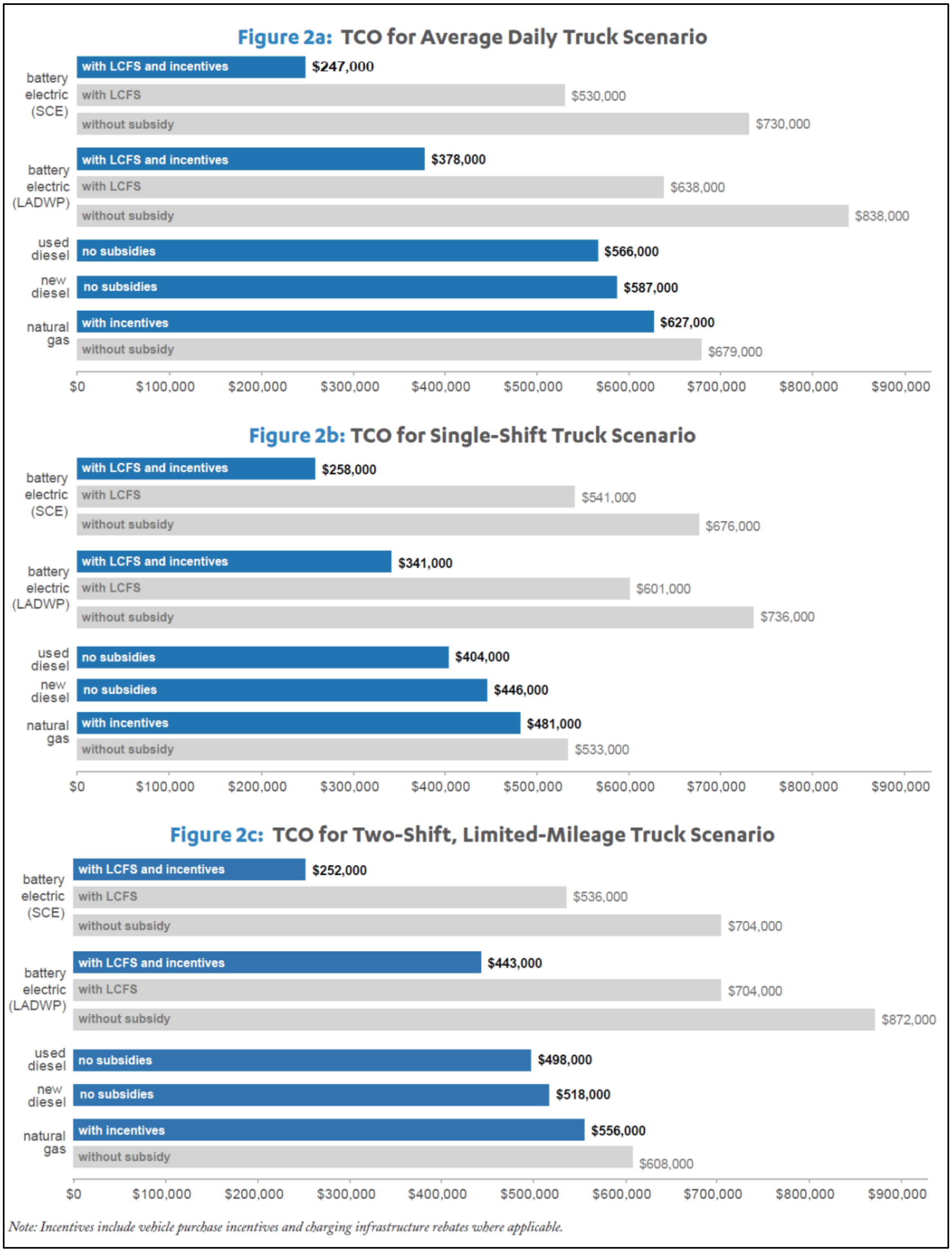
Figure 2a: TCO for Average Daily Truck Scenario

Figure 2b: TCO for Single-Shift Truck Scenario

Figure 2c: TCO for Two-Shift, Limited-Mileage Truck Scenario

Note: Incentives include vehicle purchase incentives and charging infrastructure rebates where applicable.

Figure 12. TCO for 3 separate drayage truck scenarios (source: UCLA, 2019)

LBL regional/long haul report (2021)

Phadke, Amol, Aditya Khandekar, Nikit Abhyankar, David Wooley, Deepak Rajagopal, 2021. Why Regional and Long-Haul Trucks are Primed for Electrification Now. March 2021.

The report finds:

- At the current global average battery pack price of $135 per kilowatt-hour (kWh) (realizable when procured at scale), a Class 8 electric truck with 375-mile range and operated 300 miles per day when compared to a diesel truck offers about 13% lower TCO per mile, about 3-year payback and net present savings of about $200,000 over a 15-year lifetime. This is achieved with only a 3% reduction in payload capacity.
- Electric trucks appear poised to also meet the performance demands for a large share of regional and long-haul trucking today. The authors consider typical long-haul truck driving distances, periods between and during driving, breaks, and recharging potential during the day and find this generally adequate for long-haul operation.
- However, they point out that the higher upfront capital costs of both vehicles and charging infrastructure are major barriers when electric trucking is in its infancy. Without strong policy support, coordinated investments in both vehicle manufacturing and fuel infrastructure will not be forthcoming on the scale needed to harness the true potential of battery electric trucks.

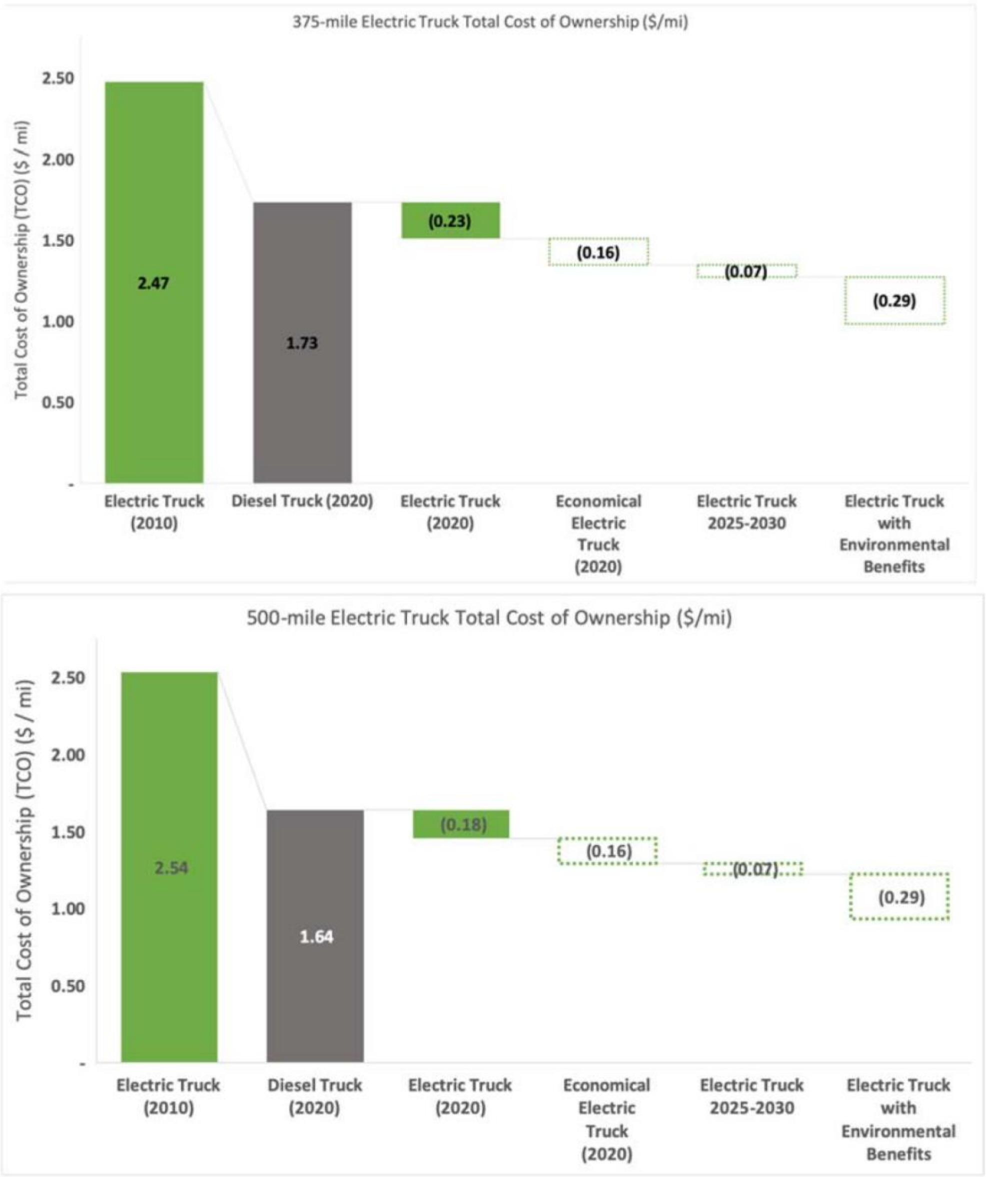

Figure 4 (Top) TCO comparison for 375-mile (797 kWh battery pack truck) operated 300 miles per day for 260 days per year. (**Bottom**) TCO comparison for 500-mile (1062 kWh battery pack truck) operated 400 miles per day for 260 days per year.

Figure 13. Per-mile TCO for a class 8 diesel truck compared with its battery electric counterparts (source: LBL, 2021)

ANL AFLEET model (2021)

AFLEET, 2021. Argonne National Laboratory. User Guide for AFLEET Tool 2020. April 2021.

Burnham, Andrew, et al., 2021. Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains. Argonne National Laboratory. ANL/ESD-21/4. July 2021.

Argonne National Laboratory (ANL) has developed the Alternative Fuel Life-cycle Environmental and Economic Transportation (AFLEET) tool which has a capacity to examine the cost of ownership of light-duty, medium-duty, and heavy-duty vehicles using simple spreadsheet inputs. AFLEET also contains a calculator that calculates a simple payback for purchasing a new alternative fuel vehicle as compared to its conventional counterpart, by examining acquisition and annual operating costs. The transparent nature of the AFLEET database allows for easy extraction of specific vehicle and cost data for our comparative analysis.

Apart from the AFLEET model, another comprehensive TCO report of ANL (Burnham et al., 2021) builds on previous work to provide an overall perspective of all relevant vehicle costs of ownership. This report considers vehicle cost and depreciation, financing, fuel costs, insurance costs, maintenance and repair costs, taxes and fees, and other operational costs in order to build a holistic TCO for vehicles of all size classes. The analysis focuses on the discounted lifetime costs of owning and operating light-, medium-, and heavy-duty vehicles, comparing across multiple powertrains.

Although ANL released both the AFLEET model and the comprehensive TCO report, they are two different studies and should not be mixed as their input values could be very different. A few key assumptions that were generated from the TCO report have been implemented somewhat into AFLEET but not all. Generally, AFLEET is current, details oriented, data rich, and transparent, and has many years of development and maintenance history. Therefore, our BET comparison analysis in the subsequent sections is based solely on the data directly extracted from the AFLEET model.

NREL TCO Report (2021)

Hunter, Chad, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birky, and Chen Zhang, 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. National Renewable Energy Laboratory. Technical Report. NREL/TP-5400-71796.

This report covers NREL's TCO analysis of six different truck powertrain technologies (diesel, diesel hybrid electric, plug-in hybrid electric, compressed natural gas, battery electric, and fuel cell) for three different truck vocations (Class 8 long haul [750-mile range and 500-mile range], Class 8 short haul [300-mile range], and Class 4 parcel delivery [120-mile range]), for three different timeframes (2018, 2025, and Ultimate). The TCO framework includes direct costs (purchase price, fuel, operating and maintenance, driver wages and benefits, insurance, tire replacements, permits, and tolls) and indirect costs (dwell time costs due to refueling/recharging and lost payload capacity costs from heavier advanced vehicle powertrains), and uses the best practices developed across the U.S. Department of Energy TCO studies. The TCO was evaluated for four scenarios that reflect typical business operating conditions (incurring or not incurring dwell-time and payload capacity costs).

The analysis finds that:

- Each powertrain technology may have an economic advantage on a TCO basis in certain business operating conditions, depending on fuel price realized. In general, battery electric powertrains may be best for shorter-range applications or when dwell time is not a concern.
- Specifically, For the Class 8 short-haul (300-mile-range) and Class 4 parcel delivery (120-mile-range) vocations, BEVs are the lowest-cost ZET if dwell time costs are not incurred, and their ultimate cost targets are achieved. Additionally, lost payload capacity cost for Class 8 short-haul (300-mile) BEVs is small due to the 2,000-lb exemption for alternative powertrain trucks.

- Electricity price is the most influential parameter to the TCO of BETs, and medium- and heavy-duty recharging cost reduction/management should be a key focus area for R&D.

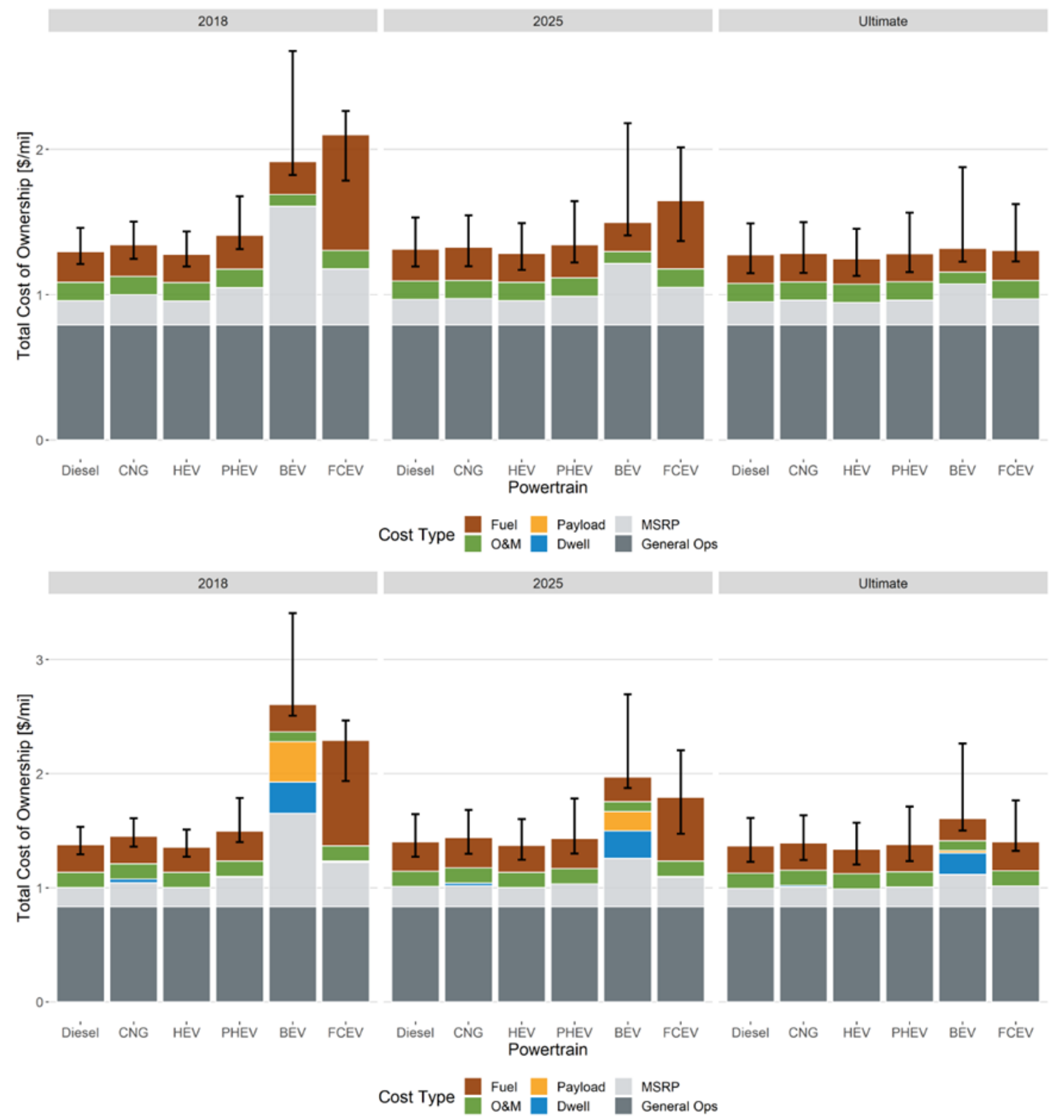

Figure ES-1. TCO ($/mile) for Class 8 long-haul tractors (750-mile range) in the Middle Atlantic region in (top) Single-Shift, Volume-Limited scenario and (bottom) Multi-Shift, Weight-Limited scenario.

Figure 14. Per-mile TCO for class 8 long-haul tractors in 2 different scenarios (source: NREL, 2021)

CALSTART TCO calculator (2021)

CALSTART, 2021. TCO calculator (V1.0). https://www.californiahvip.org/tco/.

CALSTART developed an online tool, Total Cost of Ownership Estimator (HVIP TCO Estimator V1.0), which can provide estimated cost comparisons for medium- and heavy-duty buses and trucks. We extracted the built-in default parameters for diesel and battery electric trucks and incorporated them in our detailed comparisons. This included all three types of trucks in our comparison and different time frames (e.g., 2020/25/30).

UC Davis TCO study (2021/22)

> UC Davis TCO study, 2022. *Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results*. Miller et al., Sustainable Freight Research Program, Institute of Transportation Studies, UC Davis. Forthcoming.

This study evaluates the economics of various types and classes of medium-duty and heavy-duty battery-electric and hydrogen fuel cell vehicles relative to the corresponding diesel-engine powered vehicle for 2020-2040. The study includes six vehicle types, including the three that are the focus of this report, and several variations within those types. Typical designs of each of the vehicle classes were formulated in terms of its road load characteristics and powertrain and energy storage components. The performance and energy consumption of the electrified trucks were simulated for appropriate driving cycles using the ADVISOR simulation program. The vehicle design characteristics were varied over 2020-2040 to reflect expected technology improvements. The study then focused on estimating the initial cost and the TCO for each vehicle type over the initial 5-year period (private) and the 15-year (societal) lifetime, and calculating payback periods. Calculations were done for 2020, 2025, 2030, 2035, and 2040.

In calculating battery size, the study first calculates the energy necessary to travel to desired range based solely on the simulated energy consumption and the range. The study assumes that the vehicle needs to be able to drive the desired range every day for the lifetime of the vehicle. There are several considerations that require oversizing the battery to meet that requirement. The simulation calculates the energy consumption on an ideal driving cycle without grades or heating/cooling loads. In real-world driving there are road grades, and cold or hot weather will require heating or cooling. Both grades and cabin temperature control increase energy use. Another consideration is the battery degradation. The standard criterion for battery end-of-life is a 20% reduction in battery capacity. In order to maintain a specified range over the life of the battery, the initial energy density must be increased to account for degradation. Finally, to maximize cycle life, batteries should not be discharged below 20% state-of-charge (SOC), which further increases the needed designed battery energy capacity to ensure the 80% available charge provides enough range. Overall, the battery must then be oversized by a factor of around 1.6 in 2020; we assume through various efficiencies it can be reduced to 1.5 by 2035, where it remains into the future.

The battery cost is assumed to be the cost to the truck original equipment manufacturer (OEM). The battery, and other components, must be integrated into the truck design. The OEM battery, fuel cell, and motor costs are modified with an integration factor to reflect the cost to the vehicle manufacturers to assemble/integrate the new electric drive components into the vehicle. The integration factor starts at 1.3 in 2020 and is reduced to 1.1 by 2040.

Side-by-side Comparison of Cost Modeling Details across Studies

In this section, the studies summarized above are compared and discussed, with a focus on the three truck application categories: heavy-duty long haul trucks (as shown in Table 2), medium-duty delivery trucks (as shown in Table 3), and heavy-duty drayage/short-haul trucks (as shown in Table 4). Note that only battery electric vehicle TCO assumptions and results are compared, along with their conventional diesel counterpart, even though some studies included other vehicle technologies such as fuel cell trucks. Key assumptions and variables are compared side-by-side in tables and the basis for these assumptions is described where known. Those variables with larger ranges are identified as areas for future research and discussion.

Table 2. Long haul trucks

	CARB	ANL	LBL	ICF	ICCT	NREL	NREL	UC Davis	CALSTART
Hyperlinks and truck type in original literature	ACF Discussion Document (2021) Sleeper Cab Tractor	AFLEET model (2021) Long Haul Freight Truck (Combination Long-Haul Truck)	Regional/long haul report (2021) Long Haul	MD/HD report (2019) Class 8 Long-Haul	Truck Infrastructure report (2019) Long-haul tractor-trailers	TCO Report (2021) Class 8 long-haul (range 750 mi)	TCO Report (2021) Class 8 long-haul (range 500 mi)	Forthcoming (2022) Class 8 long-haul (range 500 mi)	TCO calculator (2021) Truck 33,000+ lbs. Tractor
Diesel TCO today ($/veh)	NA	$2,514,740 lifetime	$1.64/mi. $2,558,400	$414,601 (2019)	$1,100,000 (2020)	$1.30/mi (2018) $1,300,000 Single shift Middle Atlantic region	$1.20/mi (2018) $1,200,000 Single shift Middle Atlantic region	$955,084 (2020)	$422,878 (2019)
Diesel TCO future ($/veh)	$1,200,908 (2035)	NA	NA	$491,770 (2030)	$1,080,000 (2030)	$1.25/mi (Ultimate) $1,250,000 Single shift Middle Atlantic region	$1.16/mi (Ultimate) $1,160,000 Single shift Middle Atlantic region	$948,967 (2030)	$490,214 (2030)
Electric TCO today ($/veh)	NA	$3,977,265 lifetime	$1.46/mi. $2,277,600 (2020)	$195,207 (2019)	$1,220,000 (2020)	$1.90/mi (2018) $1,900,000 Single shift Middle Atlantic region	$1.58/mi (2018) $1,580,000 Single shift Middle Atlantic region	$1,675,309 (2020)	$408,434 (2019) Including LCFS revenue
Electric TCO future ($/veh)	$1,151,046 (2035)	NA	$1.23/mi. $1,918,800 (2025-2030)	$174,514 (2030)	$1,020,000 (2030)	$1.29/mi (Ultimate) $1,290,000 Single shift Middle Atlantic region	$1.15/mi (Ultimate) $1,150,000 Single shift Middle Atlantic region	$908,528 (2030)	$427,009 (2030) Including LCFS revenue

	CARB	ANL	LBL	ICF	ICCT	NREL	NREL	UC Davis	CALSTART
Annual miles	Annual average 87,067 mi/yr[1].Total vehicle lifetime miles 1,044,802. New vehicle 100,000 mi/yr, 12-yr old vehicle 80,000 mi/yr.	170,000 mi/yr.	104,000 mi/yr. 400 mi/day. 260 days of driving. 500-mile range.	85,000 mi/yr	140,653 mi/yr (2020) 142,435 mi/yr (2030) Assume annual miles decline 2% each year. Annual average calculated: 117,269 mi/yr (2020) 118,755 mi/yr (2030)	Annual average 150,000 mi/yr (single shift), 200,000 mi/yr (multi-shift). 260 workdays. 1 million miles lifetime.	Annual average 100,000 mi/yr (single shift), 150,000 mi/yr (multi-shift). 260 workdays. 1 million miles lifetime.	120,000 mi/yr in first year, declining to 106,235 miles in year 5 (vehicles then sold after 5th year)	Custom. Default 22,500 mi/yr
Diesel mpg	5.8 mpg (2030) 5.8 mpg[2] (2035)	6.8 mpg, from Calculator.[3]	5.9 mpg	5.9 mpg Fixed in analysis.	7.7 mpg (2020) 10.4 mpg (2030) 14 mpg (2040)	8.4 mpg (2018) 10.2 mpg (2025) 12.9 mpg (Ultimate)	8.4 mpg (2018) 10.2 mpg (2025) 12.9 mpg (Ultimate)	6.1 mpg (2020) 8 mpg (2030)	6.5 mpg (current and future)

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[1] Annual mileage is the highest for newer vehicles and drops over time as the vehicle ages.
[2] The CARB report's Table 7 shows diesel fuel economy of 5.47 mpg in 2035, compared to 5.8 mpg presented in its subsequent TCO breakdown tables.
[3] However, from the ANL TCO report: 6.66 mpg (2020), 7.17 mpg (2025, low), 8.27 mpg (2025, high).

	CARB	ANL	LBL	ICF	ICCT	NREL	NREL	UC Davis	CALSTART
Electric kWh/mi	2.1 kWh/mi (2025). 0.47 mi/kWh (2025). 2.0 kWh/mi (2035). 0.50 mi/kWh (2035).	3.8 kWh/mi. 9.9 mpdge[4], from Calculator.	2.1 kWh/mi	1.3 kWh/mi. 29.5 mpg diesel equivalent[5]	1.9 kWh/mi (without trailer). 1.5 kWh/mi (2030), calculated from 2.1% annual efficiency improvement.	2.51 kWh/mi (2018) 1.58 kWh/mi (Ultimate); 14.9 mpdge (2018) 17.2 mpdge (2025) 23.6 mpdge (Ultimate)	2.46 kWh/mi (2018) 1.54 kWh/mi (Ultimate); 15.2 mpdge (2018) 18.1 mpdge (2025) 24.2 mpdge (Ultimate)	2.25 kWh/mi simulated (2020). 1.90 kWh/mi simulated (2030).	2.06 kWh/mi (current and future)
Vehicle life (years)	12 years	15 years	15 years	5 years first-owner vehicle life.	10 years	6.67 years[6] (single shift)	10 years[7] (single shift)	5 years (private TCO, first owner), 15 years (societal TCO).	Custom. Default 12 years
Discount rate	Not used	3%	6.9%	5%	4%	3% and 7%	3% and 7%	10% private 3% societal	Custom. Default 2%

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[4] Average Fuel Economy, miles per diesel gallon equivalent (mpdge) from Calculator. However, from the ANL TCO report: 11.59 mpg (2020), 12.60 mpg (2025, low), 14.67 mpg (2025, high) calculated as 2.5 kWh/mi.

[5] Based on CARB's energy economy ratio of 5x for electric compared to diesel for trucks and buses.

[6] Lifetime years are different between single-shift and multi-shift scenarios.

[7] Lifetime years are different between single-shift and multi-shift scenarios.

	CARB	ANL	LBL	ICF	ICCT	NREL	NREL	UC Davis	CALSTART
Diesel cost	$4.06/gal (2025) $4.4/gal[8] (2035)	$2.82/gal.[9] Public Station Fuel Cost, national average.	$3.30/gal. Diesel prices are held fixed in this analysis.	$3.61/gal[10] (2019) $4.8/gal (2030) California	$3.75/gal (2020) $4.71/gal (2030) Greater LA, California	Value not reported. Use AEO2021 Reference	Value not reported. Use AEO2021 Reference	$3.25/gal (2020) $3.75/gal (2030)	$4.16/gal (2019), CA $5.97/gal (2030), CA $3.20/gal (2019), US average $5.00/gal (2030), US average
Base electricity cost	$0.33/kWh (2020)[11] $0.43/kWh (2035)	$0.13/kWh. Public Station Fuel Cost, national average	$0.13/kWh. Electricity prices are held fixed in this analysis.	$0.17/kWh[12] (2019) $0.20/kWh (2030) California	$0.14/kWh (2020) $0.17/kWh (2030); $0.23/kWh (2020) fast[13] $0.26/kWh (2030) fast Greater LA, California	$0.11/kWh (2020 and 2030), mid-case	$0.11/kWh (2020 and 2030), mid-case	$0.15/kWh Add $0.02/kWh due to amortized charging station (see Charger cost below)	$0.098/kWh (2019), CA $0.138/kWh (2030), CA $0.123/kWh (2019), US average $0.177/kWh (2030), US average
Includes LCFS?	Yes @ $200/credit until 2030[14]	NA	NA	Separates out @ $150/credit, all years	No	No	No	Yes @ $100 or $200/credit, all years	Separates out @ $134, all years
Charging rate	NA	NA	NA	200 kW	500 kW	1000 kW (max)	1000 kW (max)	NA	NA

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[8] The CARB report's Figure 11 shows a diesel price of $4.5/gal in 2035, compared to $4.4/gal presented in its subsequent TCO breakdown tables.

[9] However, from the ANL TCO report: $3.08/gal (2025).

[10] Based on CEC 2018 Transportation Demand Forecast ($3.42/gal, $3.61/gal, $3.75/gal in 2018-2020 as extrapolated from CEC figure).

[11] Annual electricity prices are modeled using CEC's "Revised Transportation Energy Demand Forecast, 2018-2030". Electricity prices are relatively high because sleeper cab tractors are assumed to use publicly accessible retail charging.

[12] State-wide generation-weighted average.

[13] Based on SCE rates; fast charging station used 6 hours per day by fleet in 2020, increasing to 9 hours/day in 2030;

[14] An LCFS credit price of $200 until 2030, then declining linearly to $25 in 2045 and remaining constant thereafter.

	CARB	**ANL**	**LBL**	**ICF**	**ICCT**	**NREL**	**NREL**	**UC Davis**	**CALSTART**
Vehicle cost or initial purchase price – diesel	$153,862 (2025) $160,920 (2035)	$150,000	$125,000 Fixed today and future.	$160,000 (2019) $172,000 (2030)	$230,000 (2020) $250,000 (2030)	$165,000 (2018) $175,000 (2025) $159,000 (Ultimate) MSRP including tax	$165,000 (2018) $175,000 (2025) $159,000 (Ultimate) MSRP including tax	$134,000 (2020) $140,000 (2030)	$107,433 (current and future)
Vehicle cost or initial purchase price – electric	$304,629 (2025) $247,638 (2035)	$850,000 (current)	$246,431 (2020) $159,008 (2030)	$375,000 (2019) $191,000 (2030)	$260,000 (2020) $235,000 (2030)	$816,000 (2018) $423,000 (2025) $281,000 (Ultimate) MSRP including tax	$579,000 (2018) $316,000 (2025) $228,000 (Ultimate) MSRP including tax	$640,000 (2020) $291,000 (2030) Base case	$300,000 (current and future)
HVIP?	No	No	No	Separates out	No	No	No	No	Separates out
Vehicle power	350 kW	NA	NA	NA	700 kW Also indicated 550 kW	309 kW (2018)	309 kW (2018)	350 kW	
Battery size	1,050 kWh	NA	1,062 kWh	500 kWh	600 kWh[15]. 190 miles range (fully loaded), 250 miles range (no trailer)	2,200 kWh (2018) 1,800 kWh (2025) 1,200 kWh (Ultimate, 2050)	1,436 kWh (2018) 1,173 kWh (2025) 789 kWh (Ultimate, 2050)	1800 kWh (2020) 1520 kWh (2030)	NA
Battery $/kWh today	$350/kWh (2020) $150/kWh (2025)	NA	$135/kWh (2020)	$375/kWh[16] (2019)	$152/kWh (2020)	$197/kWh (2018)	$197/kWh (2018)	$225/kWh (2020)	NA
Battery $/kWh future	$100/kWh (2030) $75/kWh (2035)	NA	$60/kWh (2030)	$158/kWh (2030)	$74/kWh (2030)	$100/kWh (2025) $80/kWh (2050)	$100/kWh (2025) $80/kWh (2050)	$100/kWh (2030)	NA

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[15] Assumes 80% available for use.

[16] "Fully loaded" battery price, estimated to decrease by 58% by 2030 based on BNEF 2018 projections.

	CARB	ANL	LBL	ICF	ICCT	NREL	NREL	UC Davis	CALSTART
Diesel residual value ($/veh)	-$37,319 (2035)	-$36,451/veh Vehicle Resale Value (Sacramento, CA example)	NA	-$50,146 (2019) -$53,593 (2030)	$0	NA	NA	-$67,000	$0
Electric residual value ($/veh)	-$50,331 (2035)	-$206,557/veh Vehicle Resale Value (Sacramento, CA example)	NA	-$81,278 (2019) -$49,671 (2030)	$0	NA	NA	-$136,000	$0
Maintenance - diesel ($/mi)	$0.159/mi. $166,080 total	$0.179/mi	$0.12-0.29/mi. $12,000–$30,000/yr	$0.19/mi	$0.19/mi. $0.118/km	$0.152/mi Mid-case	$0.152/mi Mid-case	$0.20/mi	$0.44/mi (current and future)
Maintenance - electric ($/mi)	$0.119/mi. $124,560 total	$0.151/mi	$0.06/mi. $6,500/yr	$0.17/mi. Assume to reduce maintenance costs by 50% in 2030.	$0.17/mi. $0.107/km	$0.098/mi Mid-case	$0.098/mi Mid-case	$0.18/mi (2020) $0.15/mi (2030)	$0.23/mi (current and future)
Charger cost	$0 (EVSE cost)[17] (all years)	Not included	Not included	Included in Infrastructure cost below.	Included in Infrastructure cost below. $500/kW for 50 kW hardware; $450/kW for 350 kW+ fast hardware.	Not included	Not included	Add $0.02/kWh to electricity cost (total = $0.17/kWh) Amortized charger costs	Not included

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[17] Because sleeper cab tractors are assumed to use publicly accessible retail charging, no infrastructure costs are modelled.

	CARB	ANL	LBL	ICF	ICCT	NREL	NREL	UC Davis	CALSTART
Infrastructure cost	$0 (Infrastructure Upgrade Cost)[18] (all years)	Not included	$0.03/kWh Amortized charging infrastructure cost	$25,031 (current) and $15,797 (2030) for the charger and installation. Includes capital and O&M[19]	$182,000/veh (2020, low volume), mix of slow and fast[20] $70,000/veh (2030, high volume)	Not included	Not included	Included in electricity cost (total = $0.17/kWh)	Not included
Charger incentive?	No	No	No	Separates out	No	No	No	No	No
Other costs	Use 2020 constant dollars and does not use discount rates. Midlife Costs (2035): Diesel $35,000/veh, Battery electric $145,950/veh	In 2019 dollars. No engine rebuild cost.	Battery replacement cost (year 7): $100/kWh. No engine rebuild cost included. Include air pollution cost and GHG emissions cost	In 2019 dollars. Diesel Station O&M cost $5,000/yr. TCO includes the base HVIP voucher amount, LCFS credit value, and a utility program infrastructure incentive of 50% of the charger capital cost.	Add costs for load reduction and charging time[21]	In 2021 dollars. Assume the cost of building and operating the infrastructure is included in the fuel price charged. Include dwell time costs incurred for charging/refueling. Include lost payload capacity costs incurred.	In 2021 dollars. Assume the cost of building and operating the infrastructure is included in the fuel price charged. Include dwell time costs incurred for charging/refueling. Include lost payload capacity costs incurred.		Vehicle depreciation tax deduction. Increase in insurance for electric.

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[18] Because sleeper cab tractors are assumed to use publicly accessible retail charging, no infrastructure costs are modelled.

[19] ICF assumed two vehicles per charger, and capital costs are allocated to vehicles based on the cost per year per vehicle and first-owner vehicle life.

[20] Decreases over time with more electric trucks; includes mix of overnight (50 kW @ $25,000) and fast (350-500 kW @ $225,000) chargers

[21] Recent report of a truck driver saying electric model saves him 15 minutes per trip

Table 3. Delivery trucks

	CARB	ANL	ANL	ICF	ICF	ICCT	NREL	UC Davis	CALSTART
Hyperlinks and truck type in original literature	ACF Discussion Document (2021) Class 5 Walk-in Van	AFLEET model (2021) Delivery Step Van (Single Unit Short-Haul)	AFLEET model (2021) Delivery Straight Truck (Single Unit Long-Haul)	MD/HD report (2019) Class 6 Urban Delivery (Short-Haul)	MD/HD report (2019) Class 4/5 Delivery (Long-Haul)	Truck Infrastructure report (2019) Class 6 Delivery truck	TCO Report (2021) Class 4 parcel delivery (range 120 mi)	Forthcoming (2022) Class 4-6 delivery trucks	TCO calculator (2021) Truck 14,001-19,500 lbs. Step van
Diesel TCO today ($/veh)	$195,086 (2025)	$372,120 lifetime	$495,795 lifetime	$155,293 (2019)	$147,201 (2019)	$455,000 (2020)	$1.07/mi (2018) $321,000 Single shift Middle Atlantic region	$305,646 (2020)	$284,027 (2019)
Diesel TCO future ($/veh)	$216,067 (2035)	NA	NA	$179,137 (2030)	$169,416 (2030)	$460,000 (2030)	$1.02/mi (Ultimate) $306,000 Single shift Middle Atlantic region	$325,624 (2030)	$332,658 (2030)
Electric TCO today ($/veh)	$165,725 (2025)	$413,038 lifetime	$544,186 lifetime	$78,201 (2019)	$71,603 (2019)	$440,000 (2020)	$1.11/mi (2018) $333,000 Single shift Middle Atlantic region	$265,234 (2020)	$269,482 (2019) Including LCFS revenue
Electric TCO future ($/veh)	$169,584 (2035)	NA	NA	$76,949 (2030)	$87,029 (2030)	$330,000 (2030)	$0.90/mi (Ultimate) $270,000 Single shift Middle Atlantic region	$192,814 (2030)	$288,057 (2030) Including LCFS revenue

	CARB	ANL	ANL	ICF	ICF	ICCT	NREL	UC Davis	CALSTART
Annual miles	Annual average 13,665 mi/yr[22]. Total vehicle lifetime miles 163,979.	16,500 mi/yr	23,000 mi/yr	30,000 mi/yr	35,000 mi/yr	68,647 mi/yr Assume annual miles decline 2% each year. Annual average calculated: 57,234 mi/yr	Annual average 25,000 mi/yr (single shift), 50,000 mi/yr (multi-shift). 300 workdays. 300,000 miles lifetime.	20,000 mi/yr in first year, declining to 18,000 miles in year 5 (vehicles then sold after 5th year)	Custom. Default 22,500 mi/yr
Diesel mpg	9.1 mpg[23] (2025) 8.1 mpg (2035)	7.2 mpg	6.4 mpg	8.8 mpg	11.1 mpg	NA. 4% annual efficiency improvement	10.1 mpg (2018) 14.7 mpg (2025) 17.6 mpg (Ultimate)	11.3 mpg (2020) 12.7 mpg (2030)	9 mpg (current and future)
Electric kWh/mi	0.88 kWh/mi (2025). 0.83 kWh/mi (2035). 1.13 mi/kWh (2025). 1.2 mi/kWh (2035).	1.5 kWh/mi. 25.4 mpdge[24]	1.7 kWh/mi. 22.5 mpdge[25]	0.85 kWh/mi. 44.0 mpg diesel equivalent[26]	0.80 kWh/mi. 46.6 mpg diesel equivalent[27]	1.4 kWh/mi. 1.1 kWh/mi (2030), calculated from 2.1% annual efficiency improvement.	1.32 kWh/mi (2018) 0.71 kWh/mi (Ultimate); 28.4 mpdge (2018) 41.3 mpdge (2025) 52.3 mpdge (Ultimate)	0.83 kWh/mi simulated (2020). 0.75 kWh/mi simulated (2030).	2.06 kWh/mi (current and future)
Vehicle life (years)	12 years	15 years	15 years	7 years first-owner vehicle life.	7 years first-owner vehicle life.	10 years	12 years[28] (single shift)	5 years (private TCO, first owner), 15 years (societal TCO).	Custom. Default 12 years

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[22] Annual mileage is the highest for newer vehicles and drops over time as the vehicle ages.

[23] The fuel economy of diesel trucks is 9.1 mpg (2025) and surprisingly declines to 8.1 mpg (2035).

[24] Average Fuel Economy, miles per diesel gallon equivalent (mpdge).

[25] Average Fuel Economy, miles per diesel gallon equivalent (mpdge).

[26] Based on CARB's energy economy ratio of 5x for electric compared to diesel for trucks and buses.

[27] Based on CARB's energy economy ratio of 4.2x for electric compared to diesel for trucks and buses.

[28] Lifetime years are different between single-shift and multi-shift scenarios.

	CARB	ANL	ANL	ICF	ICF	ICCT	NREL	UC Davis	CALSTART
Discount rate	Not used	3%	3%	5%	5%	4%	3% and 7%	10% private 3% societal	Custom. Default 2%
Diesel cost	$4.06/gal (2025) $4.4/gal (2035)	$2.82/gal. Public Station Fuel Cost, national average.[29]	$2.82/gal. Public Station Fuel Cost, national average.[30]	$3.61/gal[31] (2019) $4.8/gal (2030) California	$3.61/gal[32] (2019) $4.8/gal (2030) California	$3.75/gal (2020) $4.71/gal (2030) Greater LA, California	Value not reported. Use AEO2021 Reference	$3.25/gal (2020) $3.75/gal (2030)	$4.16/gal (2019), CA $5.97/gal (2030), CA $3.20/gal (2019), US average $5.00/gal (2030), US average
Base electricity cost	$0.22/kWh (2025) $0.22/kWh (2035)	$0.13/kWh. Public Station Fuel Cost, national average	$0.13/kWh. Public Station Fuel Cost, national average.[33]	$0.17/kWh[34] (2019) $0.20/kWh (2030) California	$0.17/kWh[35] (2019) $0.20/kWh (2030) California	$0.14/kWh (2020) $0.17/kWh (2030); $0.23/kWh (2020) fast[36] $0.26/kWh (2030) fast Greater LA, California	$0.11/kWh (2020 and 2030), mid-case	$0.15/kWh Add $0.02/kWh due to amortized charging station (see Charger cost below)	$0.098/kWh (2019), CA $0.138/kWh (2030), CA $0.123/kWh (2019), US average $0.177/kWh (2030), US average
Includes LCFS?	Yes @ $200/credit until 2030[37]	NA	NA	Separates out @ $150/credit, all years	Separates out @ $150/credit, all years	No	No	Yes @ $100 or $200/credit, all years	Separates out @ $134, all years

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[29] However, from the ANL TCO report: $3.08/gal (2025).

[30] However, from the ANL TCO report: $3.08/gal (2025).

[31] Based on CEC 2018 Transportation Demand Forecast ($3.42/gal, $3.61/gal, $3.75/gal in 2018-2020 as extrapolated from CEC figure).

[32] Based on CEC 2018 Transportation Demand Forecast ($3.42/gal, $3.61/gal, $3.75/gal in 2018-2020 as extrapolated from CEC figure).

[33] However, from the ANL TCO report: $0.123/kWh (2025).

[34] State-wide generation-weighted average.

[35] State-wide generation-weighted average.

[36] Based on SCE rates; fast charging station used 6 hours per day by fleet in 2020, increasing to 9 hours/day in 2030;

[37] An LCFS credit price of $200 until 2030, then declining linearly to $25 in 2045 and remaining constant thereafter.

	CARB	ANL	ANL	ICF	ICF	ICCT	NREL	UC Davis	CALSTART
Charging rate				19-200 kW	19-200 kW	50-500 kW	1000 kW (max)	NA	NA
Vehicle cost or initial purchase price – diesel	$90,709 (2025) $95,703 (2035)	$70,000	$75,000	$63,000 (2019) $66,000 (2030)	$48,000 (2019) $51,000 (2030)	$100,000 (2020) $130,000 (2030)	$45,000 (2018) $49,000 (2025) $42,000 (Ultimate) MSRP including tax	$55,000 (2020) $57,000 (2030)	$60,000 (current and future)
Vehicle cost or initial purchase price - electric	$113,571 (2025) $105,167 (2035)	$150,000 (current)	$185,000 (current)	$166,667 (2019) $89,918 (2030)	$150,000 (2019) $79,918 (2030)	$120,000 (2020) $100,000 (2030)	$83,000 (2018) $45,000 (2025) $36,000 (Ultimate) MSRP including tax	$99,000 (2020) $61,000 (2030)	$188,542 (current and future)
HVIP?	No	No	No	Separates out	Separates out	No	No	No	Separates out
Vehicle power	150 kW	NA	NA	NA	NA	450 kW Also indicated 350 kW	146 kW (2018)	150 kW	
Battery size	140 kWh	NA	NA	150 kWh	150 kWh	300 kWh[38] 164 miles range (fully loaded), 172 miles range (empty)	231 kWh (2018) 155 kWh (2025) 109 kWh (Ultimate, 2050)	199 kWh (2020) 181 kWh (2030)	NA
Battery $/kWh today	$350/kWh (2020) $150/kWh (2025)	NA	NA	$375/kWh[39] (2019)	$375/kWh[40] (2019)	$152/kWh (2020)	$197/kWh (2018)	$225/kWh (2020)	NA
Battery $/kWh future	$100/kWh (2030) $75/kWh (2035)	NA	NA	$158/kWh (2030)	$158/kWh (2030)	$74/kWh (2030)	$100/kWh (2025) $80/kWh (2050)	$100/kWh (2030)	NA

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[38] Assumes 80% available for use.

[39] "Fully loaded" battery price, estimated to decrease by 58% by 2030 based on BNEF 2018 projections.

[40] "Fully loaded" battery price, estimated to decrease by 58% by 2030 based on BNEF 2018 projections.

	CARB	ANL	ANL	ICF	ICF	ICCT	NREL	UC Davis	CALSTART
Diesel residual value ($/veh)	-$27,108 (2025) -$28,601 (2035)	-$17,011 Vehicle Resale Value (Sacramento, CA example)	-$18,226/veh Vehicle Resale Value (Sacramento, CA example)	-$17,909 (2019) -$18,762 (2030)	-$13,645 (2019) -$14,498 (2030)	$0	NA	-$27,500	$0
Electric residual value ($/veh)	-$35,554 (2025) -$31,823 (2035)	-$36,451 Vehicle Resale Value (Sacramento, CA example)	-$44,957/veh Vehicle Resale Value (Sacramento, CA example)	-$19,375 (2019) -$23,735 (2030)	-$27,550 (2019) -$14,140 (2030)	$0	NA	-$29,300	$0
Maintenance - diesel ($/mi)	$0.210/mi	$0.198/mi	$0.201/mi	$0.19/mi	$0.20/mi	$0.20/mi $0.127/km	$0.118/mi Mid-case	$0.20/mi	$0.31/mi (current and future)
Maintenance - electric ($/mi)	$0.158/mi	$0.134/mi	$0.159/mi	$0.17/mi. Assume to reduce maintenance costs by 50% in 2030.	$0.16/mi. Assume to reduce maintenance costs by 50% in 2030.	$0.16/mi. $0.101/km	$0.076/mi Mid-case	$0.18/mi (2020) $0.16/mi (2030)	$0.16/mi (current and future)
Charger cost	$5,000/veh (EVSE cost)	Not included	Not included	Included in Infrastructure cost below.	Included in Infrastructure cost below.	Included in Infrastructure cost below. $500/kW for 50 kW hardware; $450/kW for 350 kW+ fast hardware.	Not included	Add $0.02/kWh to electricity cost (total = $0.17/kWh)	Not included

	CARB	ANL	ANL	ICF	ICF	ICCT	NREL	UC Davis	CALSTART
Infrastructure cost	$25,000/veh (Infrastructure Upgrade Cost)	Not included	Not included	$7,215 (current) and $4,832 (2030) for the charger and installation. Includes capital and O&M[41]	$7,215 (current) and $4,832 (2030) for the charger and installation. Includes capital and O&M[42]	$82,000/veh (2020, low volume), mix of slow and fast[43] $27,000/veh (2030, high volume)	Not included	Included in electricity cost (total = $0.17/kWh)	Not included
Charger incentive?	No	No	No	Separates out	Separates out	No	No	No	No
Other costs	Use 2020 constant dollars and does not use discount rates. Midlife Costs are $0 for diesel and electric	In 2019 dollars. No engine rebuild cost.	In 2019 dollars. No engine rebuild cost.	In 2019 dollars. Diesel Station O&M cost $5,000/yr. TCO includes the base HVIP voucher amount, LCFS credit value, and a utility program infrastructure incentive of 50% of the charger capital cost.	in 2019 dollars. Diesel Station O&M cost $5,000/yr.	Add costs for load reduction and charging time[44]	In 2021 dollars. Assume the cost of building and operating the infrastructure is included in the fuel price charged. Include dwell time costs incurred for charging/refueling. Include lost payload capacity costs incurred.		Vehicle depreciation tax deduction. Increase in insurance for electric.

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[41] ICF assumed two vehicles per charger, and capital costs are allocated to vehicles based on the cost per year per vehicle and first-owner vehicle life.

[42] ICF assumed two vehicles per charger, and capital costs are allocated to vehicles based on the cost per year per vehicle and first-owner vehicle life.

[43] Decreases over time with more electric trucks; includes mix of overnight (50 kW @ $25,000) and fast (350-500 kW @ $140,000) chargers

[44] Recent report of a truck driver saying electric model saves him 15 minutes per trip

Table 4. Drayage/short-haul trucks

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Hyperlinks and truck type in original literature	ACT Discussion Document (2019) Regional tractor	ACF Discussion Document (2021) Day Cab Tractor	AFLEET model (2021) Regional Haul Freight Truck (Combination Short-Haul Truck)	Regional/long haul report (2021) Regional Haul	MD/HD report (2019) Class 8 Drayage (Short-Haul)	Truck Infrastructure report (2019) Class 8 Drayage truck	Drayage report (2019) Drayage	TCO Report (2021) Class 8 short-haul (range 300 mi)	Forthcoming (2022) Class 8 short-haul	TCO calculator (2021) Truck 26,001-33,000 lbs.
Diesel TCO today ($/veh)	$571,456 (2018)	$658,436 (2025)	$1,155,389 lifetime	$1.73/mi. $2,024,100	$298,695 (2019)	$395,000 (2020)	$587,000 New diesel (average daily truck)	$1.07/mi (2018) $1,070,000 Single shift Middle Atlantic region	$397,166 (2020)	$352,374 (2019)
Diesel TCO future ($/veh)	$602,408 (2035)	$781,623 (2035)	NA	NA	$349,810 (2030)	$420,000 (2030)	NA	$1.01/mi (Ultimate) $1,010,000 Single shift Middle Atlantic region	$420,832 (2030)	$407,084 (2030)
Electric TCO today ($/veh)	$774,964 (2018)	$510,068 (2025)	$1,692,140 lifetime	$1.50/mi. $1,755,000 (2020)	$122,709 (2019)	$450,000 (2020)	$247,000 (SCE) $378,000 (LADWP) With LCFS and incentives (average daily truck)	$1.18/mi (2018) $1,180,000 Single shift Middle Atlantic region	$600,410 (2020)	$355,235 (2019) Including LCFS revenue
Electric TCO future ($/veh)	$446,081 (2035)	$574,301 (2035)	NA	$1.27/mi. $1,485,900 (2025-2030)	$159,144 (2030)	$370,000 (2030)	NA	$0.93/mi (Ultimate) $930,000 Single shift Middle Atlantic region	$416,417 (2030)	$376,155 (2030) Including LCFS revenue

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Annual miles	54,000 mi/yr. 180 mi/day. 300 operating days.	49,940 mi/yr. Total vehicle lifetime miles 599,280. Annual miles do not vary with age.	65,000 mi/yr	78,000 mi/yr. 300 mi/day. 260 days of driving. 375-mile range.	45,000 mi/yr	30,193 mi/yr Assume annual miles decline 2% each year. Annual average calculated: 25,173 mi/yr	61,880 mi/yr (average daily miles truck): Drives 238 miles a day, five days a week. 41,600 mi/yr (single-shift truck) 52,000 mi/yr (two-shift truck)	Annual average 60,000 mi/yr (single shift), 100,000 mi/yr (multi-shift). 260 workdays. 1 million miles lifetime.	45,000 mi/yr in first year, declining to 39.800 miles in year 5 (vehicles then sold after 5th year)	Custom. Default 22,500 mi/yr
Diesel mpg	5.9 mpg (2018) 7.3 mpg (2030)	6.7 mpg[45] (2025) 5.5 mpg (2035)	6.3 mpg, from Calculator.[46]	5.9 mpg	6.0 mpg	NA. 4% annual efficiency improvement	6.0 mpg[47]	6.6 mpg (2018) 8.2 mpg (2025) 10.7 mpg (Ultimate)	7 mpg (2020) 8.2 mpg (2030)	8 mpg[48] (current and future)

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[45] The fuel economy of diesel trucks is 6.7 mpg (2025) and surprisingly declines to 5.5 mpg (2035).

[46] However, from the ANL TCO report: 6.14 mpg (2020), 6.65 mpg (2025, low), 7.78 mpg (2025, high).

[47] Based on Tetra Tech survey of drayage drivers.

[48] Fuel economy estimates based on several sources: personal communication with OEMs and fleets; Argonne National Laboratory; CARB; DOE; and crowd sourced estimates as logged on Fuelly.com. Where fuel economy estimates were not readily available, projections were made based off of other similar vehicle types, sizes, and fuel types.

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Electric kWh/mi	2.1 kWh/mi (2018). 1.7 kWh/mi (2027+)	1.85 kWh/mi (2025). 1.75 kWh/mi (2035). 0.54 mi/kWh (2025). 0.57 mi/kWh (2035)	3.63 kWh/mi. 10.3 mpdge[49], from Calculator.	2.1 kWh/mi	1.25 kWh/mi. 30.0 mpg diesel equivalent[50]	1.9 kWh/mi (without trailer). 1.5 kWh/mi (2030), calculated from 2.1% annual efficiency improvement.	2.4 kWh/mi[51]	2.35 kWh/mi (2018) 1.48 kWh/mi (Ultimate); 15.9 mpdge (2018) 18.7 mpdge (2025) 25.3 mpdge (Ultimate)	2.35 kWh/mi simulated (2020). 2.11 kWh/mi simulated (2030).	2.32 kWh/mi (current and future)
Vehicle life (years)	12 years	12 years	15 years	15 years	7 years first-owner vehicle life.	10 years	12 years life (new) 6 years (used)	16.67 years[52] (single shift)	5 years (private TCO, first owner), 15 years (societal TCO).	Custom. Default 12 years
Discount rate	5%	Not used	3%	6.9%	5%	4%	7%	3% and 7%	10% private 3% societal	Custom. Default 2%

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[49] Average Fuel Economy, miles per diesel gallon equivalent (mpdge). However, from the ANL TCO report: 11.90 mpg (2020), 12.91 mpg (2025, low), 15.41 mpg (2025, high) calculated as 2.4 kWh/mi.

[50] Based on CARB's energy economy ratio of 5x for electric compared to diesel for trucks and buses.

[51] High end of data collected by UC Riverside of a TransPower truck, ranged from 2.0 – 2.4 kWh/mi (rationalized to account for charging losses)

[52] Lifetime years are different between single-shift and multi-shift scenarios.

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Diesel cost	$3.74/gal (2018) $4.6/gal (2030)	$4.06/gal (2025) $4.41/gal (2035)	$2.82/gal. Public Station Fuel Cost, national average.[53]	$3.30/gal. Diesel prices are held fixed in this analysis.	$3.61/gal[54] (2019) $4.8/gal (2030) California	$3.75/gal (2020) $4.71/gal (2030) Greater LA, California	$3.87/gal[55] California	Value not reported. Use AEO2021 Reference	$3.25/gal (2020) $3.75/gal (2030)	$4.16/gal[56] (2019), CA $5.97/gal (2030), CA $3.20/gal (2019), US average $5.00/gal (2030), US average
Base electricity cost	$0.15/kWh (2018) $0.17/kWh (2030)	$0.21/kWh (2025) $0.21/kWh (2035)	$0.13/kWh. Public Station Fuel Cost, national average	$0.13/kWh. Electricity prices are held fixed in this analysis.	$0.17/kWh [57] (2019) $0.20/kWh (2030) California	$0.14/kWh (2020) $0.17/kWh (2030); $0.23/kWh (2020) fast[58] $0.26/kWh (2030) fast Greater LA, California	$0.104/kWh (LADWP)[59] $0.097/kWh (SCE)[60] Average off-peak energy price. Additionally, LADWP has demand charge.	$0.11/kWh (2020 and 2030), mid-case	$0.15/kWh Add $0.02/kWh due to amortized charging station (see Charger cost below)	$0.098/kWh [61] (2019), CA $0.138/kWh (2030), CA $0.123/kWh (2019), US average $0.177/kWh (2030), US average

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[53] However, from the ANL TCO report: $3.08/gal (2025).

[54] Based on CEC 2018 Transportation Demand Forecast ($3.42/gal, $3.61/gal, $3.75/gal in 2018-2020 as extrapolated from CEC figure).

[55] Average diesel price in CA in 2018, EIA; diesel exhaust fluid: $2.90/gallon

[56] Average diesel price in CA in 2018, EIA (note: does not match EIA values used in the UCLA study)

[57] State-wide generation-weighted average.

[58] Based on SCE rates; fast charging station used 6 hours per day by fleet in 2020, increasing to 9 hours/day in 2030;

[59] Includes the base rate, adjustments, and a $0.02 discount for EV charging.

[60] Seasonally adjusted average off-peak EV-TOU-9 (SCE's new commercial EV rate without demand charges until 2024).

[61] Demand charges not considered

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Includes LCFS?	Yes @ $100/credit, all years	Yes @ $200/credit until 2030[62]	NA	NA	Separates out @ $150/credit, all years	No	Separates out @ $115-$135/credit, vary with year	No	Yes @ $100 or $200/credit, all years	Separates out @ $134, all years[63]
Charging rate	80 kW	NA	NA	NA	200 kW	50-500 kW	39-119 kW	1000 kW (max)	NA	NA
Vehicle cost or initial purchase price – diesel	$134,000 (2018)[64] $146,442 (2030)	$143,862 (2025) $150,920 (2035)	$130,000	$125,000 Fixed today and future.	$110,000 (2019) $118,000 (2030)	$220,000 (2020) $250,000 (2030)	$105,599 (new)[65] $50,236 (used)[66]	$153,000 (2018) $163,000 (2025) $146,000 (Ultimate) MSRP including tax	$119,000 (2020) $123,000 (2030)	$73,805 (current and future)
Vehicle cost or initial purchase price - electric	$474,930[67] (2018) $195,960 (2030)	$201,999 (2025) $176,028 (2035)	$480,000 (current)	$210,573 (2020) $145,006 (2030)	$250,000 (2019) $133,000 (2030)	$250,000 (2020) $220,000 (2030)	$300,000[68] (current)	$374,000 (2018) $223,000 (2025) $171,000 (Ultimate) MSRP including tax	$272,500 (2020) $159,800 (2030)	$247,860 (current and future)
HVIP?	No	No	No	No	Separates out	No	Separates out. HVIP reduces BET cost by $165,000	No	No	Separates out
Vehicle power	350 kW	350 kW	NA	NA	NA	600 kW Also indicated 500 kW	NA	332 kW (2018)	300 kW	NA

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[62] An LCFS credit price of $200 until 2030, then declining linearly to $25 in 2045 and remaining constant thereafter.
[63] 134.10 is the average weekly credit price from the date of first reporting on April 21, 2016 through May 23, 2019.
[64] Vehicle price only, not including taxes or financing (which are included in the study in another term "total vehicle cost").
[65] UCLA assumes that upfront costs for the purchase of trucks and any required infrastructure, plus taxes and less any available incentive funding are financed.
[66] Based on Tetra Tech survey of drayage drivers.
[67] Vehicle price only, not including taxes or financing (which are included in the study in another term "total vehicle cost").
[68] Estimate based on NY Voucher Incentive Program incentive for BYD's Class 8 tractor.

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Battery size	510 kWh	450 kWh	NA	797 kWh	250 kWh	500 kWh[69] 175 miles range (fully loaded), 212 miles range (no trailer)	Not explicitly indicated, but the mentioned BYD class 8 truck has a battery size 435 kWh[70]	823 kWh (2018) 682 kWh (2025) 452 kWh (Ultimate, 2050)	564 kWh (2020) 506 kWh (2030)	NA
Battery $/kWh today	$600/kWh (2018) $350/kWh (2020)	$350/kWh (2020) $150/kWh (2025)	NA	$135/kWh (2020)	$375/kWh[71] (2019)	$152/kWh (2020)	Doesn't separate out	$197/kWh (2018)	$225/kWh (2020)	NA
Battery $/kWh future	$100/kWh[72] (2030)	$100/kWh (2030) $75/kWh (2035)	NA	$60/kWh (2030)	$158/kWh (2030)	$74/kWh (2030)	NA	$100/kWh (2025) $80/kWh (2050)	$100/kWh (2030)	NA
Diesel residual value ($/veh)	-$15,453 (2018) -$16,888 (2030)	-$33,363 (2025) -$34,999 (2035)	-$31,591/veh Vehicle Resale Value (Sacramento, CA example)	NA	-$31,270[73] (2019) -$33,544 (2030)	$0	$0	NA	-$59,500	$0

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[69] Assumes 80% available for use.

[70] Represents BYD's Class 8 tractor. The BYD 8TT, which has an advertised range of 124 miles at full load and 167 miles at half load.

[71] "Fully loaded" battery price, estimated to decrease by 58% by 2030 based on BNEF 2018 projections.

[72] Use light-duty battery prices with a five-year delay.

[73] 40% of the initial purchase price.

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Electric residual value ($/veh)	-$7,727 (2018) -$8,444 (2030)	-$46,845 (2025) -$37,780 (2035)	-$116,644/veh Vehicle Resale Value (Sacramento, CA example)	NA	-$32,522[74] (2019) -$22,527 (2030)	$0	$0	NA	-$78,500	$0
Maintenance - diesel ($/mi)	$0.19/mi	$0.198/mi. $118,898 total	$0.179/mi	$0.15-0.38/mi. $12,000–$30,000/yr	$0.20/mi	$0.19/mi. $0.118/km	$0.22/mi (used) $0.16/mi (new)	$0.152/mi Mid-case	$0.20/mi	$0.44/mi (current and future)
Maintenance - electric ($/mi)	$0.14/mi	$0.149/mi. $89,174 total	$0.151/mi	$0.08/mi. $6,500/yr	$0.17/mi. Assume to reduce maintenance costs by 50% in 2030.	$0.17/mi. $0.107/km	$0.08/mi[75]	$0.098/mi Mid-case	$0.18/mi (2020) $0.16/mi (2030)	$0.23/mi (current and future)

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[74] 40% of the balance of truck + 32% of battery (accounting for the loss of battery capacity), relative to the less expensive new electric truck at the time of resale.

[75] Based on CARB's 2015 estimate that battery electric maintenance costs are 25 – 80 percent lower than diesel. Taken at central estimate of that range.

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Charger cost	$50,000/veh	$75,000/veh (EVSE cost)	Not included	Not included	Included in Infrastructure cost below.	Included in Infrastructure cost below. $500/kW for 50 kW hardware; $450/kW for 350 kW+ fast hardware.	Included in Infrastructure cost below.	Not included	Add $0.02/kWh to electricity cost (total = $0.17/kWh)	Not included
Infrastructure cost	$68,698/veh [76] (Infrastructure Upgrade Cost)	$88,000/veh (Infrastructure Upgrade Cost)	Not included	$0.03/kWh Amortized charging infrastructure cost	$32,841 (current) and $21,738 (2030) for the charger and installation. Includes capital and O&M[77]	$58,000/veh (2020, low volume), mix of slow and fast[78] $28,000/veh (2030, high volume)	$105,000/charger[79]	Not included	Included in electricity cost (total = $0.17/kWh)	Not included
Charger incentive?	No	No	No	No	Separates out	No	Separates out	No	No	No

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[76] Infrastructure costs are spread out over a 20-year period.

[77] ICF assumed two vehicles per charger, and capital costs are allocated to vehicles based on the cost per year per vehicle and first-owner vehicle life.

[78] Decreases over time with more electric trucks; includes mix of overnight (50 kW @ $25,000) and fast (350-500 kW @ $225,000) chargers

[79] Uses CARB's assumptions for charger and infrastructure costs. CARB estimates that charging equipment has a 28-year service life and therefore could serve multiple trucks. However, because the cost is upfront, the TCOs include the full cost of the chargers.

	CARB	CARB	ANL	LBL	ICF	ICCT	UCLA	NREL	UC Davis	CALSTART
Other costs	Diesel midlife engine rebuild $0 Battery replaced @ 300,000 mi, $42,949/veh (2018) $30,233/veh (2030)	Use 2020 constant dollars and does not use discount rates. Midlife Costs: Diesel $0, Battery electric $40,545/veh (2025) $31,275/veh (2035)	In 2019 dollars. No engine rebuild cost.	Battery replacement cost (year 7): $100/kWh No engine rebuild cost included. Include air pollution cost and GHG emissions cost	In 2019 dollars. Diesel Station O&M cost $5,000/yr. TCO includes the base HVIP voucher amount, LCFS credit value, and a utility program infrastructure incentive of 50% of the charger capital cost.	Add costs for load reduction and charging time[80]	Assume financing for vehicle and infrastructure. Assume batteries will not need replacement during the truck life.	In 2021 dollars. Assume the cost of building and operating the infrastructure is included in the fuel price charged. Include dwell time costs incurred for charging/refueling. Include lost payload capacity costs incurred.		Vehicle depreciation tax deduction. Increase in insurance for electric.

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[80] Recent report of a truck driver saying electric model saves him 15 minutes per trip.

Comparative Analysis and Discussion

The detailed side-by-side comparison tables show significant variations in many major metrics which contribute to the variations in the TCO estimates by different studies. The similarities and differences for important metrics, along with the overall lifetime TCO estimates, are assessed in many figures that follow. This is done for various variables, showing the comparisons for each of the three main types of trucks, and for near term and longer term estimates.

Overall TCO estimates ($/vehicle)

Generally, a direct comparison of overall TCO estimates between studies will show a wide range and should be considered cautiously. As mentioned, one important reason is that the underlying modeling scope and coverage are often very different, e.g., in terms of which costs are included and how they are measured. These underlying differences are a central focus of this comparative analysis. We show the TCOs mainly as a reference point that can be referred to when considering the range of underlying assumptions.

We compared the lifetime TCO estimates associated with common coverage (i.e., a subset) of the cost components, typically including vehicle cost, fuel/energy cost, maintenance cost, infrastructure cost, resale/residual value, and policy incentives (such as LCFS credit revenue). Figure 15 presents a comparison of overall TCO estimates associated with common coverage of TCO components. To make the scope and coverage comparable, Figure 15 does not present the additional cost/revenue considerations such as lost payload and dwell-time penalty (NREL and ICCT), two-shift scenarios (NREL), or environmental benefits associated with electric trucks (LBL and ANL).

Almost all the studies report a substantial decline in the overall TCO estimates over time for BETs, reaching an approximately comparable level with their diesel counterpart in the future. In contrast, the diesel TCO results do not change much in each study between today and the future. However, the TCO magnitudes for both BETs and diesel trucks vary much between studies, as a result of their different assumptions and parameter values that we will discuss in subsequent sections. This further highlights the importance of this work which compares the TCO modeling inputs and coverage side-by-side in detail.

The huge differences in TCO estimates across the studies are partly due to the significant variations in the annual vehicle miles traveled (VMT) used as input to calculate the overall cost in each study. ICF and CALSTART present the lowest overall TCO results for diesel trucks and BETs. ICF long-haul uses a low annual VMT of 85,000 miles/year (for both diesel and electric trucks), as compared to the literature average of about 120,000 miles/year as shown in Figure 16. Similarly, CALSTART uses a very low default VMT for long-haul trucks at 22,500 miles/year which obviously brings down CALSTART’s overall TCO estimate dramatically, as shown in Figure 15. This is also the case for drayage/short-haul trucks in CALSTART. However, in the delivery truck case, CALSTART still uses the annual distance driven of 22,500 miles/year which is close to the literature average for this truck type, as shown in Figure 16, and thus its TCO estimate is close to the average TCO calculated from all studies.

As with the ICF and a few other studies, policy incentives are playing an extremely important role in reducing the overall TCO for BETs. On top of using a low VMT, ICF presents the lowest overall TCO results for BETs also because of the effect of all the three major policy incentives: the base HVIP voucher amount (e.g., $150,000 for electric class 8 trucks), LCFS credit value (at a credit price of $150/credit), and a utility program infrastructure incentive of 50% of the charger capital cost.

ANL and LBL present very high estimates for TCOs, mostly because the two studies use high numbers for VMT, vehicle price, and vehicle lifetime, among other things. For example, in the ANL work, long-haul trucks have an annual VMT of 170,000 miles/year, much higher than the literature average of about 120,000 miles/year; long-haul electric trucks have the most expensive price at $850,000/vehicle across all studies; and these long-hauls have a very long vehicle life of 15 years.

The AFLEET model by the ANL researchers does not specify a scenario year, so its value is considered as for the current year scenario, although many numbers could be meaningful for the future years as well. Note that the AFLEET model also has additional considerations for external costs associated with petroleum use, greenhouse gas (GHG) emissions, and air pollution; however, their external cost magnitudes are not included in the numbers presented in Figure 15, in order to compare with the other TCO studies most of which do not take into account the externalities.

Figure 15. Comparison of overall TCO estimates associated with common coverage of costs

Annual miles of travel

The distance trucks are driven each year has an important impact on their operating and fuel costs, and thus on their TCO estimates. The more miles trucks are assumed to travel, the more battery capacity they will need (increasing truck purchase cost and possibly increasing energy use per mile and/or lowering payload). For BETs, it will also mean more miles at a lower per-mile energy cost than diesel trucks, improving BET TCO from an energy cost point of view.

As shown in Figure 16, for both long-haul trucks and short-haul/drayage heavy duty trucks, the different studies use a quite varied set of assumptions for the annual VMT. However, all the studies assume no change (or very slight change as with the ICCT study long-haul trucks) in this travel from near to long term.

The differences in annual miles driven may reflect different data sources but also different underlying assumptions of truck purpose. Very long-haul trucks can travel up to 1000 miles in a day (e.g., 60 miles per hour over 16 hours, if multiple drivers are available), but 500 miles per day is a more realistic high-end number over the course of a year. At 500 miles per day, and operating 300 days per year, a truck would travel 150,000 miles. Only one study (ANL) goes above this level. They range from about 80,000 to 170,000 miles, with an average across studies of 120,000 miles, or about 400 miles per day over 300 days per year. The CALSTART VMT is not shown in Figure 16 as its default numbers are constant across all 3 truck types, at 22,500 miles/year, which does not represent long-haul trucks or drayage/short-haul trucks well. Most studies use the annual average miles to calculate the TCO, while some specify the first-year mileage and assume the mileage will drop with vehicle age (such as UC Davis and ICCT studies), which brings down the average.

For drayage or “day trucks”, the requirements include more urban driving and more stopping, which leads to lower daily travel than long-haul trucks travelling mainly on highways. Yet the wide variation in daily mileage (in this case between 25,000 and 75,000 miles per year) persists.

Delivery trucks have perhaps the biggest variation of all, by a factor of nearly 4, from 15,000 to nearly 60,000 miles per year. Differences likely relate to the specific type and use of the vehicle, which can be seen in the two reported vehicle types from the ANL and ICF studies.

Figure 16. Annual average VMT comparison across studies and truck types

Fuel economy or energy consumption rates (MPG for diesel and kWh/mi for electric)

The energy efficiency of trucks is important to their energy cost, and can vary by application, duty cycle, weather conditions and other factors. It is important to use in-use, on-road estimates when possible, and new trucks should be compared to other new trucks (and stock average to stock average) where possible. All the studies focused on new trucks and most appear to be on-road estimates with the exception of NREL. Theirs does not appear to adjust for in use performance, and also shows by far the largest improvement to future diesel efficiency. Most other studies show near term efficiency between about 6 and 7 miles per gallon (MPG), with long term in a few cases going to 8 MPG. NREL's estimates start at 8 and go to 12 MPG for diesel long-haul trucks.

As shown in Figure 17, for electric trucks (in kWh/mi), lower is better for efficiency and most studies show strong improvements from near to longer term. For long-haul trucks, near term estimates range rather dramatically between about 1.3 and 3.8 kWh/mi, with long term estimates ranging from 1.3 to 2.5. ANL has the most pessimistic estimates, with ICF the most optimistic.

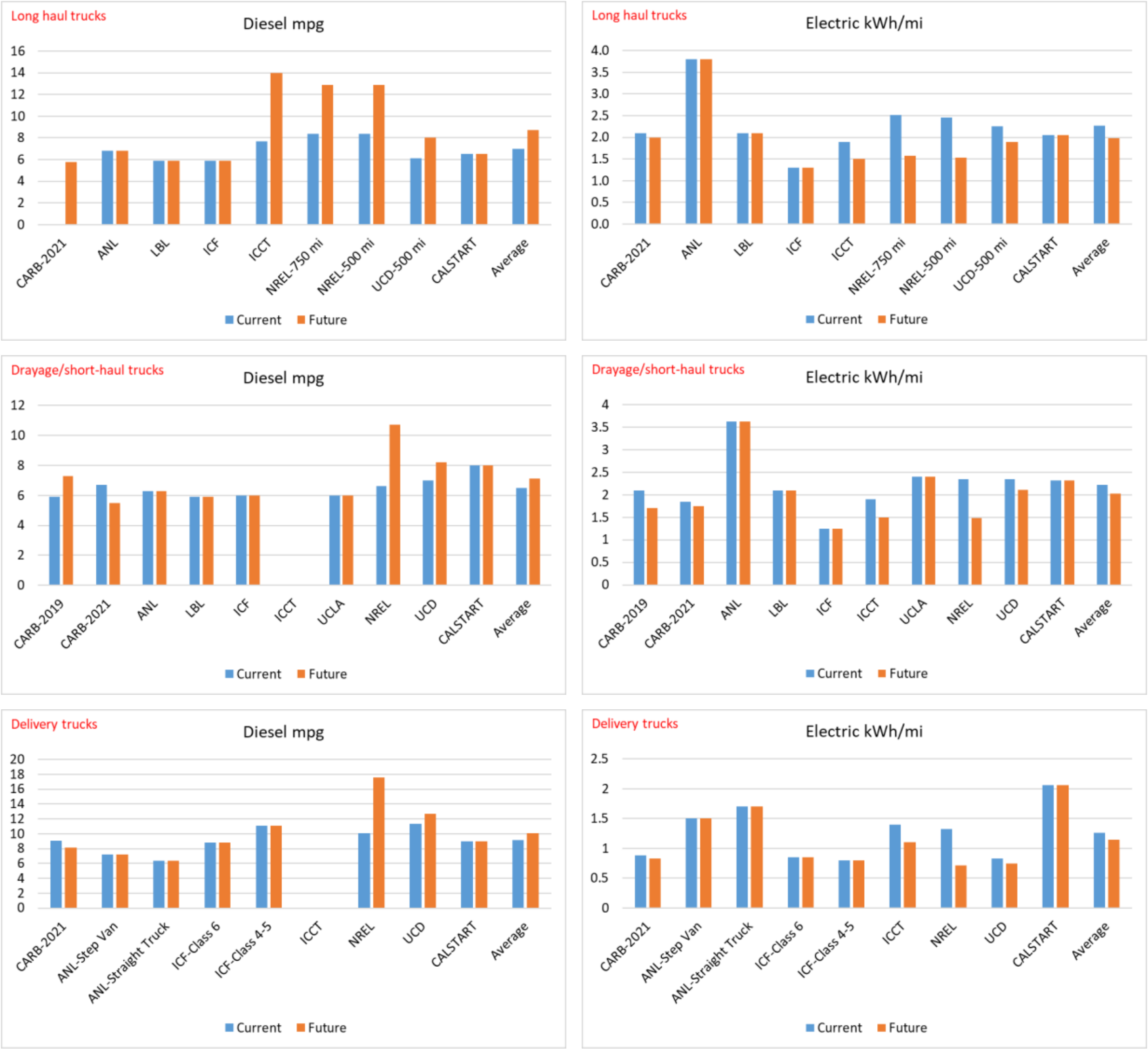

Figure 17. Fuel economy or energy consumption rates comparison across studies and truck types (MPG for diesel and kWh/mi for electric)

Figure 18 shows the fuel economy comparison on a miles per diesel gallon equivalent (MPDGE) basis, which presents a substantial difference between diesel and battery electric trucks and this finding appears to be universal. In Figure 18 we put all truck types into MPG (diesel equivalent) units, converting the electric trucks to MPG on a lower heating value (LHV) energy basis. The ratio of BEV truck to diesel truck efficiency varies considerably, with diesel energy use per mile between 1.5 and 4x higher than BEV, with the average across studies about 3x. The ANL report and UC Davis' own work on relative truck efficiency suggests that there may be a much bigger difference in tested efficiency than is likely occurring in actual on-road use. We estimate about a 25-33% advantage for long-haul BETs compared to diesel trucks, in kWh/mi units.

Short haul estimated efficiencies are much closer across studies, with NREL an outlier for diesel trucks and ANL an outlier on electric short-haul trucks.

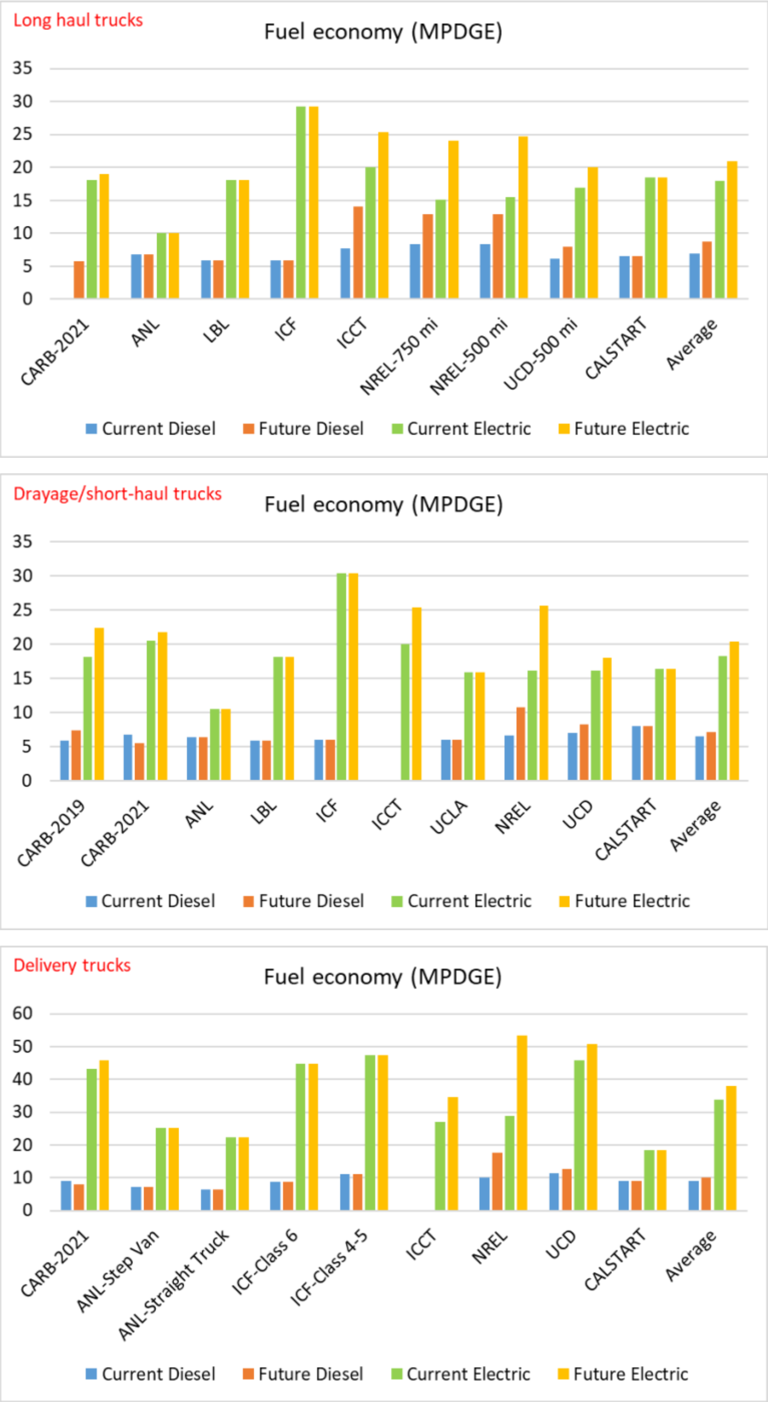

Figure 18. Fuel economy comparison of diesel and electric trucks on a miles per diesel gallon equivalent (MPDGE) basis, across studies and truck types

Fuel/energy cost (diesel in $/gal and electricity in $/kWh)

The retail price of electricity and diesel fuel assumed in these studies is another important input into the overall energy cost. Variations in these prices directly affect fuel cost and TCO. Differences between gasoline and electricity cost (and variations in this difference) can be particularly important in creating differences in TCO between studies.

All of the studies use either very similar or identical fuel costs (in the given time frame) for the three types of trucks. Most of the studies assume near-term diesel prices of $3-4/gal.

Diesel costs vary depending in part on whether the studies were considering national average or California prices. All studies use taxed diesel price. Electricity costs (or average rates) show a range of about $0.10 to 0.17 per kWh. Most studies are assuming at-base charging for these rates. CARB is an outlier here, assuming a publicly accessible retail price of electricity for long-haul trucks that is more consistent with high-priced fast charging.

Figure 19. Fuel/energy cost comparison across studies and truck types (diesel in $/gal and electricity in $/kWh)

Battery size per truck (kWh) and battery cost ($/kWh)

The assumed battery capacity of trucks is always linked to the target driving range of the truck and its efficiency. Each study makes use of this relationship. However different studies use different assumptions about capacity needed to cover adverse conditions (such as hot or cold weather, steep elevations, etc.) and how battery state-of-charge minimum (or capacity reserve) is set.

The required battery size varies fairly dramatically across the studies, especially for long haul but also for the other two truck types. The variation tends to drop somewhat for the long-term estimates (since the low capacity estimates tend not to drop and the high ones do), but the difference across studies is still substantial.

The price of batteries reflects production cost and, in some cases, a cost to manufacture the vehicle with the battery components provided. The price of electric vehicles is an important function of the battery capacity and price. Thus, battery size (or capacity) and price affect most aspects of the electric truck.

The estimated near-term cost of batteries in dollars per kWh of battery capacity (generally for the full pack used on a truck) varies considerably, in part related to the age of the study. The lowest cost is in the LBL study, at $135/kWh, and the highest is the ICF study at $375/kWh. CARB also used a relatively high price of $350/kWh, which again is surprising since their assumed use of batteries is in the mid-range and their overall truck purchase cost (shown below) is among the lowest. In the longer term, battery costs drop across the board, by over half in some studies. The lowest absolute future cost is seen in the LBL study, reaching $60/kWh, while the cost remains highest in the ICF study at $158/kWh.

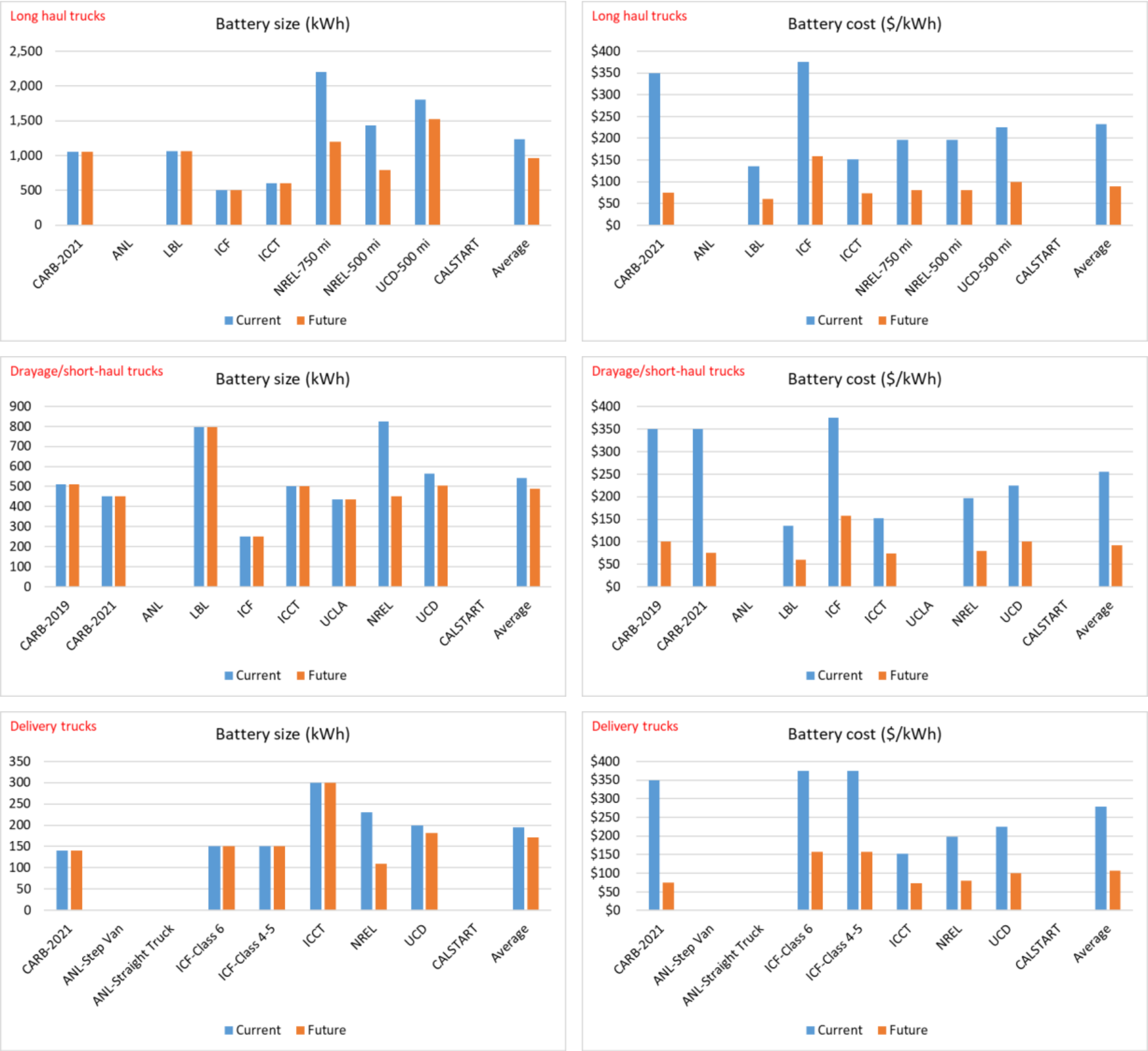

Figure 20. Battery size per truck (kWh) and battery cost ($/kWh) comparison across studies and truck types

Diesel and electric vehicle prices ($/vehicle)

The purchase price of long-haul trucks varies considerably across the studies, particularly for electric trucks but also for diesel trucks, which is surprising since this is a large established market. Note that different data sources, ways of taking averages, and other assumptions lead to differences. One major difference between diesel and electric truck prices across the studies is that diesel truck prices are not expected to change much into the future (although low NOx standards and upcoming additional GHG standards will add some costs), while battery-electric truck prices are expected to drop by half or more, as a function of battery costs declining.

For example, for diesel long hauls most studies suggest an initial purchase price or cost between $125k and $160k per truck, though ICCT estimates costs over $200k. Electric truck near term variation is much larger; several studies estimate a long-haul truck price between $200k and $400k but three over $750k. The variation links to both battery price and the capacity of batteries assumed to be on the vehicle. Counter-intuitively, the two studies (apart from ANL) with the highest assumed BET purchase cost have the lowest battery capacity assumptions, which should result in a less expensive truck. In the long run, the variation in BEV truck prices is between about $150k and $250k, still higher than diesel trucks but close enough to have a good chance for TCO parity given fuel and operating cost savings. Note that this finding is different from light-duty EV cost projections, where there is consensus of price parity with conventional internal combustion engine (ICE) vehicles in the next few years.

Findings are similar in direction (if not magnitude) for the other two types of trucks.

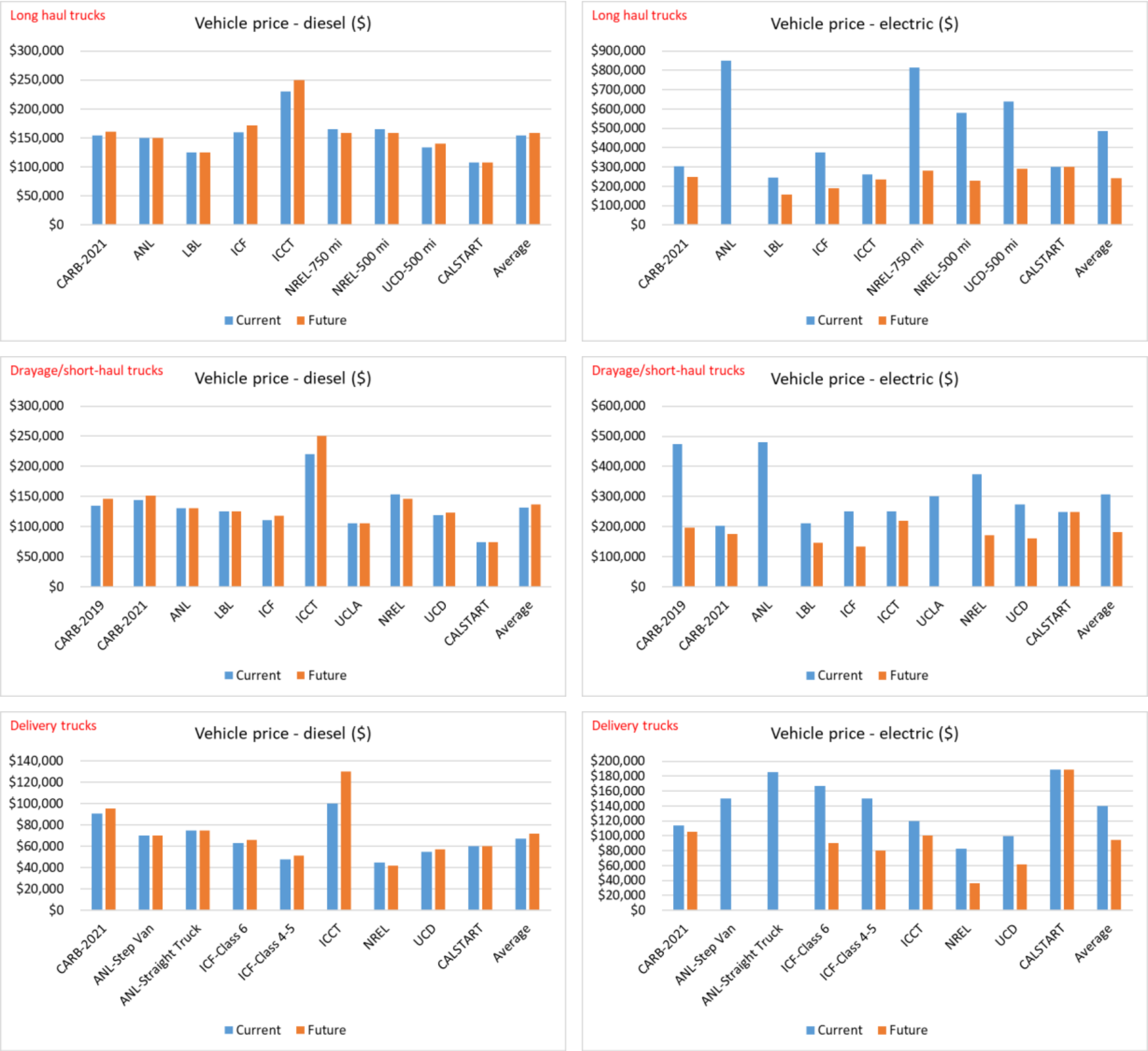

Figure 21. Diesel and electric vehicle price comparison across studies and truck types ($/vehicle)

Maintenance costs ($/mi)

Maintenance costs of trucks (in principle including both repair and scheduled maintenance) can include many specific costs, some of which are not likely to vary much between diesel and electric trucks (such as tires). Some of these costs of course do not even exist for some components, such as oil changes for electric trucks or battery service for diesel trucks. The studies show a fairly narrow range in average maintenance cost per mile of travel for diesel trucks (apart from CALSTART), with a $0.15 to $0.20 per mile typical range for long-haul, $0.20 to $0.25 per mile for short haul/drayage (likely related to lower miles over which to spread certain fixed costs and that drayage are often older) and right around $0.20 per mile for delivery.

However, for electric trucks much larger ranges are seen, such as a range for long haul of $0.06 to $0.18 per mile in the near term (apart from CALSTART), with a tendency for the studies to clump into a lower cost and higher cost group. Long term costs generally don’t change much except that for a couple of studies, these costs drop from the higher to lower cost group.

Most studies do not vary electric maintenance costs between near term and long term. However, recognizing that maintenance and repair costs may drop significantly in the future as systems and vehicles are optimized, two studies (UCD and ICF) apply a declined maintenance cost for the future.

For all three truck types, the average maintenance costs across the studies for BEV trucks is $0.05 to $0.10 lower than diesel. The cost differences per mile are high enough to have a significant impact on the overall TCO competitiveness of BETs, so the differences are an important area for further research.

Figure 22. Maintenance cost comparison across studies and truck types ($/mi)

Summary and Conclusions

We conducted a thorough review of key studies of the TCO for battery electric trucks, in the U.S. or California context. We compared and discussed these important studies in detail, with a focus on the three major truck categories: long haul trucks, delivery trucks, and drayage/short-haul trucks. We found that, in the TCO modeling, there exists a wide range of differences in modeling scope, coverage, methodology, assumptions, and key parameters, among other things. Generally, caution is needed in making a direct comparison of overall TCO estimates between the studies. One important reason is, again, that their modeling scope and coverage are often very different, e.g., in terms of whether or not to include costs for dwell time for recharging, lost payload capacity, single-shift vs. two-shift, and environmental externalities. However, we made an effort to compare the lifetime TCO estimates associated with common coverage (i.e., a subset) of the cost components, typically including vehicle cost, fuel/energy cost, maintenance cost, infrastructure cost, resale/residual value, and policy incentives (such as LCFS credit revenue). The comparison turns out that the overall TCO results for BETs vary substantially between the studies.

Our detailed side-by-side comparison of key parameters and assumptions shows a wide range in values for many parameters, though at the same time, most studies are close to an average across all the studies, with one or two outliers. While in this report we did not attempt to assess which estimates are “better” or “worse” than others, we hope that these findings will help to spur additional work to come to consensus on key parameters and, thus, consensus on near-term and longer-term TCOs by technology and truck class and can lead to a stronger consensus on policy making and decision behavior for fleets.

As a logical next step, further comparisons of various TCO modeling inputs could be made across the research groups, and possibly a workshop to see if consensus can be reached for as many inputs as possible. Such a workshop was not included in the current study but would be of interest in the near future.

References

Hall, Dale, Nic Lutsey, 2019. Estimating the infrastructure needs and costs for the launch of zero-emission trucks. August 2019. https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf

ICF, 2019. Comparison of Medium- and Heavy-Duty Technologies in California. December 2019. https://caletc.com/assets/files/ICF-Truck-Report_Final_December-2019.pdf

Filippo, James Di, Colleen Callahan, Naseem Golestani, 2019. Zero-Emission Drayage Trucks: Challenges and Opportunities for the San Pedro Bay Ports. https://innovation.luskin.ucla.edu/wp-content/uploads/2019/10/Zero_Emission_Drayage_Trucks.pdf

Phadke, Amol, Aditya Khandekar, Nikit Abhyankar, David Wooley, Deepak Rajagopal, 2021. Why Regional and Long-Haul Trucks are Primed for Electrification Now. March 2021. https://eta-publications.lbl.gov/sites/default/files/updated_5_final_ehdv_report_033121.pdf

CALSTART, 2021. TCO calculator (V1.0). https://www.californiahvip.org/tco/.

AFLEET, 2021. Argonne National Laboratory. User Guide for AFLEET Tool 2020. April 2021.

Burnham, Andrew, et al., 2021. Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains. Argonne National Laboratory. ANL/ESD-21/4. July 2021. https://publications.anl.gov/anlpubs/2021/05/167399.pdf

CARB, 2019. Advanced Clean Trucks Total Cost of Ownership Discussion Document. Preliminary Draft for Comment. California Air Resources Board (CARB). February 22, 2019.

CARB, 2021. Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document. California Air Resources Board (CARB). September 9, 2021.

Hunter, Chad, Michael Penev, Evan Reznicek, Jason Lustbader, Alicia Birky, and Chen Zhang, 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. National Renewable Energy Laboratory. Technical Report. NREL/TP-5400-71796. September 2021. https://www.nrel.gov/docs/fy21osti/71796.pdf

UC Davis TCO study, 2022. Evaluation of the Economics of Battery-Electric and Fuel Cell Trucks and Buses: Methods, Issues, and Results, Miller et al., Institute of Transportation Studies, UC Davis. Forthcoming.

Data Summary

Products of Research

This project assesses the current and future performance and costs of battery electric trucking. This project reviews and compares 10 key recent studies of the total cost of ownership (TCO) of battery electric trucks, today and in the future, compared to a baseline diesel truck. This project extracts the reviewed data on TCO estimates and assumptions, across 3 important types of truck, including their estimates for a range of important vehicle attributes, costs, and operating factors, such as vehicle purchase cost, efficiency, fuel cost, maintenance cost, required range and thus battery pack sizing, and other factors.

Data Format and Content

Data for this study is bibliographic in nature and can be found in the References section.

Data Access and Sharing

The data collected for the study is completely based on a literature review of 10 research reports, Excel spreadsheet models, or web-based models that are all publicly available. The reviewed reports and models are accessible through the References in this report.

The specific data collected and compared is listed and described in the side-by-side comparison tables in this report.

Reuse and Redistribution

The data used in the report is available to all readers, as the data is explicitly presented in the report.