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National Renewable Energy Laboratory

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-71796
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Suggested Citation
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*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-71796. https://www.nrel.gov/docs/fy21osti/71796.pdf.

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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Acknowledgments

The authors wish to thank the U.S. Department of Energy (DOE) Hydrogen and Fuel Cell Technologies Office, and Neha Rustagi, Sunita Satyapal, and Fred Joseck in particular, for their continued support in developing the Scenario Evaluation and Regionalization Analysis (SERA) model over the years. The authors would also like to acknowledge Brian Bush at the National Renewable Energy Laboratory for his development of the SERA model over the years, Yuche Chen at Vanderbilt University for his support of the operating and maintenance cost literature review, and Aaron Brooker at the National Renewable Energy Laboratory for his guidance and support with vehicle powertrain modeling. The authors would also like to give a special thanks to Neha Rustagi at the Hydrogen and Fuel Cell Technologies Office and Jake Ward at the Vehicle Technologies Office for their significant effort helping coordinate and catalyze collaboration across multiple parallel analysis projects related to commercial vehicle electrification.

The authors would also like to give a special thanks to all the other contributors and reviewers of this analysis that provided useful feedback through interim presentations and reports. In particular, the authors would like to thank Dimitrios Papegeorgopoulos, Ned Stetson, Jesse Adams, Jason Marcinkoski, and Greg Kleen at the Hydrogen and Fuel Cell Technologies Office. At the Vehicle Technologies Office, the authors would like to thank Samm Gillard, Brian Cunningham, Kevin Stork, Susan Rogers, Madhur Boloor, Dennis Smith, Mark Smith, and Linda Bluestein. From the DOE Office of the Deputy Assistant Secretary of Transportation, we would like to thank Michael Berube and Rachael Nealer. From Strategic Analysis, Inc., we would like to thank Brian James and Jennie Huya-Kouadio. Additionally, the authors would like to thank Ram Vijayagopal, Amgad Elgowainy, and Aymeric Rousseau from Argonne National Laboratory, and Burak Ozpineci, Scott Curran, and Ron Graves from Oak Ridge National Laboratory. We would also like to thank Matteo Muratori, Michael Lammert, John Farrell, and Keith Wipke from the National Renewable Energy Laboratory. Finally, we would like to thank the peer reviewers from industry and organizations external to DOE, including Giovanna Bucci at Bosch; Marc Melaina at Boston Governmental Services; Fang Yan, Leslie Goodbody, and Andrew Martinez at the California Air Resources Board; Jason Hanlin at the Center for Transportation and the Environment; Vivek Sujan at Cummins; Mihai Dorobantu at Eaton Corporation PLC; Brian Goldstein and Justo Robles at Energy Independence Now; Boris Kort-Packard and Phil Galbach at Federal Express; and James Kast at Toyota Motor Corporation.

Abstract

The medium- and heavy-duty transportation sector is experiencing rapid changes in powertrain technology innovation, with recent announcements of battery electric and fuel cell electric trucks being offered. The economics of these alternative powertrain vehicles are uncertain and difficult to compare directly. This analysis seeks to provide a rigorous, techno-economic analysis of all of these alternative powertrain vehicles within the same analytic framework. Specifically, this report evaluates the total cost of ownership (TCO) of six different truck powertrain technologies (diesel, diesel hybrid electric, plug-in hybrid electric, compressed natural gas, battery electric, and fuel cell electric) 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 time frames (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).

This 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, and are complemented by fuel cell powertrains that may be better for longer ranges or operating scenarios that require higher uptime. Specifically, the Class 8 long-haul (750-mile-range) fuel cell electric vehicle (FCEV) is the lowest-cost zero-emissions vehicle (ZEV) if technology targets are met (regardless of dwell and payload costs). For the Class 8 long-haul (500-mile-range) vocation, FCEVs and battery electric vehicles (BEVs) are very competitive with diesel if Ultimate targets are met (regardless of dwell and payload costs). If dwell time costs are incurred, FCEVs are the lowest-cost ZEV for Class 4 parcel delivery, Class 8 short haul (300 miles), and Class 8 long haul (500 miles). For the Class 8 short-haul (300-mile-range) and Class 4 parcel delivery (120-mile-range) vocations, BEVs are the lowest-cost ZEV if dwell time costs are not incurred and Ultimate targets are achieved. Additionally, lost payload capacity cost for Class 8 long-haul (500+ mile) FCEVs or Class 8 short-haul (300-mile) BEVs is small due to the 2,000-lb exemption for alternative powertrain trucks. This analysis also shows that electricity price and hydrogen fuel price are the most influential parameters to the TCO of all trucks, and medium- and heavy-duty refueling/recharging cost reduction/management should be a key focus area for R&D. In summary, this analysis shows that medium- and heavy-duty trucks with battery and fuel cell electric powertrains could be economically competitive with diesel powertrains under several operating scenarios as early as 2025 for shorter-range applications (<500-mile Class 8 tractors, 120-mile Class 4 delivery) if high diesel prices (>$3/gal) and low hydrogen/electricity prices are realized.

Acronym List

AEO	Annual Energy Outlook
BEV	battery electric vehicle
CNG	compressed natural gas
DCFC	direct current fast charger
DOE	U.S. Department of Energy
FASTSim	Future Automotive Systems Technology Simulator
FCEV	fuel cell electric vehicle
gge	gasoline gallon equivalent
GVWR	gross vehicle weight rating
HEV	hybrid electric diesel vehicle
HFTO	Hydrogen and Fuel Cell Technologies Office
LTL	less-than-truck load
M/HDT	medium- and heavy-duty truck
MSRP	manufacturer's suggested retail price
NREL	National Renewable Energy Laboratory
O&M	operating and maintenance
PHEV	plug-in hybrid electric vehicle
SERA	Scenario Evaluation and Regionalization Analysis
T3CO	Transportation Technology Total Cost of Ownership
TCO	total cost of ownership
VIUS	Vehicle Inventory and Use Survey
VMT	vehicle miles traveled
ZEV	zero-emissions vehicle

Executive Summary

The medium- and heavy-duty transportation sector is experiencing rapid changes in technology innovation. Alternative powertrains, including fuel cell electric and battery electric, have been announced within the last few years for truck applications across the medium- and heavy-duty spectrum. Because trucks are used primarily for business applications, the value proposition associated with a truck is a key metric that helps determine whether the truck technology will be adopted. The total cost of ownership (TCO) is a useful metric that owners and operators use to assess the value proposition of a truck purchase. Although not the only metric a business will consider, the TCO provides a benchmark that allows for direct comparison across different truck options.

This report aims to analyze multiple powertrain technologies using a consistent and extensive analytic framework applied to each technology and commercial vehicle application. The report evaluates the TCO for three truck applications and six powertrains. The truck applications include Class 8 long-haul (sleeper, 750-mile range and 500-mile range), Class 8 short-haul (day cab, 300-mile range), and Class 4 parcel delivery (120-mile range) trucks. The powertrains analyzed are conventional (diesel), diesel hybrid-electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), compressed natural gas (CNG), fuel cell electric vehicle (FCEV), and battery electric vehicle (BEV). The TCO includes direct and indirect costs incurred by owning and using the truck that are specific to each powertrain. Direct costs included in this analysis are the upfront purchase cost (segmented by powertrain component), purchase price, fuel, operating and maintenance (O&M), driver wages and benefits, insurance, tire replacements, permits, and tolls. The indirect costs included in this analysis are dwell time costs due to refueling/recharging and lost payload capacity costs from potentially heavier advanced vehicle powertrains.

The TCO modeling framework involves two National Renewable Energy Laboratory (NREL) models, which were integrated to create a full, end-to-end TCO model. First, the vehicle performance and cost modeling was completed using NREL's Future Automotive Systems Technology Simulator (FASTSim) model. Second, the spatially resolved TCO was modeled using NREL's Scenario Evaluation and Regionalization Analysis (SERA) model. These models were integrated together to form the Transportation Technology Total Cost of Ownership (T3CO) model to rapidly and flexibly evaluate the TCO of commercial vehicles.

T3CO first estimates the upfront vehicle cost. Vehicle models for each truck application (Class 8 long haul [750-mile and 500-mile ranges], Class 8 short haul, and Class 4 parcel delivery) were built in FASTSim to match observed conventional vehicle performance and cost data including fuel economy, acceleration, and manufacturer's suggested retail price. Real-world, representative drive cycles from NREL's Fleet DNA database were used in the vehicle model. FASTSim takes the diesel truck, removes the diesel-specific powertrain components (e.g., engine, aftertreatment), and builds the new powertrain to meet the acceleration requirements of the truck. Input powertrain component cost and performance data were based on current status (2018 used as a baseline for current technology due to data availability), future projections from literature, the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy technology performance and cost targets, and additional scenario assumptions. Vehicles were assessed for three technology time frames: 2018, DOE 2025 scenario assumptions, and DOE Ultimate scenario assumptions.

T3CO then estimates the TCO analysis, including all direct and indirect costs. Low, mid, and high costs for each cost component were analyzed. Regional fuel costs (diesel, CNG, electricity) were based on the 2021 Annual Energy Outlook, whereas hydrogen costs were taken from demonstration data and future DOE targets. O&M costs were based on an extensive literature survey. Lost payload capacity costs were based on the costs to purchase an additional truck to move the lost cargo capacity. The dwell time cost was based on the refueling/recharging time and the cost per hour that carriers charge for dwell fees.

The TCO was estimated for four scenarios representing different commercial vehicle applications: (1) Single-Shift, Volume-Limited; (2) Single-Shift, Weight-Limited; (3) Multi-Shift, Volume-Limited; and (4) Multi-Shift, Weight-Limited. Single-shift operation implies no dwell time costs, whereas volume-limited correlates with no lost payload capacity costs.

Class 8 long-haul (750-mile-range) truck TCO in the Single-Shift, Volume-Limited scenario and the Multi-Shift,

Weight-Limited scenario in the Middle Atlantic U.S. Census Division region is shown in Figure ES-1. These two scenarios (without incurring either dwell-time and payload capacity costs, or incurring both dwell-time and payload capacity costs) are shown as they reflect the edge cases in this analysis. Error bars represent uncertainty in fuel prices and O&M costs.

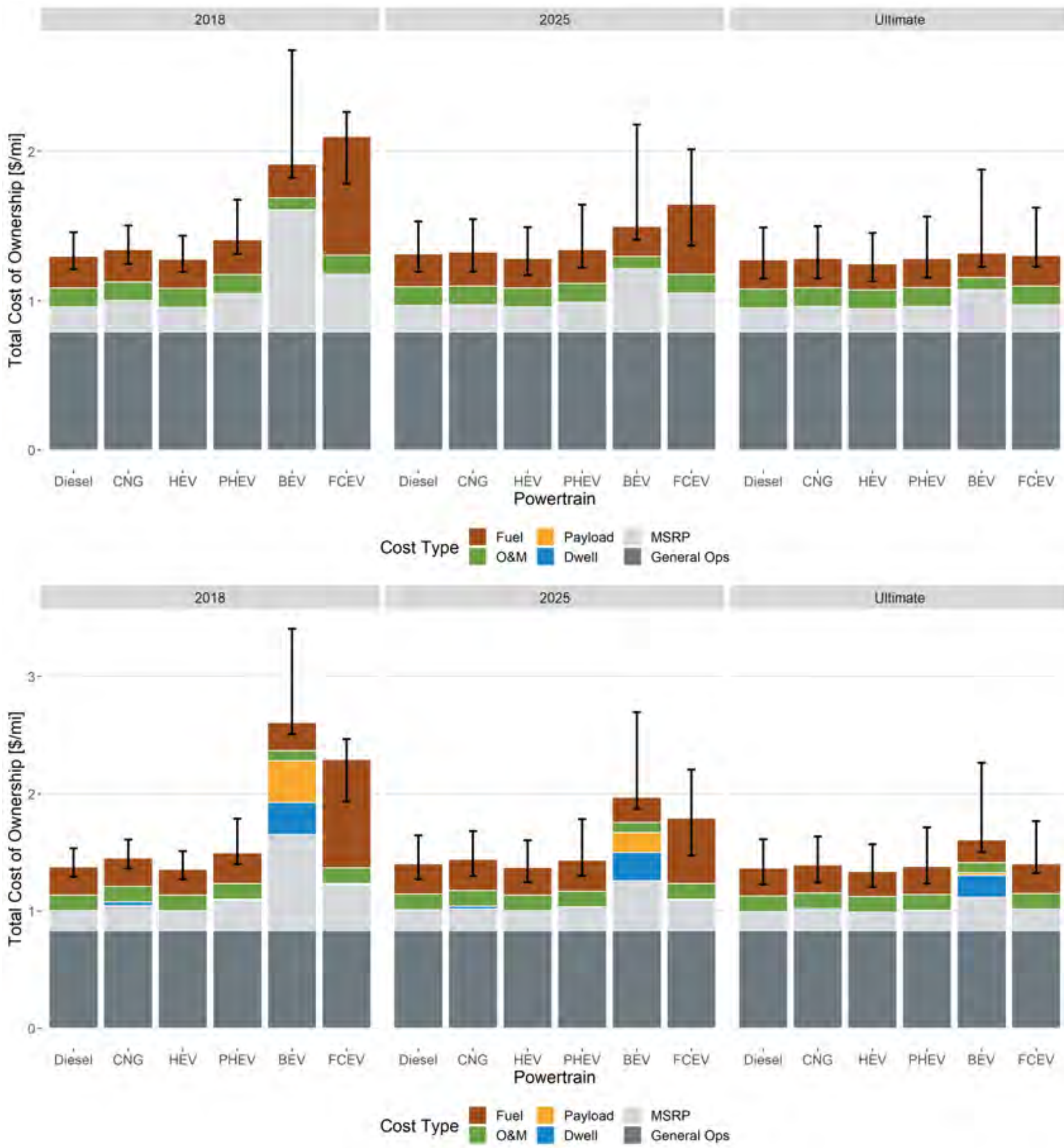

Figure ES-1. TCO ($/mile) for Class 8 long-haul tractors (750-mile range) in the Middle Atlantic region in (top) Single-Shift, Volume-Limited scenario and (bottom) Multi-Shift, Weight-Limited scenario.

As seen in Figure ES-1, the advanced powertrain TCO is significantly higher than the diesel truck TCO in the 2018 time frame, but rapidly decreases as technology cost and performance improves to the 2025 and Ultimate scenario assumptions. If no dwell or payload costs are incurred, the BEV and FCEV can be within the range of TCO uncertainty as soon as 2025 and very competitive if the Ultimate scenario assumptions are achieved. Payload costs primarily impact only the BEV powertrain and reduce to effectively zero as the Ultimate scenario assumptions are achieved. If dwell time costs are incurred, the FCEV powertrain is the lowest-cost zero-emission vehicle powertrain.

Figure ES-2 shows the 500-mile-range Class 8 long-haul truck TCO in the Middle Atlantic U.S. Census Division region. Although mostly similar to the 750-mile range summarized in Figure ES-1, the shorter range results in lower onboard battery and hydrogen fuel storage requirements. The smaller battery pack reduces the potential BEV payload cost in the 2018 and 2025 time frames, as seen in Figure ES-2. Additionally, the BEV TCO is within the range of uncertainty of the diesel truck TCO as soon as 2025 if no dwell time costs are incurred, whereas the FCEV TCO is within the range of uncertainty (error bar ranges overlap) by 2025 regardless of dwell or payload costs.

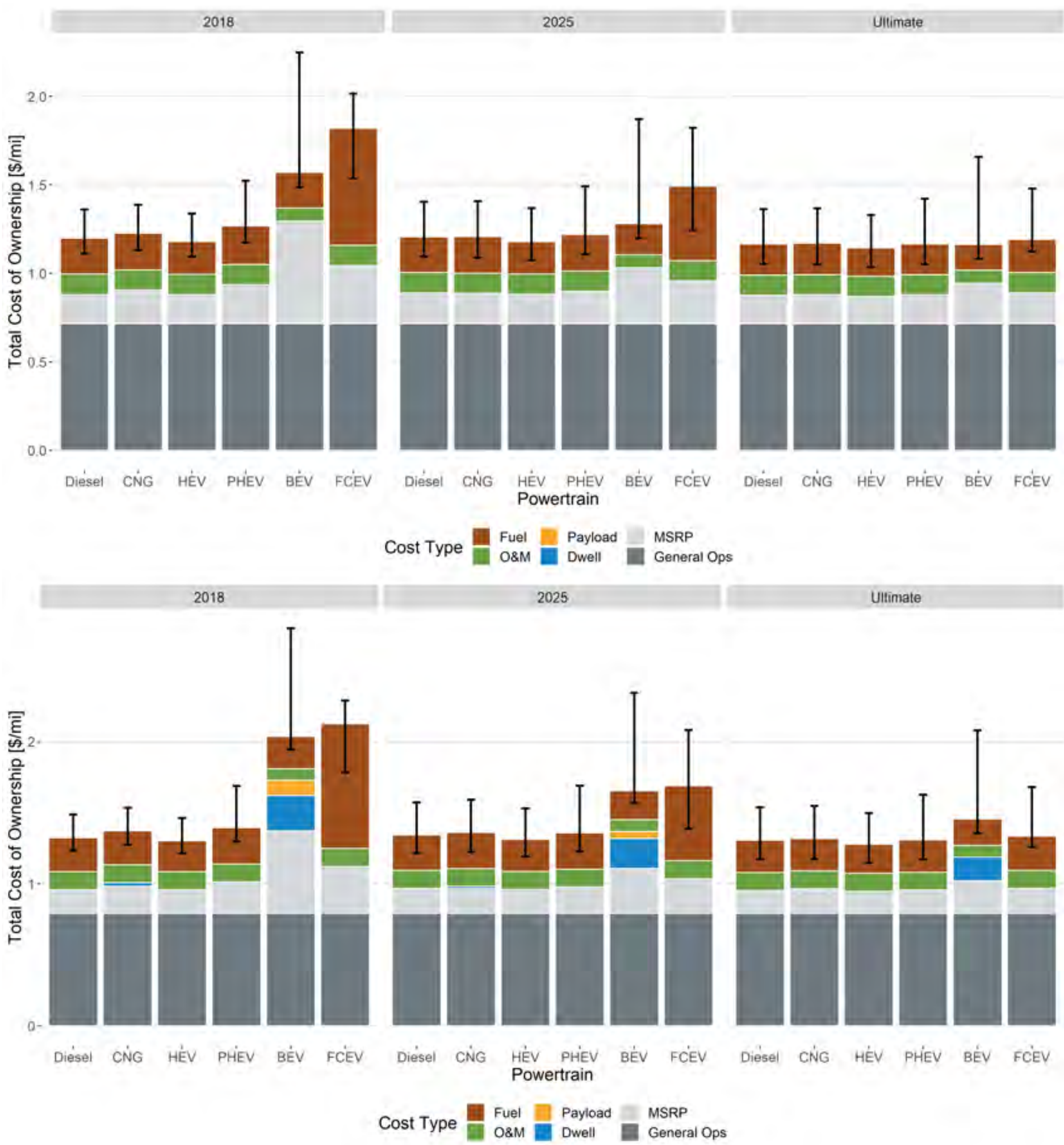

Figure ES-2. TCO ($/mile) for Class 8 long-haul tractors (500-mile range) in the Middle Atlantic region in (top) Single-Shift, Volume-Limited scenario and (bottom) Multi-Shift, Weight-Limited scenario.

For Class 8 short-haul (300-mile-range) trucks, the TCO in the Single-Shift, Volume-Limited scenario and the Multi-Shift, Weight-Limited scenario in the Middle Atlantic U.S. Census Division region are shown in Figure ES-3. Because the onboard energy storage requirements are lower than the Class 8 long haul and the 2,000-lb weight-limit exemption for advanced powertrain trucks is accounted for, the impact of payload costs is minimal for all powertrains. If dwell time costs are not incurred, the BEV could potentially achieve TCO parity with the diesel incumbent if low electricity prices are realized. By 2025, both the BEV and FCEV are within the range of uncertainty and both could be economically attractive if low fuel prices could be achieved. If dwell time costs are incurred, the FCEV is the lowest-TCO zero-emission vehicle (ZEV).

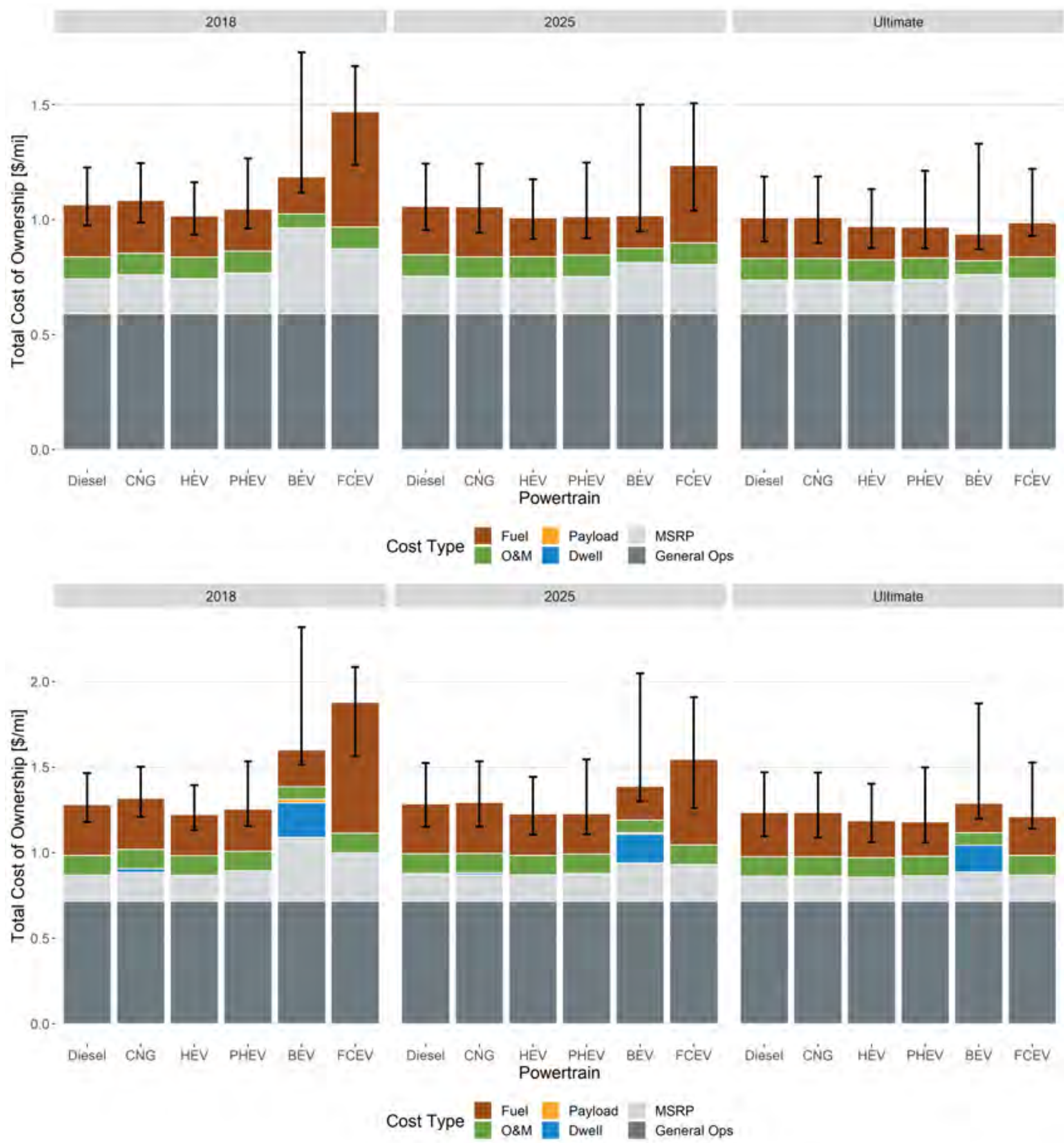

Figure ES-3. TCO ($/mile) for Class 8 short-haul tractors (300-mile range) in the Middle Atlantic region in (top) Single-Shift, Volume-Limited scenario and (bottom) Multi-Shift, Weight-Limited scenario.

Figure ES-4 summarizes the TCO results for the Class 4 parcel delivery trucks in the Single-Shift, Volume-Limited scenario and the Multi-Shift, Weight-Limited scenario in the Middle Atlantic U.S. Census Division region. For the Single-Shift, Volume-Limited scenario, all powertrains have TCOs within the range of fuel and O&M cost uncertainty with current (2018) technology status except the FCEV due to the high upfront purchase price and hydrogen price ($7–$10/kg). The BEV and FCEV costs significantly decline in the 2025 time frame and, in the absence of dwell time costs, the BEV becomes the lowest-cost powertrain. In the Multi-Shift, Weight-Limited operation, dwell time is a significant cost driver of TCO for the BEV due to frequent recharging events but it is complemented by the FCEV, which has faster refueling times and may be able to help decarbonize this market segment.

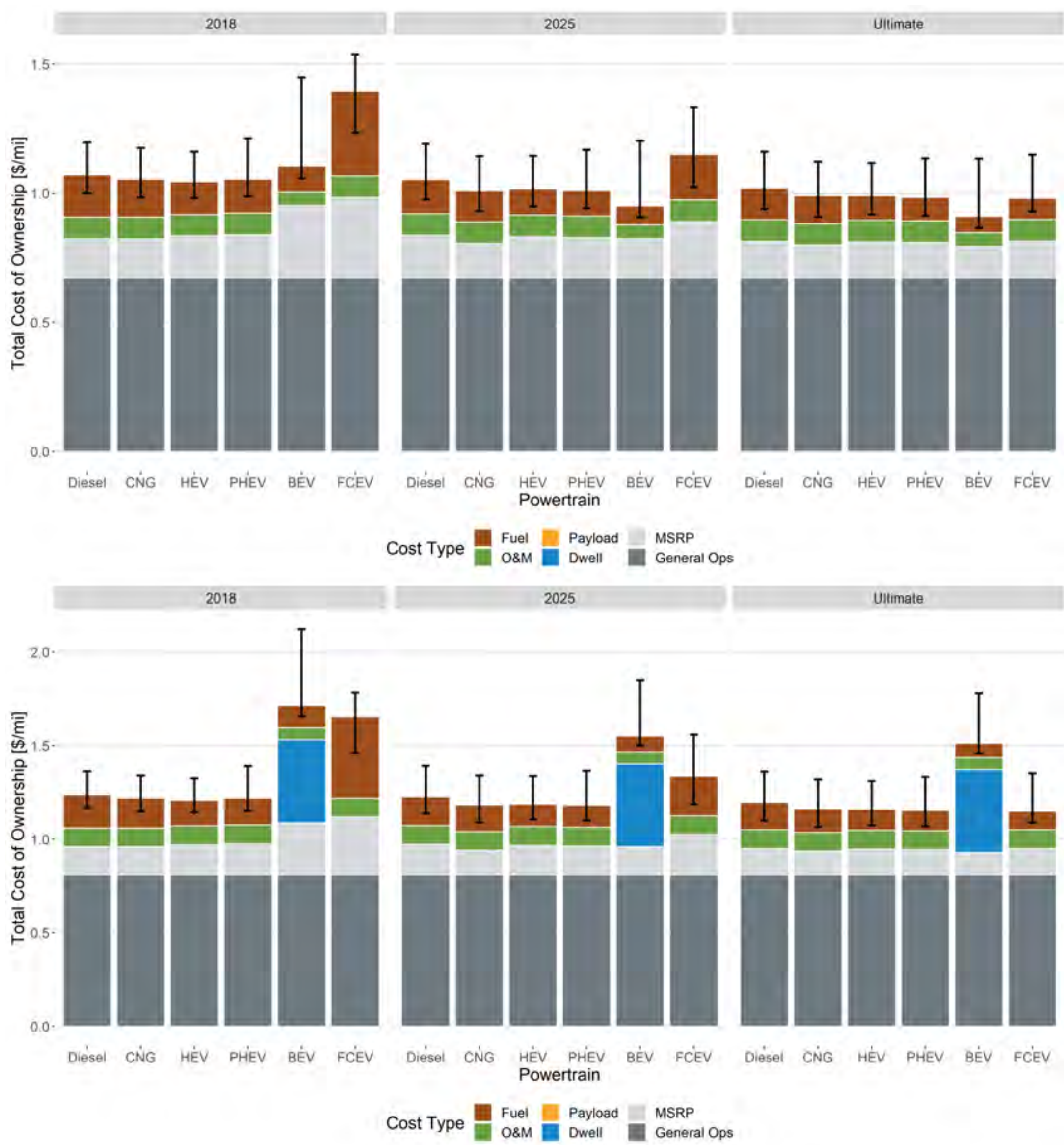

Figure ES-4. TCO ($/mile) for Class 4 parcel delivery truck (120-mile range) in the Middle Atlantic region in (top) Single-Shift, Volume-Limited scenario and (bottom) Multi-Shift, Weight-Limited scenario.

Context, Constraints, and Limitations

Medium- and heavy-duty vehicle decarbonization is critical for the transition to a net-zero economy. During the time this analysis was ongoing, there were multiple coordinated and collaborative efforts across the U.S. Department of Energy and U.S. national laboratory system focused on analyzing commercial vehicle decarbonization pathways. In particular, two closely related and collaborative parallel efforts included the *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains* (Burnham et al. 2021) and the *Vehicle Technologies and Hydrogen and Fuel Cells Technologies Research and Development Programs Benefits Assessment Report for 2020* (Brooker et al. 2021). Specifically, Burnham et al. (2021) focuses on outlining a data framework for total cost of ownership evaluations across light-, medium-, and heavy-duty vehicles, identifying data gaps, and filling those where possible. Related, Brooker et al. (2021) focuses on technology evolution pathways and commercial vehicle adoption modeling across the light-, medium-, and heavy-duty vehicle sectors. This current project focuses most deeply on applying a scenario analysis to evaluate the total cost of ownership challenges and opportunities for medium- and heavy-duty vehicles with advanced powertrains. Among other aspects, this work provided the basis for dwell time and payload-cost evaluations included in Burnham et al. (2021) and coordinated vehicle modeling assumptions and approach with Brooker et al. (2021). Although each report is distinct, they are all coordinated where possible but differ in their analysis objective.