
# Powertrain Performance and Total Cost of Ownership Analysis for Class 8 Yard Tractors and Refuse Trucks

Spencer Gilleon, Michael Penev, and Chad Hunter

*National Renewable Energy Laboratory*

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## NOTICE

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*Cover Photo by Dennis Schroeder: NREL 38588.*

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Abstract

Advanced powertrain technologies, specifically fuel cell electric powertrains, have gained attention as viable alternatives for medium- and heavy-duty (M/HD) vehicles. However, it is unclear how these alternative powertrain vehicles stack up against their diesel counterparts in terms of performance and total cost of ownership (TCO). Furthermore, there are vehicle segments within the M/HD sector that have remained unstudied for fuel cell electric applications. This analysis aims to provide a comparative scoping-level TCO and performance analysis for two heavy-duty vocation vehicles (Class 8 U.S. port-side yard tractor and Class 8 U.S.-based refuse truck) for both conventional diesel and heavy-duty fuel cell electric (HDFC) powertrains. The refuse truck analysis also considered compressed natural gas powertrains (CNG) for comparison. The analysis includes seven timeframes (2020, 2025, 2030, 2035, 2040, 2045, and 2050) for comparison. This simplified TCO analysis includes only direct costs (fuel price, glider purchase price, and operating & maintenance costs) and excludes any associated indirect cost (e.g., dwell time costs and other opportunity based costs). Representative drive cycles for each vehicle were based on on-board GPS logged data and chosen by the analysis team to represent average, non-extreme driving conditions. At the time the analysis was performed, the Inflation Reduction Act was not in effect and therefore any potential subsidies and future cost reductions enacted under the Inflation Reduction Act were not included.

Based on the operational setpoints used in this analysis, HDFC powertrains for both yard tractors and refuse trucks have the potential to achieve TCO advantages over conventional diesel powertrains (and CNG for refuse truck applications) in the near- to mid-term future while meeting the necessary duty cycle performance requirements. Yard tractors and refuse trucks spend a significant amount of time operating at low speeds, with long durations of idling, and experience numerous start/stop occurrences. These operational characteristics favor fuel cell performance as fuel cells operate with higher efficiencies at lower percentages of total power output. Conversely, conventional diesel and CNG engines are most efficient at higher percentages of total power output. This helps HDFC powered yard tractors and refuse trucks realize improved fuel economy when compared to their diesel counterparts, which helps reduce total fuel costs and therefore, total TCO. The analysis demonstrates that fuel prices play a significant role in determining TCO for each vehicle and should remain an R&D focus area. Overall, under the analysis' specified conditions, HDFC yard tractors have the potential to achieve cost parity with diesel yard tractors as early as 2025. For refuse trucks, HDFC refuse trucks have the potential to achieve cost parity with diesel and CNG refuse trucks in 2030 and 2040, respectively.

# List of Acronyms

| | |
|---|---|
| AEO | Annual Energy Outlook |
| CNG | Compressed Natural Gas |
| 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 |
| HDFC | Heavy-duty Fuel Cell |
| HFTO | Hydrogen and Fuel Cell Technologies Office |
| M/HD | Medium- and Heavy-Duty |
| mpdge | Miles per Diesel Gallon Equivalent |
| mpg | Miles per Gallon |
| MSRP | Manufacturer's Suggested Retail Price |
| NPV | Net Present Value |
| NREL | National Renewable Energy Laboratory |
| O&M | Operating (Operation) & Maintenance |
| OEM | Original Equipment Manufacturer |
| PANYNJ | Port Authority of New York and New Jersey |
| POHA | Port of Houston |
| POLA | Port of Los Angeles |
| POLB | Port of Long Beach |
| PTO | Power Take-Off |
| SEATAC | Port of Seattle |
| SERA | Scenario Evaluation and Regionalization Analysis |
| T3CO | Transportation Technology Total Cost of Ownership |
| TCO | Total Cost of Ownership |
| TEA | Techno-economic Analysis |
| U.S. | United States (of America) |
| VIUS | Vehicle Inventory and Use Survey |
| VMT | Vehicle Miles Traveled |

# Executive Summary

Analysis of hydrogen fuel cell applications in the transportation sector has advanced considerably in recent years. Within the on-road sector, light-duty vehicles have been studied over the last two decades, while medium- and heavy-duty (M/HD) truck and bus electrification has become more of a focus in the last four years. However, the evaluation of fuel cells in the contexts of other vocational on-road vehicles (utility, parcel delivery, box vans), off-road vehicles including captive trucking (mining, ports, heavy machinery), rail, marine, and aviation is also important and these applications have not been areas of focus by the research community.

This report compares conventional diesel powertrain technologies with hydrogen fuel cell powertrain (FCEV) technologies for port-side yard tractors and refuse trucks using an extensive analytical framework applied to each vehicle technology application. This report includes a scoping-level analysis of the Total Cost of Ownership (TCO), techno-economic analysis (TEA), and powertrain performance for two separate Class 8 vehicle types and applications: a U.S.-based refuse truck (on-road, 200-mile range) and a U.S.-based port-side yard tractor (off-road, 200-mile range). The analysis for the refuse truck also included a compressed natural gas (CNG) powertrain for comparison to conventional diesel and FCEV as CNG refuse trucks have a significant market share within this segment.

Both vocational, heavy-duty on-road and off-road vehicles primarily exist for commercial and business purposes; therefore, the value proposition and costs associated with these vehicles can help identify future advanced powertrain technology adoption within these sectors. TCO and TEA provide metrics that fleet owners and vehicle operators can use to determine an on-road or off-road truck's value proposition and whether the truck purchase makes economic sense for the fleet. TCO is not the only metric ultimately needed to be considered by fleet owners and operators; however, TCO is a critical benchmarking tool for comparing various powertrains and truck options directly. TCO also helps identify fuel cell market applications with more near-term potential, which is critical for determining early adopter applications and scaling of fuel cell technology.

We used NREL's Transportation Technology Total Cost of Ownership (T3CO) modeling framework to complete this analysis. T3CO enables users to flexibly evaluate the TCO of vocational vehicles in this context and leverages two of NREL's established models and tools: FASTSim (Future Automotive Systems Technology Simulator) and SERA (Scenario Evaluation and Regionalization Analysis). The combination of these models to form T3CO allows for vehicle performance and cost modeling as well as spatially resolved TCO analysis. Representative duty cycles from NREL's Fleet DNA data repository were used for both the refuse truck and yard tractor applications. Direct costs, which include upfront purchase costs, vehicle operating and maintenance costs (O&M), and purchase price, are applied to each vehicle's operation, ownership, and specific powertrain and are included in the TCO analysis. Indirect costs such as dwell time costs and payload opportunity costs were not included in this scoping-level analysis but can be included in future work. At the time this analysis was performed, the Inflation Reduction Act was not in effect and therefore any potential subsidies and future cost reductions enacted under the Inflation Reduction Act were not included.

Vehicle models for the refuse truck and yard tractor were built in FASTSim by matching the performance and cost of both vehicles under the conventional diesel application. Input data used in this report is based on current technology statuses (2018 baseline), projections from literature and U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE EERE) technology

targets, and additional model defaults and scenario assumptions. The vehicles were evaluated starting in the technology year 2020 and expanded out to 2050 in five-year increments.

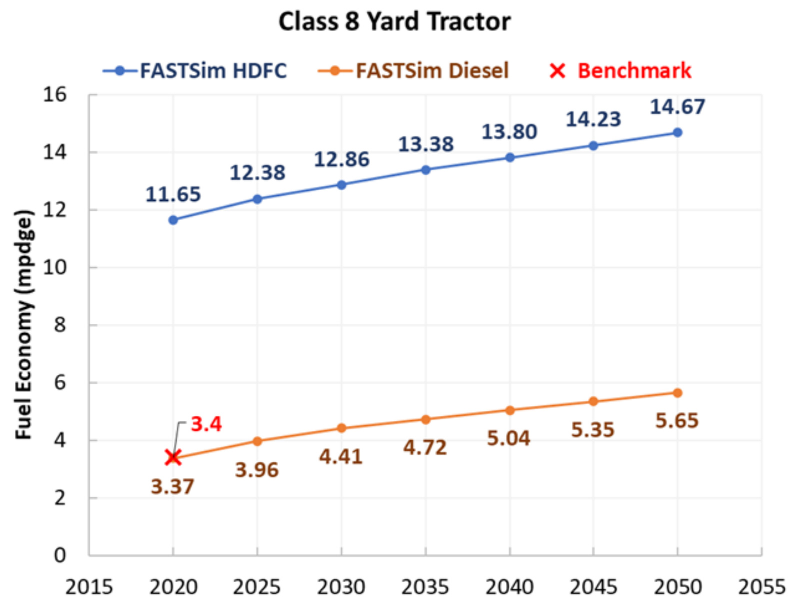


**Figure 1. Fuel economy projections for technology years 2020 through 2050 for Class 8 Yard Tractors (200-mile range) for conventional diesel and heavy-duty fuel cell (HDFC) powertrains.**

Figure 1 summarizes fuel economy results for the Class 8 yard tractor diesel and HDFC powertrains. Our results project HDFC yard tractors have the potential to exceed diesel fuel economy projections by a factor of approximately three. The assumed duty cycle for our modeled refuse truck is a significant driver of this results. Yard tractors generally experience a significant amount of starts and stops as well as idling time during their duty cycle, both of which are favorable operational conditions for HDFC powertrains. These findings suggest fuel cell technology may provide significant operational benefits to yard tractor fleets under such conditions.

Figure 2 below summarizes the fuel economy results for the three Class 8 refuse truck powertrains studied.  Our results project similar fuel economy trends for diesel and CNG refuse trucks. We also project that HDFC refuse trucks may have the potential to exceed both diesel and CNG fuel economy projections by a factor of approximately two to three. Here as well, the assumed duty cycle for our modeled refuse truck is a significant driver of these results. Refuse trucks generally experience a significant amount of starts and stops during their duty cycles, especially when operating in areas of high population density. As with yard tractors, our results demonstrate this is a favorable operational characteristic for HDFCs compared to diesel and CNG. Again, these findings suggest fuel cell technology may provide significant operational benefits to refuse truck fleets under such conditions.

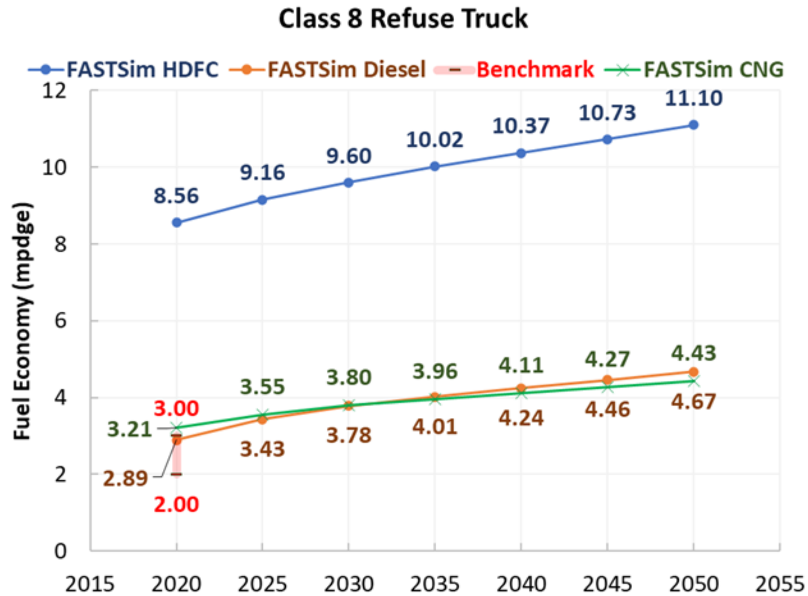


**Figure 2. Fuel economy projections for technology years 2020 through 2050 for Class 8 Refuse Trucks (200-mile range) for conventional diesel, CNG, and heavy-duty fuel cell (HDFC) powertrains.**

Figure 3 summarizes the TCO results for both HDFC and conventional diesel U.S. port-side yard tractors. We project HDFC yard tractors to have a significantly higher TCO compared to the diesel yard tractor in the year 2020. Because of projected improvements around HDFC performance and cost, HDFC yard tractors have the potential to achieve cost parity with diesel yard tractors in 2025. Beyond 2025, HDFC yard tractors project to have a lower TCO than their diesel counterparts. These findings suggest fuel cell technology may yield near-term TCO benefits for port-side yard tractor fleets relative to diesel under the cost, performance, and duty cycle conditions we assumed. Figure 4 shows that, in our modeling results, the refuse truck TCO for the HDFC powertrain option is again considerably higher than both the conventional diesel and CNG powertrain options in 2020. However, the HDFC TCO decreases rapidly because of assumed improvements in technology performance, increased component manufacturing rates, and cost projected in 2025 and beyond. Under these assumed conditions, HDFC refuse trucks have the potential to achieve cost parity with conventional diesel refuse trucks and CNG refuse trucks in the tech years 2035 and 2040, respectively. We project a slightly lower TCO for CNG compared to conventional diesel because of CNG's lower projected fuel cost. In the years 2045 and 2050, HDFC refuse trucks project to have the lowest TCO of the three powertrain options. These findings suggest fuel cell technology may not yield near-term TCO benefits for refuse truck fleets relative to diesel or CNG, under the cost, performance, and duty cycle conditions we assumed. However, this fuel cell technology may become an attractive option for refuse truck fleets in the medium- to long-term.

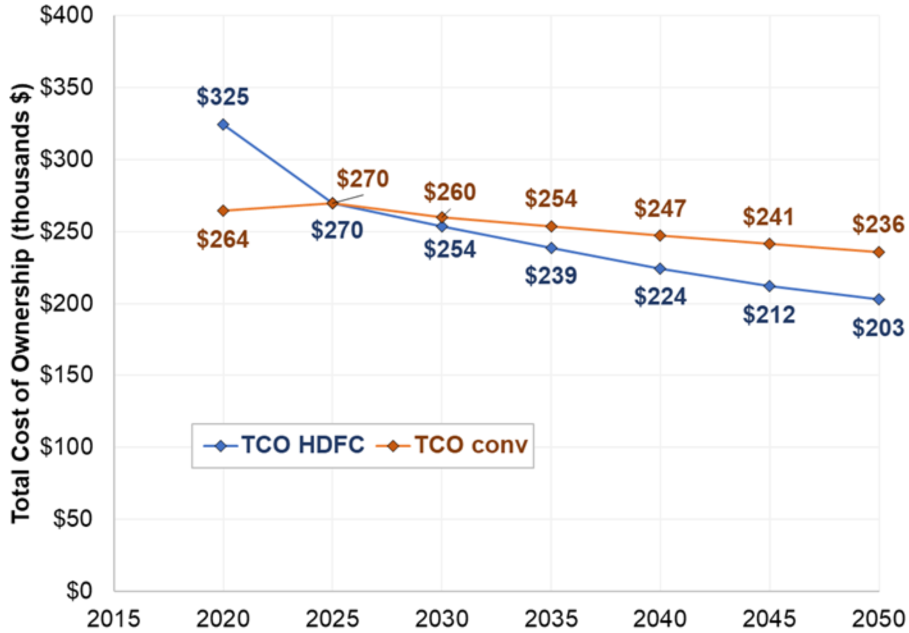


**Figure 3. Total Cost of Ownership projections for technology years 2020 through 2050 for Class 8 Yard Tractors (200-mile range) for conventional diesel and heavy-duty fuel cell (HDFC) powertrains.**

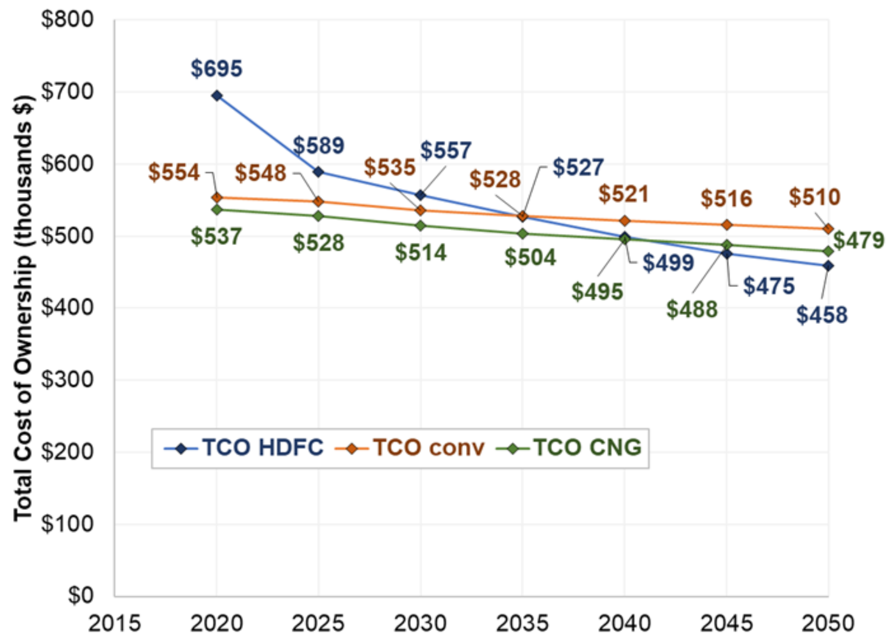


**Figure 4. Total Cost of Ownership projections for technology years 2020 through 2050 for Class 8 Refuse Trucks (200-mile range) for conventional diesel, CNG, and heavy-duty fuel cell (HDFC) powertrains.**

The decarbonization of M/HD commercial vehicles continues to play a critical role in achieving a net-zero carbon emissions economy. While this report focuses primarily on yard tractors and refuse trucks, it more broadly is successful at building upon NREL's blueprint for reproducing simplified TCO for numerous M/HD commercial vehicle segments across the advanced powertrain landscape. *Spatial and*

*Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks* (Hunter et al. 2021), *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains* (Burnham et al. 2021), *Vehicle Technologies and Hydrogen and Fuel Cells Technologies Research and Development Programs Benefits Assessment Report for 2020* (Brooker et al. 2021) are recent reports produced by NREL and the U.S. national laboratory system that complement this analysis and help outline further data gaps and evaluation processes for understanding advanced powertrain adoption within the commercial vehicle market.

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# 1 Introduction

Analysis of low-temperature, hydrogen fuel cell powertrains (FCEV) in the transportation sector has advanced considerably in recent years, especially in the context of medium- and heavy-duty (M/HD) truck applications (Heid et al. 2017; Hyundai 2020; Tesla 2021; Nikola 2021; O'Dell 2018). A majority of recent studies have focused on Class 8 long-haul or day cab freight trucks. While these long-haul and day cab freight applications represent a majority of M/HD truck energy consumption and emissions, other M/HD applications may have characteristics which align as well or better with the strengths of fuel cell technology. These other applications may, in some cases, represent near-term opportunities to deploy and scale up FCEVs. However, little research has been done on FCEV applications and powertrains for both M/HD *on-road* vocational trucks (e.g., refuse, dump, delivery, utility) and M/HD *off-road* vocational trucks (mining, yard tractors, construction, agriculture). Being vocational vehicles, these trucks are closely tied to fleet and individual operators for providing services, and inherently, generating revenue. Therefore, the economics surrounding these truck segments is crucial for vehicle adoption and market penetration. Total cost of ownership (TCO) is therefore a central metric for directly comparing and evaluating the potential for FCEVs among vocational truck applications.

The goal of TCO analysis is to compile all direct costs associated with each vehicle into a single metric, which can then be leveraged to compare different vehicle types, options, and powertrain applications. TCO does not provide detailed financial breakdowns such as payback periods, debt equity financing metrics, and other opportunity costs, but it does provide a useful indicator of the overarching economics associated with each vehicle type. TCO information enables operators to make economic evaluations and decisions that directly affect their vehicle fleets and operational requirements. Generating and disseminating this information can influence FCEV adoption within the vocational vehicle sector.

Hunter et al. 2021 demonstrated methods for performing TCO analysis and projections of drivetrain options for M/HD vehicles in the context of Class 4 and 8 on-road freight trucks. These methods use comprehensive dynamic vehicle models, variable duty cycles to allow for non-vertical powertrain integration and benchmark against conventional diesel powertrains (including diesel improvements and future projections). These analyses by Hunter et al. do not extend into other vocational Class 8 trucks beyond long-haul and short-haul tractors. However, they do serve as a roadmap and framework for investigating the TCO of other M/HD vehicle sectors while enabling estimations of powertrain efficiency (fuel economy).

The work performed in this report extends the methodology of Hunter et al. to additional vocational Class 8 trucks. The two vehicles selected for this analysis include a Class 8 on-road refuse truck and a Class 8 off-road, port-side yard tractor (also known as a yard hustler). FCEV applications for these truck types have not been studied heavily by the research community to date. Both trucks offer centralized refueling opportunities as well as unique duty cycles when compared to other on-road Class 8 freight trucks.

The powertrain options considered for each of these trucks include conventional diesel (diesel) and heavy-duty fuel cell electric (HDFC). An additional compressed natural gas (CNG) option was included for comparison for the Class 8 refuse truck scenario. CNG refuse trucks have gained a significant market share and major fleets owners like Waste Management are aiming for CNG make up over 80% of their collections fleets (Maria Rachal 2021). This is largely because CNG provides similar performance to diesel with typically lower fuel costs (Sandhu et al. 2021).

# 2 Methodology

The Class 8 heavy-duty transportation sector encompasses a wide variety of vehicle types and vocational uses. Significant attention has been dedicated to advanced powertrain considerations for on-road Class 8 tractors (long-haul and day cab) (Heid et al. 2017; Phadke et al. 2021; Hunter and Laboratory 2019; NACFE 2020; Adams 2020; Marcinkoski 2019), but further research is needed to extend analyses to other sectors within the Class 8 designation for both on-road and off-road vocational applications.

This report utilizes NREL's Transportation Technology Total Cost of Ownership tool (T3CO)[1], which is a combination of NREL's Future Automotive Systems Technology Simulator (FASTSim)[2] and NREL's Scenario Evaluation and Regionalization Analysis Model (SERA)[3]. The goal of these models is to enable levelized assessments of full vehicle life cycle costs for advanced powertrain technologies for commercial vehicle segments. T3CO takes a holistic approach when assessing TCO, which allows fleet owners and operators to objectively evaluate TCO comparisons across several powertrain options. It also allows for direct cost comparisons for buying, operating, maintaining, fueling, and cost of driving a commercial vehicle. T3CO leverages duty cycles from NREL's Fleet DNA database[4], which is a clearinghouse of commercial fleet vehicle operating data. Representative duty cycles for both Class 8 yard tractors and refuse trucks were pulled from NREL's Fleet DNA repository.

Typical direct costs associated with TCO were considered for Class 8 yard tractors and Class 8 refuse trucks. These include vehicle purchase price, fuel feedstock costs, powertrain component costs, balance-of-plant (BOP) costs, and operating and maintenance (O&M) costs. The analysis was simplified by assuming the vehicle purchase cost to be an upfront cost versus being financed by fleet owners over a longer period. Future iterations of this analysis could leverage user-defined financing assumptions for a more detailed TCO. The following sections in this chapter detail the evaluation process and approaches taken to model component costs and other vehicle performance metrics.

Indirect costs associated with dwell time due to refueling and/or payload reductions from the potentially heavier powertrain components were not included in this scoping-level analysis but can be included in future iterations of this analysis. However, details around the dwell times and load capacities experienced by each vehicle type are highly variable depending on the duty cycle and representative data with a greater fidelity in these sectors is needed. Based on similar analyses within Class 8 segments, dwell times and load capacities could have a significant effect on TCO (Hunter et al. 2021). The included direct costs were combined to output the TCO and net present value (NPV) of each Class 8 vehicle and powertrain option studied. Also, any future cost reductions or subsidies enacted by the Inflation Reduction Act were not considered or assumed for this analysis.

Detailed designs such as light-weighting and unique chassis for each powertrain and vehicle option were not considered for this analysis. Further work is needed to complete appropriate storage volume packaging and chassis designs for the implementation of the advanced hydrogen fuel cell powertrain and necessary BOP components.

[1] NREL's T3CO Tool (https://www.nrel.gov/transportation/t3co.html)
[2] NREL's FASTSim Tool (https://www.nrel.gov/transportation/fastsim.html)
[3] NREL's SERA model (https://www.nrel.gov/hydrogen/sera-model.html)
[4] NREL Fleet DNA Database (https://www.nrel.gov/transportation/fleettest-fleet-dna.html)

## 2.1 Down-Selection of Class 8 Vocations Evaluated

The down-selection of the vehicles evaluated in this report was influenced by interests of the analysis team and the funding source, the Environmental Protection Agency's Office of Transportation and Air Quality (EPA OTAQ).

### *2.1.1 Class 8 Yard Tractors*

While U.S. port energy consumption is a relatively small component of the total U.S. energy consumption (approximately 1.2% of the total U.S. energy consumption), their proximity and overall energy localization with respect to populated areas offers incentives for ports to assess and consider clean energy options (EIA 2021; Steele and Myers 2019; California Air Resource Board 2015). At major U.S. container ports, the vehicle typically with the highest fleet size, usage hours, and energy consumption is the Class 8 yard tractor or yard hustler (California Air Resource Board 2015). Recent work by Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL) helps demonstrate the percent of energy consumption consumed by yard tractors. A supporting graphic can be seen in Figure 5 (Steele and Myers 2019).

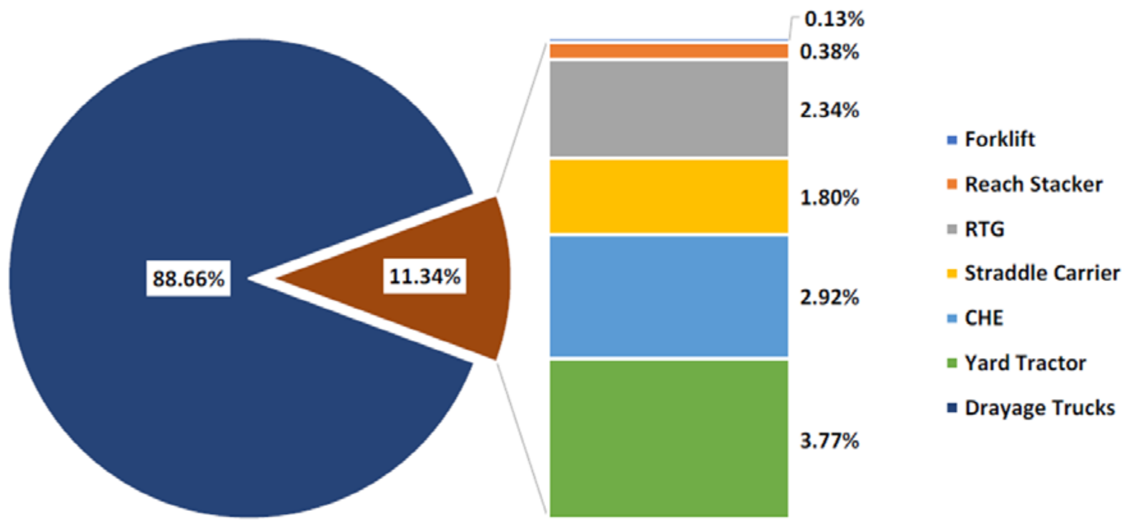


**Figure 5. Energy consumption breakdown by port-side vehicle type at major U.S. ports (Steele and Myers 2019).**

Figure 5 also demonstrates that Class 8 drayage vehicles realize the highest potential energy consumption at major ports and therefore have garnered the most attention in literature and demonstration projects. While these trucks were not the focus of this study, understanding that these trucks have a large potential for energy demand could help increase hydrogen demand at U.S. ports and influence the infrastructure needed to support these other non-road and off-road cargo handling vehicles. Yard tractors are specifically near-port vehicles with highly consistent, predictable duty cycles. This supports the need for centralized, on-site refueling infrastructure for these tractors, which can both help operators plan for refueling times within the duty cycle and also make hydrogen fuel deliveries more economical and streamlined.

Port-side yard tractors also offer operational characteristics that could benefit from advanced powertrain types like hydrogen fuel cells. These characteristics include high amounts of starts/stops, overall low operational speeds, high idle times, and low fuel economy (3-4 mile per diesel gallon equivalent) (Deloitte and Ballard 2020; National Renewable Energy Laboratory 2020).

### 2.1.2 Class 8 Refuse Trucks

Approximately 90% of all refuse trucks on-road today (out of ~180,000 total trucks) have diesel powertrains (Daniel C. Vock 2014). However, fleet operators are pushing for their new truck purchases to be CNG refuse trucks (Sandhu et al. 2021; Maria Rachal 2021). This could result in fleet owners being incentivized in the near-term to continue to seek advanced powertrain options for their fleets as diesel trucks become outdated, in need of retirement, and more strictly monitored to reduce emissions. DOE estimates that refuse trucks and haulers have an average fuel economy between 2-3[5] miles per gallon diesel equivalent (mpdge). As a nationwide fleet, one study estimates refuse trucks can consume greater than 1.2 million gallons of diesel annually (Shea 2011). Like Class 8 yard tractors, refuse trucks offer unique drive and duty cycle characteristics such as a high number of starts/stops, lower average driving speeds, and medium to high idling times during trash collection (Deloitte and Ballard 2020; National Renewable Energy Laboratory 2020). These operational attributes can be characterized and confirmed by leveraging NREL's Fleet DNA database[6] and are shown in Figure 6 and Figure 7. Other attractive attributes seen by refuse trucks include the fleet's potential to have centralized refueling depots, power take-off (PTO) considerations, and potential for multi-shift operations year-round.

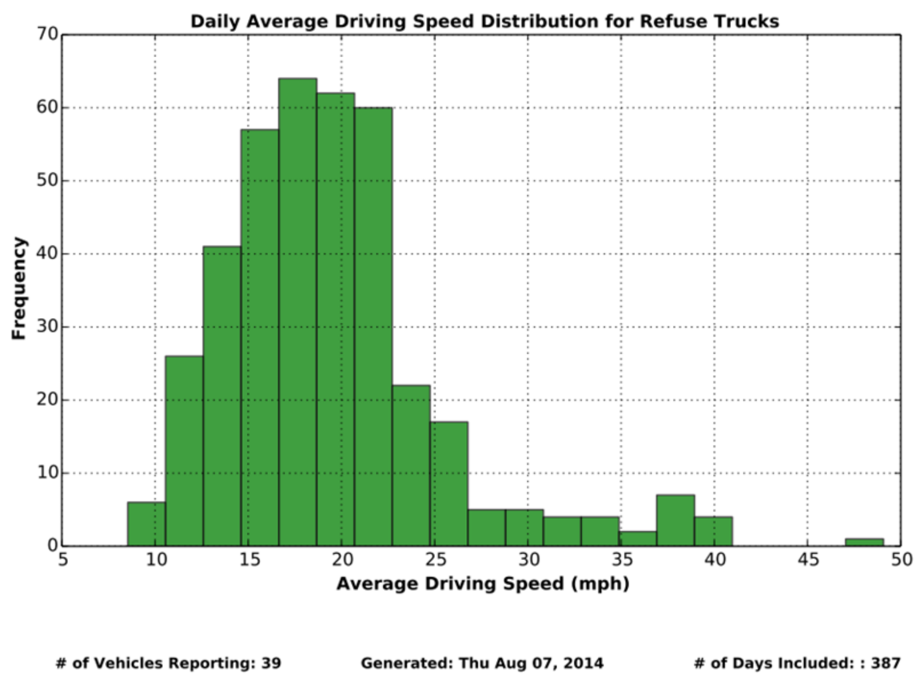


**Figure 6. Distribution for daily average driving speeds for U.S. based refuse trucks. Data from NREL's Fleet DNA database.**

[5] Average Fuel Economy by Major Vehicle Category (https://afdc.energy.gov/data/10310)
[6] NREL Fleet DNA Database (https://www.nrel.gov/transportation/fleettest-fleet-dna.html)

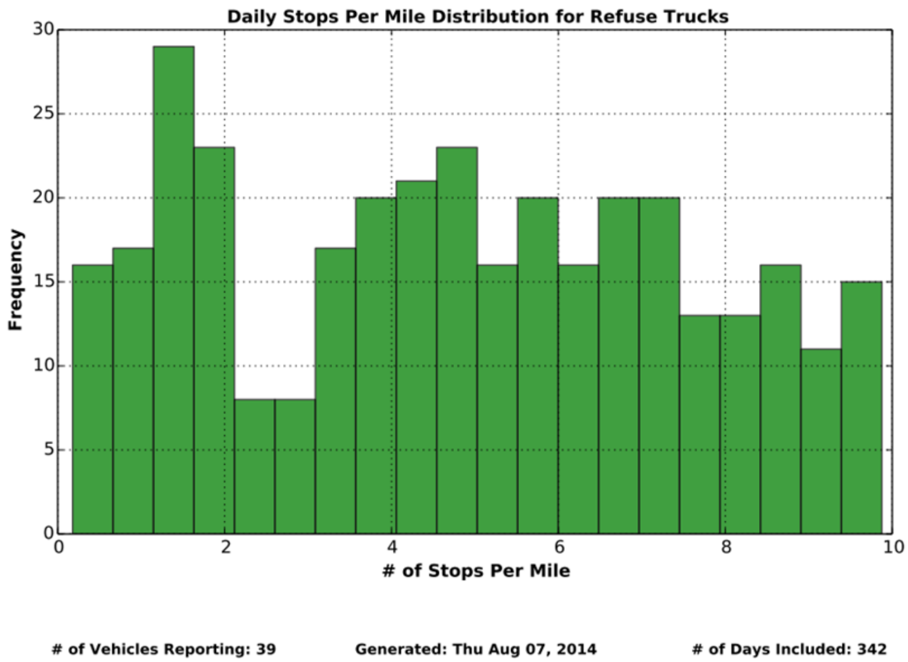


**Figure 7. Distribution for average daily stops per mile for U.S. based refuse trucks. Data from NREL's Fleet DNA database.**

## 2.2 Vehicle Powertrain Modeling & Key Parameters

NREL's FASTSim model enables rigorous vehicle evaluations for light-, medium-, and heavy-duty vehicle performance. The following vehicle powertrains were assessed in this report:

- Conventional diesel (diesel)
- Fuel cell electric vehicles (FCEVs)
- Compressed Natural Gas (CNG, refuse trucks only)

The FASTSim model uses a total of 53 vehicle parameters and specifications. These are summarized and listed as the following:

- Vehicle and cargo mass and weight distribution
- Frontal area
- Drag coefficient
- Glider weight and cost
- Fuel storage system weight, volume, and cost
- Engine power, efficiency curve, mass, and cost
- Battery energy, power, degradation, and cost
- Electric motor power, efficiency map, ramp rate, and cost
- Wheel inertia, tire rolling resistance, tire radius, wheelbase, number of wheels, and friction
- Energy management specifications and components
- Specification for power electronics, auxiliary loads, transmission, and other balance-of-plant (BOP) specifications

Using the duty cycles for each vehicle, the FASTSim model simulated the selected vehicle characteristics defined while vehicle speed and observed road grade are updated on a second-by-second basis. Vehicle acceleration and other performance metrics are also calculated each second. The result of this simulation yields vehicle fuel efficiency and road performance.

Ultimately, FASTSim evaluates alternative powertrain options for hypothetical scenarios where specified driving and duty cycle requirements are met for a certain vocation. Non-powertrain related attributes such as aerodynamics, glider mass, drag coefficient, rolling resistance, and transmission are all kept constant during the simulation as FASTSim focuses primarily on powertrain related differences. For this analysis, light-weighting and other modifications, which may be necessary for real implementation of alternative powertrains, were not considered. For example, non-powertrain components, fuel storage layout, and general chassis design was kept constant for each alternative powertrain analysis. This leads to the glider mass being augmented with the additional mass brought on by each powertrain type considered. A similar approach is taken for vehicle costs as well (i.e., glider cost is augmented with the additional costs of each powertrain type).

FASTSim sizes the vehicle's powertrain based on the duty requirements determined by the duty cycle. Each powertrain is appropriately sized to meet performance metrics like acceleration, road gradeability experienced, and vehicle range. From this operational analysis, fuel economy projections can be made for the vehicle over the selected duty cycle. Various duty cycles can be analyzed and may yield different fuel economy projections. Baseline, representative duty cycles were used for both Class 8 yard tractors and refuse trucks. No extreme conditions or rare occurrences were selected to represent either duty cycle.

Major outputs of the FASTSim component of the T3CO model are vehicle fuel economy, vehicle specifications, a breakdown of component costs, and the upfront vehicle manufacturer suggested retail price (MSRP).

#### 2.2.1 Powertrain and Fuel Storage Sizing Estimations

FASTSim is designed to compare select powertrains by removing the conventional powertrain components and outfitting the vehicle with the alternative powertrain components. Therefore, replacement fuel cell powertrain and related components were sized by FASTSim to match the performance of the conventional diesel powertrain for both the Class 8 yard tractor and refuse truck. A visual example of this can be seen in Figure 8 (Hunter et al. 2021).

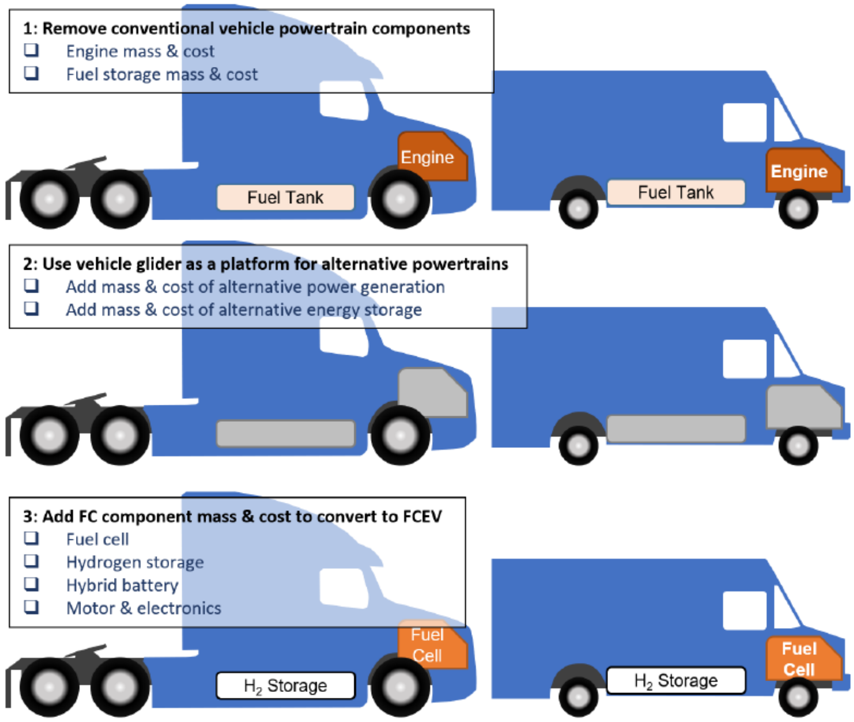


**Figure 8. Overview of the FASTSim methodology for estimating alternative powertrains for comparison to conventional diesel propulsion systems. Alternative powertrain components are sized to match the vocational requirements and performance of the diesel system (Hunter et al. 2021).**

The acceleration experienced by the conventional diesel powertrain during the representative duty cycle was used as a key metric for the powertrain conversion (i.e., the fuel cell powertrain power output for the yard tractor or truck was sized to meet the same performance seen by the conventional diesel powertrain option). The CNG power converter was assumed to be the same engine as the conventional diesel power converter for simplicity. For the CNG scenario, the main change was made to fuel prices and the fuel efficiency curve for the power converter.

Table 1 shows the representative conventional diesel powertrain sizes for the Class 8 yard tractor and refuse truck used for the analysis and for matching the fuel cell powertrain power output.

**Table 1. Engine output power for conventional diesel options for the selected vehicle. The corresponding fuel cell powertrain was sized to match the power outputs of these diesel engines.**

| Vehicle Type | Engine Power Output (Horsepower) | Engine Output Power (kW) |
|---|---|---|
| Class 8 Yard Tractor | 225 | 168 |
| Class 8 Refuse Truck | 380 | 283 |

Fuel storage capacity was estimated similarly to the powertrain. A representative fuel storage (e.g., tank size in gallons) was determined and the relative hydrogen fuel storage tank and capacity was sized to hold the same quantity of fuel energy to meet the range requirements set by the diesel fuel tank. The conventional diesel tank sizes, corresponding storage weights (diesel fuel included), and estimated hydrogen fuel storage capacity needed can be seen in Table 2.

Table 2. Engine output power for conventional diesel options for the selected vehicle. The corresponding fuel cell powertrain was sized to match the power outputs of these diesel engines.

| Vehicle Type | Fuel Storage Capacity (gallons diesel) | Fuel Storage Weight (kg) | $H_2$ Fuel Storage Energy Equivalent (kg-$H_2$) |
|---|---|---|---|
| Class 8 Yard Tractor | 50 | 160 | 16 |
| Class 8 Refuse Truck | 75 | 240 | 30 |

These powertrain sizes were determined by the analysis team to be representative of each vehicle segment for this scoping-level analysis. Future iterations of this work are flexible to include various powertrain sizing that may be seen within each of these segments.

### 2.2.2 Vehicle Mass, Frontal Area, and Other Key Parameter Estimations

Representative vehicle models for both Class 8 yard tractors and refuse trucks were developed for this analysis and are key input parameters for the FASTSim model, specifically frontal area and glider mass. However, for both these vehicle types, because typical operation is at low speeds, frontal area does not play a significant role in drag and determination of fuel economy.

The Class 8 yard tractor chassis dimensions were based on a Kalmar Ottawa T2 6x4 DOT/EPA Certified Yard Tractor Standard Specifications (Kalmar Ottawa 2019). Figure 9 shows the dimensions of the yard tractor specified for this analysis.

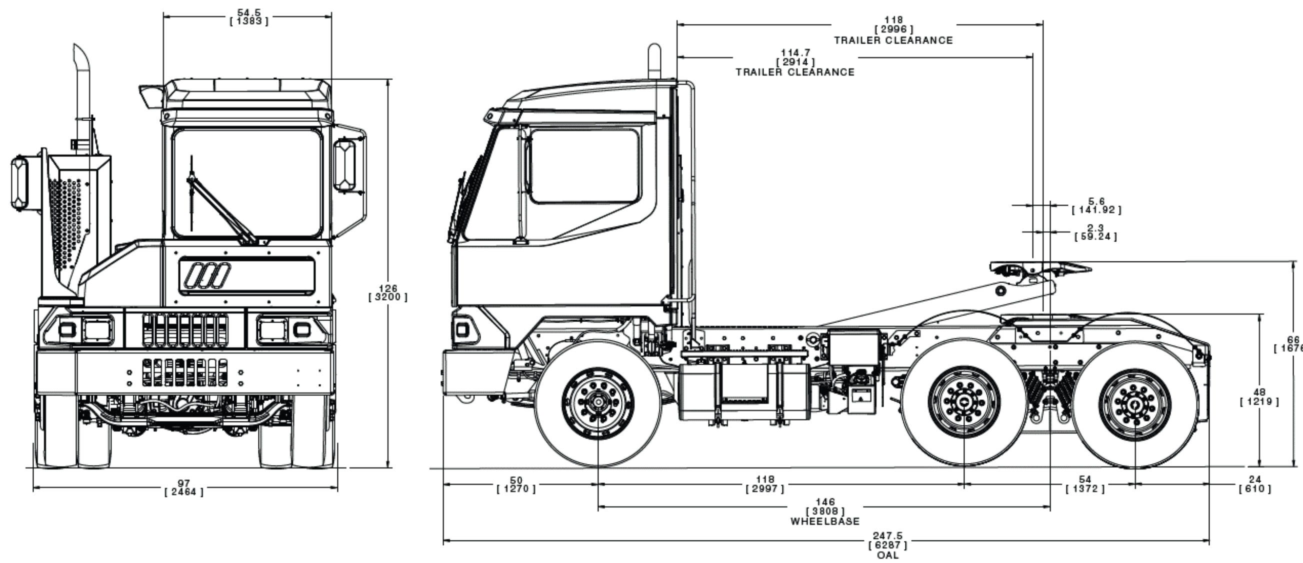


**Figure 9. Kalmar Ottawa 6x4 yard tractor size and dimensions used for FASTSim vehicle model.**

During the yard tractor's duty cycle, a shipping container is typically hauled and adds to the vehicle's overall height and frontal area calculation. A generic container height and width was assumed and added to the frontal area calculation. Below in Table 3 are the frontal area estimations for the Class 8 yard tractor used as an input to the FASTSim model.

**Table 3. Total frontal area calculation for the Class 8 yard tractor. Includes the additional height added by the container during handling.**

| Parameter | Height (m) | Width (m) |
|---|---|---|
| Front of Truck | 3.20 | 2.46 |
| Front of Container | 2.27 | 2.29 |
| Fifth Wheel Height | 1.58 | - |
| Container + Fifth Wheel Height | 3.85 | - |
| Total Frontal Height & Width | 3.85 | 2.46 |
| **Total Frontal Area** | **9.47 m$^2$** | |

For the glider mass estimation, the yard tractor (without cargo) chassis, fuel storage (including fuel), transmission, and engine were estimated and summed to get a total glider mass input for FASTSim. The mass estimations can be seen below in Table 4.

**Table 4. Total glider mass calculation for the Class 8 yard tractor.**

| Weight | lbs. | kg |
|---|---|---|
| Yard Tractor Vehicle | 22,700 | 10,300 |
| Fuel Storage (50 gal) | 350 | 160 |
| Transmission | 790 | 360 |
| Engine (225 HP, 168 kW) | 1,710 | 774 |
| **Total Glider Mass** | **19,850** | **9,000** |

A weighted-average cargo mass estimation and maximum total vehicle weight as well as maximum cargo mass estimation was made for the Class 8 yard tractor based on vehicle duty cycle data from NREL's Fleet DNA (Figure 10) (Kotz et al. 2020).

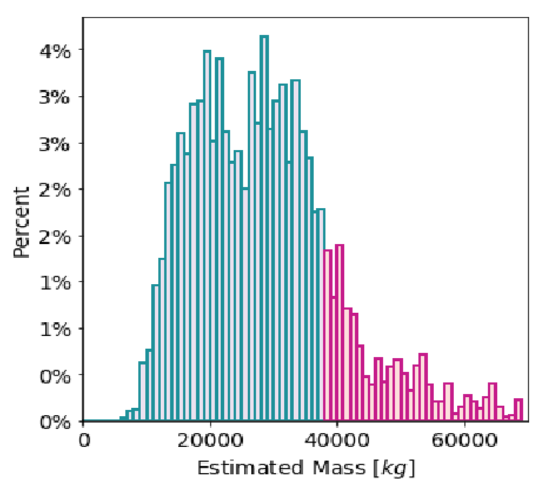


**Figure 10. Estimated total yard tractor mass (tractor + cargo) based on NREL Fleet DNA data and duty cycle used in this analysis (Kotz et al. 2020).**

The select cargo mass estimations for the Class 8 yard tractor can be viewed in Table 5. The weighted-average cargo mass value for the yard tractor was further used in this analysis when estimating the average fuel economy results.

**Table 5. Weighted-average cargo mass (vehicle mass with average cargo load minus vehicle mass without cargo), and maximum cargo estimations for the Class 8 yard tractor.**

| Weight | lbs. | kg |
|---|---|---|
| Weighted-average Cargo Mass | 39,300 | 17,960 |
| Maximum Total Vehicle Mass | 151,000 | 68,300 |
| Maximum Cargo Mass | 128,000 | 58,000 |

The Class 8 yard tractor had a design mileage range of 200 miles, a vehicle lifetime (projected lifespan before needing a major powertrain overhaul) of 10 years, and a vehicle miles traveled (VMT) estimate of 16,000 miles per year.

The Class 8 refuse truck's chassis dimensions were based on a readily available specification sheet for an Autocar ACX 6x4 Refuse Truck. Dimensions for the specification sheet are shown below in Figure 11.

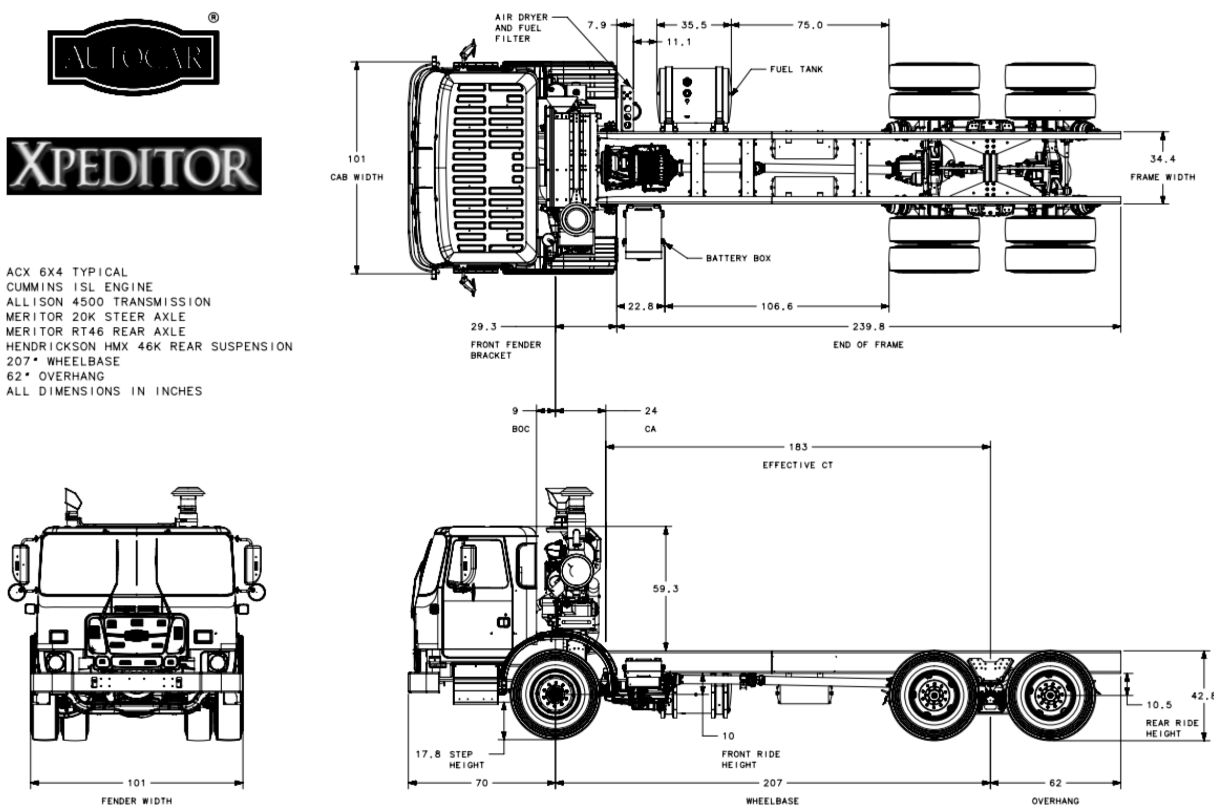


**Figure 11. Representative dimensions for the Class 8 refuse truck[7].**

[7] Autocar ACX 6x4 Refuse Truck (https://d3w5dxa1iffln.cloudfront.net/media/1759/acx_6x4_specs_v2.pdf)

A general container (trash collector body) dimension was also added to the refuse truck to account for the addition frontal area measurement considerations. For this specific refuse truck, only additional height was added by the container as the container was assumed to have the same width contribution as the main truck chassis. Using these generic dimensions, a frontal area estimation for the representative refuse truck was made and can be viewed in Table 6.

**Table 6. Total frontal area calculation for the Class 8 refuse truck. An additional height was added to the truck's chassis to account for the height added by the trash collection container.**

| Parameter | Height (m) | Width (m) |
|---|---|---|
| Front of Truck | 2.59 | 2.56 |
| Front of Container | 3.50 | 2.56 |
| Total Frontal Height & Width | 3.50 | 2.56 |
| **Total Frontal Area** | **8.96 $m^2$** | |

For the refuse truck's glider mass estimation, the chassis (without cargo), fuel storage (including fuel mass), transmission, and engine were estimated and summed to get a total glider mass input for FASTSim. The mass estimations can be seen below in Table 7.

**Table 7. Total glider mass calculation for the Class 8 refuse truck.**

| Weight | lbs. | kg |
|---|---|---|
| Refuse Truck (empty) | 33,000 | 15,000 |
| Fuel Storage (75 gal) | 530 | 240 |
| Transmission (incl. Power Take-Off | 1,070 | 400 |
| Engine (380 HP, 283 kW) | 2,880 | 1,310 |
| **Total Glider Mass** | **37,480** | **16,950** |

A weighted-average cargo mass estimation and maximum total vehicle weight as well as maximum cargo mass estimation was made for the Class 8 refuse truck based on vehicle duty cycle data from NREL's Fleet DNA. The select cargo mass estimations for the Class 8 refuse truck can be viewed in Table 8. Unlike the yard tractor, the refuse truck must adhere to on-road vehicle weight specifications and gross vehicle weight ratio (GVWR) limits. The weighted-average cargo mass estimation was further used in this analysis to assist in estimating the fuel economy of the refuse truck.

**Table 8. Weighted-average cargo mass (vehicle mass with average cargo load minus vehicle mass without cargo), maximum total vehicle weight (GVWR), and maximum cargo estimations for the Class 8 refuse truck.**

| Weight | lbs. | kg |
|---|---|---|
| Weighted-average Cargo Mass | 17,000 | 7,700 |
| Maximum Total Vehicle Mass | 66,000 | 30,000 |
| Maximum Cargo Mass | 33,000 | 15,000 |

The Class 8 refuse truck had a design mileage range of 190 miles, a vehicle lifetime (projected lifespan before needing a major powertrain overhaul) of 10 years, and a VMT estimate of 25,000 miles per year.

Other key vehicle parameters used by FASTSim for each vehicle are wheel inertia, number of vehicle wheels, a generic component mass multiplier, an estimated transmission efficiency, and default cost mark-up. The parameters are available for reference in Table 9 below.

**Table 9. Other key parameter inputs used as inputs for FASTSim modeling for both the Class 8 yard tractor and Class 8 refuse truck.**

| Parameter | Class 8 Yard Tractor | Class 8 Refuse Truck |
|---|---|---|
| Wheel Inertia (kg-m$^2$) | 10 | 10 |
| Number of Wheels | 14[8] | 10 |
| Component Mass Multiplier[9] | 1.2 | 1.2 |
| Transmission Efficiency (%)[8] | 95 | 95 |
| Cost Markup[8] | 1.5 | 1.5 |

FASTSim also requires input coefficients for drag and wheel rolling resistance projected out by each technology year studied. Those parameters along with the relative improvements over time are displayed in Table 10. These values were used as defaults for both the Class 8 yard tractor as well as the refuse truck. Also included in the analysis for each vehicle was a small, 20 kW Li-ion battery within the balance-of-plant. This was added to cover any regenerative breaking captured by the HDFC powertrains. The magnitude or quality of the regenerative breaking however was not assessed in this study.

**Table 10. Drag coefficient, wheel rolling resistance coefficient, and projected fuel costs for technology years 2020 through 2050.**

| Commercial Year | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Drag Coefficient[10] | 0.60 | 0.55 | 0.52 | 0.50 | 0.48 | 0.47 | 0.45 |
| Wheel Rolling Resistance Coefficient[9] | 0.0054 | 0.0054 | 0.0054 | 0.0054 | 0.0054 | 0.0054 | 0.0054 |

### 2.2.3 Representative Duty cycles & Fuel Economy Estimations

Representative duty cycles for each Class 8 vehicle consist of second-by-second speed data during the duration of the duty cycle. Key characteristics, such as start/stop time, idle time, and average speed were taken into account when selecting the appropriate duty cycle for both the yard tractor and the refuse truck. Both duty cycles were derived from NREL's Fleet DNA Database (National Renewable Energy Laboratory 2020). For the yard tractor, the duty cycle data was collected by on-board GPS instrumentation for a select yard tractor operating at the Port Authority of New York and New Jersey (Kotz, Kelly, and Gagne 2020). For the refuse truck, the duty cycle data was also collected via on-board GPS instrumentation for a refuse truck operating in the Miami Dade County area. Raw visualizations and the important cycle metrics for the yard tractor and the refuse truck duty cycles can be seen in Figure 12 and Figure 13, respectively.

[8] Includes container trailer wheel set
[9] FASTSim defaults
[10] FASTSim default values for Class 8 Tractors

| Average yard tractor cycle from Port Authority of NY-NJ | | |
|---|---|---|
| **Parameter** | **Unit** | **Value** |
| Duration | hh:mm | 6:11 |
| Distance Traveled | mi | 30.9 |
| Average Speed | mph | 5 |
| Max Speed | mph | 20.4 |
| Stopped Time | hh:mm | 2:31 |

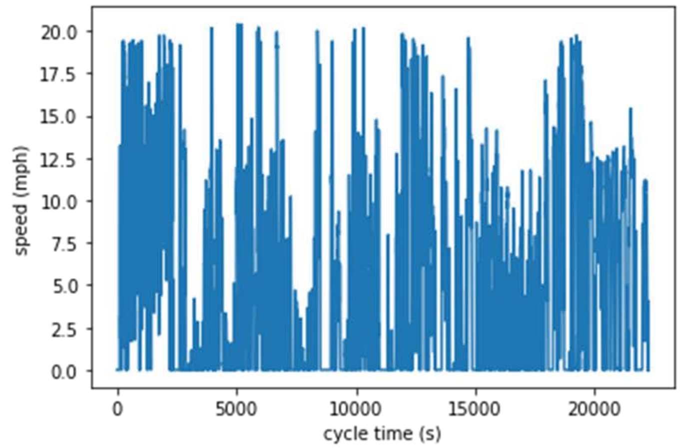


**Figure 12. Representative duty cycle for the Class 8 yard tractor with accompanying duty cycle attributes and metrics.**

The representative yard tractor cycle demonstrates a low average moving speed (~5 mph) and a significant amount of stopped/idle time (greater than a third of the total cycle time). As previously mentioned, these attributes offer favorable operational characteristics for fuel cell powertrains as fuel cells typically achieve peak efficiency at lower percentages of power output and consume little to no fuel while idle or at a complete stop.

| Miami-Dade Refuse Truck Average Drive Cycle | | |
|---|---|---|
| **Parameter** | **Unit** | **Value** |
| Duration | hh:mm | 7:55 |
| Distance Traveled | mi | 87.9 |
| Average Speed | mph | 11.1 |
| Max Speed | mph | 65.8 |
| Stopped Time | hh:mm | 2:24 |

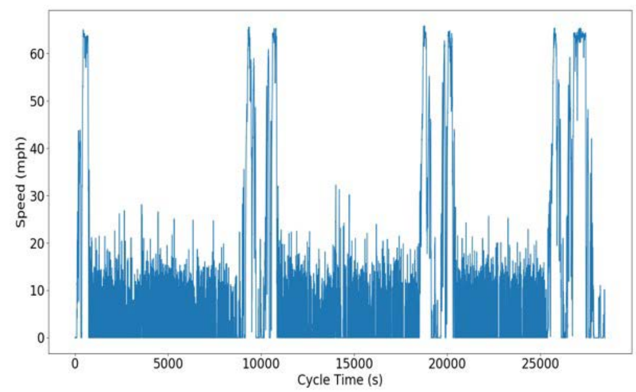


**Figure 13. Representative duty cycle for the Class 8 refuse truck with accompanying duty cycle attributes and metrics. *Note the sections of the duty cycle below a speed of 30 mph pertain to the truck's trash collection period while the sections approaching 60 mph reference the time that the refuse truck is traveling from one collection zone to the next.**

As with the yard tractor cycle, the refuse truck cycle demonstrates low average moving speeds (~11 mph) and a significant amount of stopped/idle time (slightly less than a third of the total cycle time). Again, these attributes offer favorable operations for fuel cell powertrains. Unlike the yard tractor, the refuse truck does reach highway speeds. Diesel powertrains reach peak efficiency as power demand increases; therefore, during highway driving and at the time of writing this report, diesel powertrains can potentially have more favorable operations versus fuel cell powertrains during these instances of the duty cycle.

All fuel economy estimations generated in the results section of this report use these representative duty cycles with powertrain components and fuel storage sized to meet the cycle's operational characteristics and requirements with the relevant weighted-average cargo load discussed in the previous sections. No individual duty cycle for either of these vehicles can capture every duty cycle experienced by real-world users of these vehicle types. The cycles used in this study were vetted by the analysis team and the members of the EPA clients for relevancy to the project and analysis goals. However, the use of a single duty cycle for each representative vehicle represents a source of uncertainty in our results. Further work could investigate the robustness of our results to variations in duty cycle characteristics.

## 2.3 Powertrain Performance and Cost Data Assumptions

Vehicle performance benchmarking for each powertrain type was completed for both the Class 8 yard tractor and refuse truck. These benchmarks combined with the specific vocational vehicle duty cycles and powertrain power profiles help FASTSim make fuel economy estimations. Engine efficiency curves were created using DOE efficiency tech targets for Class 8 long-haul truck powertrains (Marcinkoski 2019). These target efficiency values were interpolated to create profiles on a year-by-year basis allowing for curves to represent each target year assessed in this report (e.g., 2020, 2025, 2030, 2035, 2040, 2045, 2050). The efficiency curves were then adjusted using the relevant duty cycle and engine power profiles to be representative of either the Class 8 yard tractor or refuse truck.

The diesel, HDFC, and CNG (applicable to the refuse truck only) engine efficiency curve estimations used for the Class 8 yard tractor and Class 8 refuse truck are shown in Figure 14.

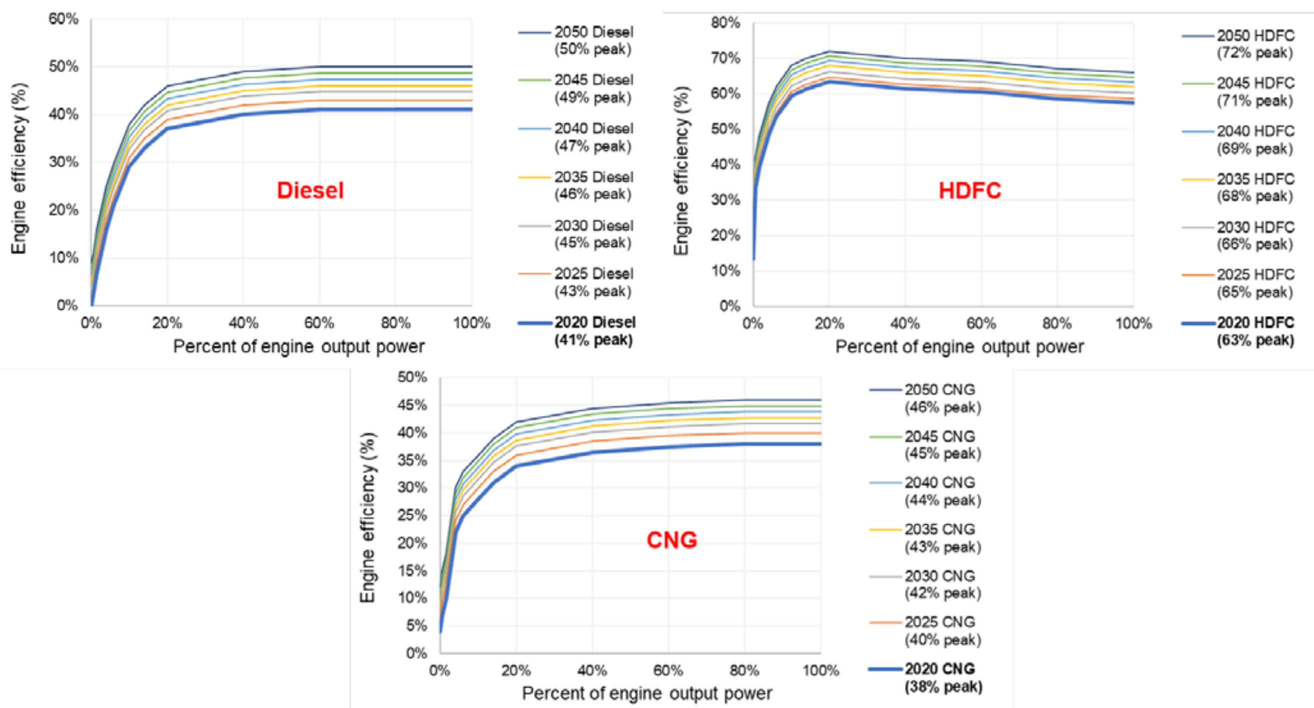


**Figure 14. Class 8 yard tractor and refuse truck engine efficiency curve estimations for diesel, HDFC, and CNG (refuse truck only) powertrains based on representative duty cycle.**

Diesel engines tend to be more efficient as power output increases while HDFCs reach peak efficiency more in the 15-25% power output range. This drivetrain feature strengthens the case for using HDFCs in yard tractor applications. Available data suggests most of the yard tractor duty cycle is spent in idle or at low power outputs during the process of loading, unloading, and waiting for cargo containers. Refuse truck duty cycles may also benefit from this drivetrain feature of HDFCs as, during trash collection, refuse trucks spend a majority of the duty cycle at low speeds and power outputs with numerous start/stop characteristics. Combining these engine efficiency curves with the representative duty cycles for both the yard tractor and refuse truck, we can extract expected average engine efficiencies for each vehicle. These averages for the yard tractor and refuse truck can be seen in Table 11 and

Table 12, respectively.

**Table 11. Class 8 yard tractor average powertrain efficiency based on efficiency curve, representative duty cycle, power profile, and DOE class 8 engine tech and performance targets.**

| Conventional Diesel | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Average Engine Efficiency (%) | 21.2 | 24.4 | 27.1 | 28.9 | 30.7 | 32.4 | 34.1 |
| **HDFC** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Average Engine Efficiency (%) | 56.3 | 57.2 | 58.8 | 60.6 | 61.9 | 63.2 | 64.5 |

**Table 12. Class 8 refuse truck average engine efficiency based on efficiency curve, representative duty cycle, power profile, and DOE class 8 engine tech and performance targets.**

| Conventional Diesel | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Average Engine Efficiency (%) | 28.2 | 32.6 | 35.6 | 37.5 | 39.3 | 41.1 | 42.7 |
| **HDFC** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Average Engine Efficiency (%) | 59.5 | 60.6 | 62.3 | 64.1 | 65.4 | 66.7 | 68.1 |
| **CNG** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Average Engine Efficiency (%) | 31.7 | 34.1 | 36.1 | 37.3 | 38.5 | 39.7 | 40.9 |

Table 13 displays the baseline powertrain performance metrics and cost data used as inputs for the FASTSim and T3CO models. This data was leveraged from previous NREL studies assessing Class 8 vehicle types (Hunter et al. 2021; Hunter and Laboratory 2019).

**Table 13. Technology cost and performance metrics used in FASTSim and T3CO modeling framework for Class 8 yard tractors and refuse trucks for select powertrain types (Hunter et al. 2021).**

| Conventional Diesel | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Engine Cost ($/kW) | 47.3 | 47.3 | 47.3 | 47.3 | 47.3 | 47.3 | 47.3 |
| Fuel Storage ($/kWh) | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Engine Specific Power (kW/kg) | 0.275 | 0.275 | 0.275 | 0.275 | 0.275 | 0.275 | 0.275 |
| Storage Specific Mass (kWh/kg) | 9.88 | 9.88 | 9.88 | 9.88 | 9.88 | 9.88 | 9.88 |
| **FCEV** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Engine Cost ($/kW) | 190 | 135 | 120 | 105 | 90 | 75 | 60 |
| Fuel Storage ($/kWh) | 36 | 16 | 14.4 | 12.8 | 11.2 | 9.6 | 8 |
| Engine Specific Power (kW/kg) | 0.96 | 1.02 | 1.03 | 1.04 | 1.06 | 1.07 | 1.08 |
| Storage Specific Mass (kWh/kg) | 1.48 | 1.80 | 1.88 | 1.96 | 2.04 | 2.12 | 2.20 |
| Auxiliary Battery Cost ($/kWh) | 197 | 170 | 152 | 134 | 116 | 98 | 80 |
| **CNG (Refuse Only)** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Engine Cost ($/kW) | 55 | 55 | 55 | 55 | 55 | 55 | 55 |
| Fuel Storage ($/kWh) | 7.47 | 4.70 | 4.52 | 4.35 | 4.17 | 4.00 | 3.82 |
| Engine Specific Power (kW/kg) | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| Storage Specific Mass (kWh/kg) | 4.21 | 4.47 | 4.60 | 4.72 | 4.85 | 4.97 | 5.10 |

Specific engine power for the conventional diesel powertrain is based on defaults set by the FASTSim model (National Renewable Energy Laboratory 2018a). Diesel engine costs are provided by previous NREL FASTSim and T3CO completed work (Brooker et al. 2021).

For the HDFC powertrain applications, projected fuel cell specific power values were taken from work completed by Strategic Analysis, Inc. (James et al. 2018), which has been extensively reviewed by the Hydrogen and Fuel Cell Technology Office (HFTO) at DOE. Fuel cell powertrain and power related component costs were also based on work provided by Strategic Analysis, Inc. for medium- and heavy-duty fuel cells and by target-setting guidance from HFTO (James, Houchins, and Huya-Kouadio 2021; Hunter et al. 2021). The storage mass and cost data are based on status updates via DOE Hydrogen and Fuel Cells Program Record (Adams, Houchins, and Ahluwalia 2019).

Peak efficiency, engine cost data, and other performance metrics for the CNG powertrain comes from previous NREL work and through personal communication with the Vehicle Technology Office (VTO) at DOE (Hunter et al. 2021). CNG refuse trucks continue to gain market share within this segment, which again is why CNG powertrains were included in the refuse truck portion of this study.

Note that all the cost data provided above reference component manufactured costs only and not purchase prices. To determine a purchase price or vehicle MSRP, a cost markup must be applied. A markup of 1.5 is provided by the FASTSim modeling framework as a default and is used accordingly in the analysis. To reiterate, price and cost implications brought on by the newly implemented Inflation Reduction Act are not included or considered in this analysis.

### 2.3.1 Fuel Costs

Fuel costs are determined by the powertrain fuel consumption rates as well as the input fuel price tables used by FASTSim. The fuel prices used in this study are listed in Table 14. Diesel and CNG fuel price historical estimates and future projections are taken from the U.S. Energy Information Administration's 2021 Annual Energy Outlook (AEO) (U.S. Energy Information Administration 2021). Hydrogen fuel prices were taken directly from Hunter et al. 2021 but were ultimately based on HFTO cost targets and observed fuel cost data for hydrogen fuel cell buses in California (Eudy 2019). Note that again, this analysis does not consider any potential impacts or other subsidy programs on hydrogen fuel prices as a result of the Inflation Reduction Act.

**Table 14. Project fuel prices for each powertrain type studied.**

| Conventional Diesel | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Diesel Fuel Cost ($/gal)[11] | 2.93 | 3.08 | 3.29 | 3.47 | 3.57 | 3.76 | 3.88 |
| Hydrogen Fuel Cost ($/kg)[12] | 10 | 7 | 6.4 | 5.8 | 5.2 | 4.6 | 4 |
| CNG Fuel Cost ($/gge)[13] | 1.71 | 1.58 | 1.56 | 1.47 | 1.44 | 1.43 | 1.45 |

### 2.3.2 Operation & Maintenance Cost Assumptions

Operation and maintenance (O&M) costs can be significant for vocational vehicles and must be accounted for to make accurate TCO projections through the T3CO model. Vocational vehicles like yard tractors are subjected to harsh and aggressive environments, underscoring the importance of timely and proper maintenance. These impacts can have significant effects on vehicle lifetime and performance. Included in O&M costs are typical vehicle maintenance service items such as oil changes, engine maintenance, system adjustments, and other general maintenance items. O&M data was collected in previous NREL work and helped inform cost assumptions for each powertrain type (Hunter et al. 2021). O&M data for yard tractors and refuse trucks is not as readily available, so literature findings for advanced powertrain buses were used as a representative baseline for developing a maintenance cost for the diesel, CNG, and HDFC powertrains in these vocational vehicle contexts (Hunter et al. 2021; Eudy and Post 2021). Figure 15 shows a spread of the O&M cost data found in literature for Class 6 buses. This data was used to create a summary table shown in Table 15.

[11] AEO 2021 Fuel Price Table: Diesel
[12] Chad Hunter et al. 2021
[13] AEO 2021 Fuel Price Table: CNG

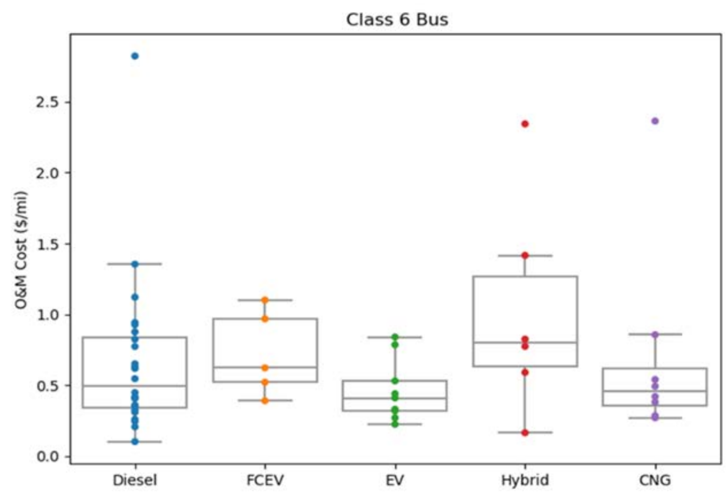


**Figure 15. O&M cost data for select advance powertrain types based on literature finds and summarized by Hunter et al. 2021.**

The data points shown in red in Table 15 were used to derive a maintenance scale factor for going from diesel O&M to HDFC O&M. The percent increase from the median diesel O&M value to the median HDFC O&M value is roughly 25%. A diesel O&M cost for typical U.S.-based yard tractors was found in literature (Jon Leonard 2012); this is shown in Table 16. Similarly, refuse truck O&M cost data was found for both the diesel and CNG powertrains (Ballard 2021; Kevin Chandler, Paul Norton, and Nigel Clark 2001). To get the relative HDFC O&M costs assumed for the yard tractor and refuse truck, the 25% cost markup was applied to the diesel O&M value. The resulting HDFC O&M cost reference used as a FASTSim input can be seen in Table 16.

**Table 15. Summary of O&M cost data for Class 6 buses seen in Figure 15. Data points shown in red were baseline values used to develop a cost markup for value between diesel and HDFC yard tractor and refuse truck O&M ($/mi).**

| O&M Cost ($/mi) | Bound | Diesel | HDFC | EV | Hybrid | CNG |
|---|---|---|---|---|---|---|
| Class 6 Bus | Lower | 0.344 | 0.521 | 0.320 | 0.636 | 0.356 |
| | Median | 0.497 | 0.622 | 0.410 | 0.799 | 0.456 |
| | Upper | 0.837 | 0.968 | 0.530 | 1.27 | 0.619 |

**Table 16. Yard tractor diesel and HDFC O&M cost values used in the T3CO model.**

| O&M Cost ($/mi) | Diesel | HDFC | CNG |
|---|---|---|---|
| Class 8 Yard Tractor | 0.198 | 0.248 | - |
| Class 8 Refuse Truck | 0.45 | 0.55 | 0.72 |

## 2.4 SERA model contributions to T3CO

NREL's SERA modeling components in T3CO aim to provide a vehicle stock module that tracks VMTs, energy consumption, and vehicles expenses spatially and temporally (Hunter et al. 2021). SERA is also able to guide infrastructure planning and development within transportation sectors but was not leveraged for this report. This report also studies individual vehicles, but SERA can additionally provide regionally explicit analysis for entire vehicle fleets, which could be considered as supplemental work to complement this analysis.

A process flow diagram, outline, and overview for how FASTSim (vehicle powertrain cost modeling) and SERA (TCO) feed into T3CO can be seen in Figure 16. The TCO determined in this analysis is based on a total vehicle lifetime interval versus a specific ownership timeframe. This vehicle lifetime is represented by annual vehicle miles traveled (miles/year), the specific powertrain's performance, and design mileage discussed in Sections 2.2 and 2.3.

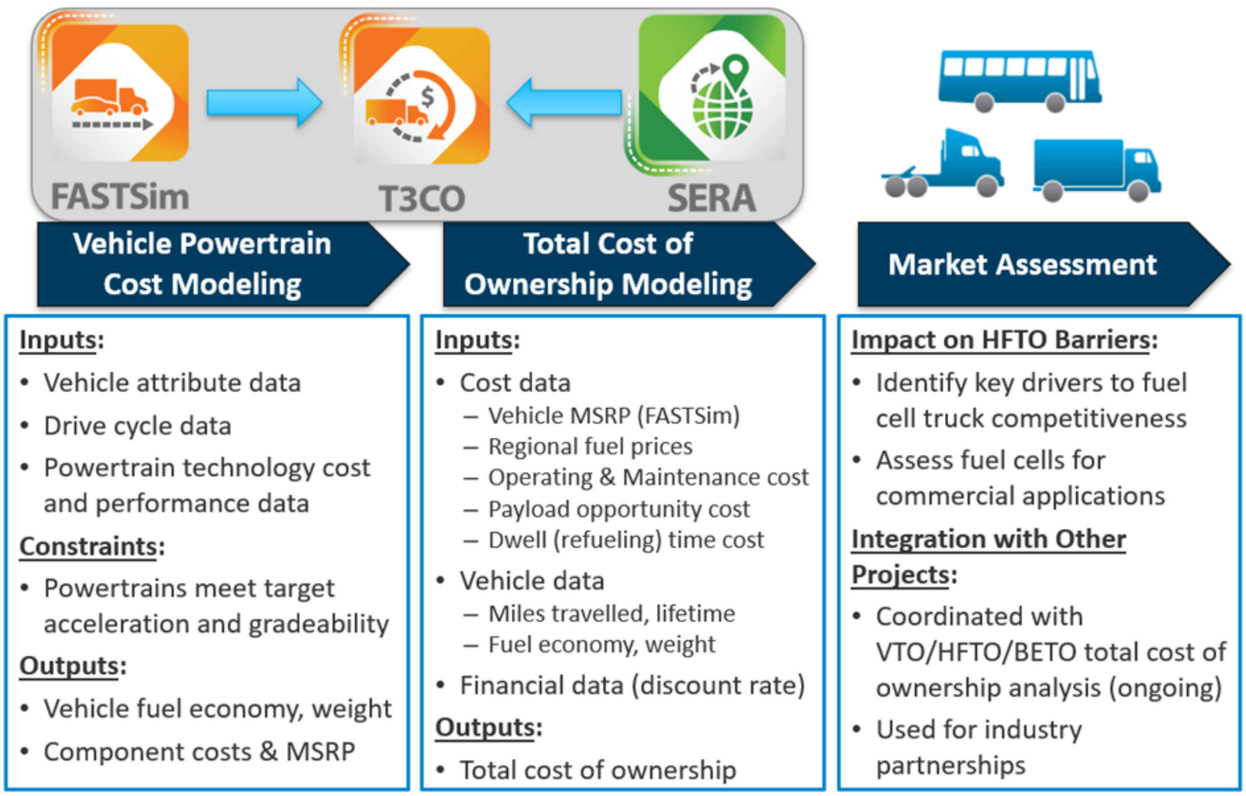


**Figure 16. T3CO, FASTSim, and SERA modeling approach and flow process.**

# 3 Results

The results from this analysis are outlined in this section and include the modeling results for fuel economy estimations, vehicle weight, price, and total cost of ownership for both the Class 8 yard tractor as well as the Class 8 refuse truck.

## 3.1 Vehicle Modeling and Performance

NREL's FASTSim model was used to determine the vehicle fuel economy, weight, and total MSRP for each powertrain type studied for the Class 8 yard tractor and refuse truck. Components for each vehicle were sized to meet vocational requirements set by each vocation's representative duty cycle. Vehicle weight inputs used in the FASTSim model can be referenced in Section 2.2.2, while vehicle baseline production cost is comprised of the following:

- Vehicle glider (with no light-weighting or modifications made for advanced powertrains)
- Fuel converter (powertrain)
- Fuel storage
- Auxiliary batteries
- Power electronics
- Electric motor
- Transmission

#### 3.1.1 Weight Breakdown: Class 8 Yard Tractors

The powertrain sizing methodology can again be referenced in Section 2.2.2. Figure 17 shows a breakdown of the weight distribution for the conventional diesel and heavy-duty fuel cell vehicles for the Class 8 yard tractor. The breakdown does not include the weight-average cargo rating or maximum cargo rating for viewing simplicity. The most influential component weight (outside of glider) for the diesel tractor is the diesel engine and for the hydrogen fuel cell tractor, it is the fuel storage system. Diesel engines add significant weight while diesel storage system can be extremely light comparatively. Fuel cells add significant weight as well, but the advance materials needed for hydrogen storage tend to make the fuel storage system significantly heavier than the diesel storage counterpart. Overall, the diesel system (diesel engine + diesel fuel storage) is heavier than the fuel cell system (fuel cell + hydrogen storage tank) as the relative weight difference between the heavier diesel engine and the fuel cell is more significant than the weight differences between the two storage system types.

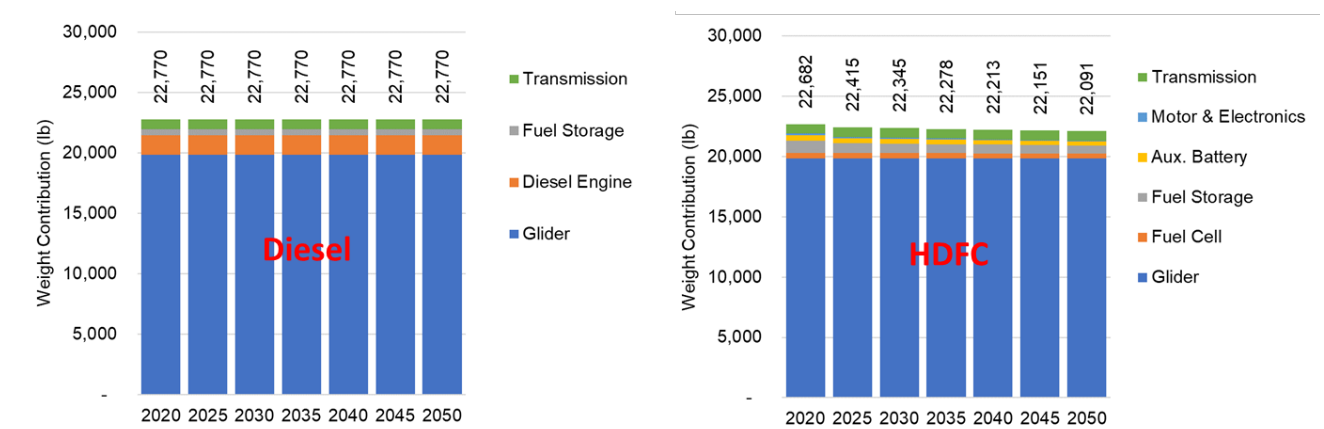


**Figure 17. Weight breakdown for the Class 8 yard tractor for diesel and HDFC powertrain options.**

Table 17 is included to show the specific weight contributions (in lbs.) for each powertrain type for Class 8 yard tractors.

**Table 17. Class 8 yard tractor breakdown of weight contributions by major vehicle component.**

| Conventional Diesel | Weight Contribution (lbs.) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Major Component** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Transmission | 794 | 794 | 794 | 794 | 794 | 794 | 794 |
| Fuel Storage | 510 | 510 | 510 | 510 | 510 | 510 | 510 |
| Diesel Engine | 1,619 | 1,619 | 1,619 | 1,619 | 1,619 | 1,619 | 1,619 |
| Glider | 19,847 | 19,847 | 19,847 | 19,847 | 19,847 | 19,847 | 19,847 |
| **HDFC** | **Weight Contribution (lbs.)** | | | | | | |
| **Major Component** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Transmission | 794 | 794 | 794 | 794 | 794 | 794 | 794 |
| Motor & Electronics | 148 | 118 | 104 | 90 | 75 | 61 | 46 |
| Auxiliary Battery | 447 | 412 | 395 | 379 | 363 | 347 | 331 |
| Fuel Storage | 983 | 808 | 774 | 742 | 713 | 686 | 661 |
| Fuel Cell | 463 | 436 | 431 | 426 | 421 | 416 | 412 |
| Glider | 19,847 | 19,847 | 19,847 | 19,847 | 19,847 | 19,847 | 19,847 |

### 3.1.2 Weight Breakdown: Class 8 Refuse Trucks

The same powertrain sizing methodology was applied to the Class 8 refuse trucks. The weight breakdown for the diesel, HDFC, and CNG powertrain options can be seen in Figure 18. As expected, the diesel engine and the hydrogen fuel storage are the major contributors to the weight breakdown outside of the glider mass, similar to the yard tractors. For the CNG powertrain option, both the fuel storage and the CNG engine play a significant role in contributing to the weight. This is because the CNG engine has some added engine weight to account for the CNG fuel change and the heavier fuel storage (as compared to diesel) is due to the reinforced materials needed to store the compressed gas at the needed pressure. As seen with yard tractors, the total fuel cell system projects to be a lighter system by weight overall when compared to the diesel and CNG systems. Table 18 is also included for a more specific viewing of the weight contributions brought on by each major vehicle component for all three powertrain types considered.

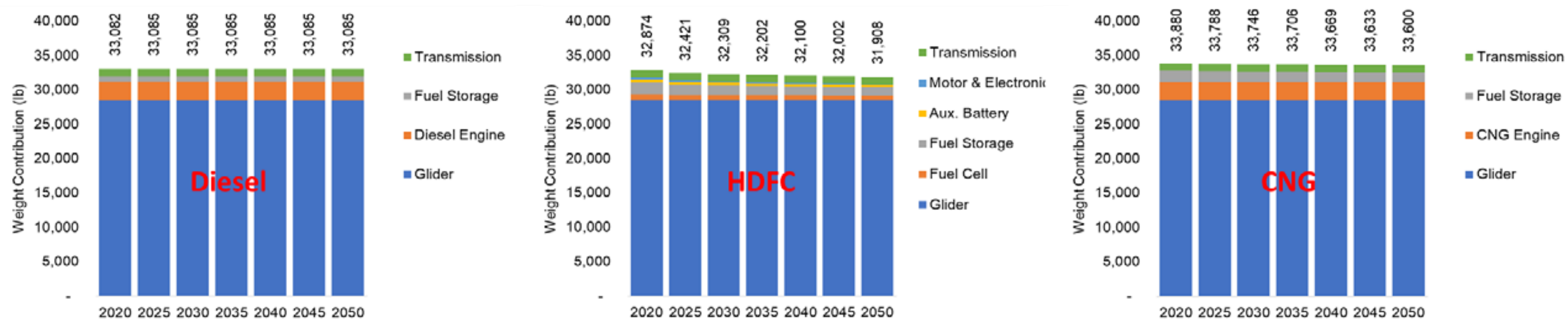


**Figure 18. Weight breakdown for the Class 8 refuse truck for diesel, HDFC, and CNG powertrain options.**

**Table 18. Class 8 refuse truck breakdown of weight contributions by major vehicle component.**

| Conventional Diesel | Weight Contribution (lbs.) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Major Component** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Transmission | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 |
| Fuel Storage | 765 | 765 | 765 | 765 | 765 | 765 | 765 |
| Diesel Engine | 2,731 | 2,731 | 2,731 | 2,731 | 2,731 | 2,731 | 2,731 |
| Glider | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 |
| **HDFC** | **Weight Contribution (lbs.)** | | | | | | |
| **Major Component** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Transmission | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 |
| Motor & Electronics | 250 | 200 | 175 | 151 | 127 | 103 | 78 |
| Auxiliary Battery | 447 | 412 | 395 | 379 | 363 | 347 | 331 |
| Fuel Storage | 1,807 | 1,486 | 1,423 | 1,365 | 1,311 | 1,262 | 1,216 |
| Fuel Cell | 781 | 735 | 726 | 718 | 710 | 702 | 694 |
| Glider | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 |
| **CNG** | **Weight Contribution (lbs.)** | | | | | | |
| **Major Component** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Transmission | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 | 1,071 |
| Fuel Storage | 1,613 | 1,521 | 1,480 | 1,440 | 1,403 | 1,367 | 1,333 |
| CNG Engine | 2,677 | 2,677 | 2,677 | 2,677 | 2,677 | 2,677 | 2,677 |
| Glider | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 | 28,518 |

### 3.1.3 Projected Fuel Economy

The representative duty cycles and vehicle specifications (e.g., frontal area, rolling resistance, drag coefficient) described in Section 2.2 above are used as inputs into FASTSim to estimate each vehicle's fuel economy. Figure 19 shows the estimated fuel economies for the conventional diesel and HDFC Class 8 yard tractor with a 200-mile range and a payload capacity of approximately 39,300 lbs. To validate the model, a benchmark fuel economy of 3.4 miles per diesel gallon equivalent (mpdge) was used to compare model fuel economy results for 2020. This benchmark value was based on real-world data from representative yard tractors studied by NREL at the Port Authority of New York and New Jersey (Kotz et al. 2020). Figure 19 shows the average fuel economy projections for the HDFC are roughly three times greater than fuel economy for the conventional diesel vehicle, due to the fuel cell's higher operational powertrain efficiency (refer to Table 11 for average engine efficiencies) during the yard tractor duty cycle, which includes numerous starts and stops and spends a significant amount of time idling while loading and unloading cargo. HDFC yard tractor fuel economy trends towards improvement into future technology years as HDFCs are projected to become lighter and more efficient[14]. Diesel yard tractor fuel economy also realizes an improvement as new diesel regulations come online and push diesel powertrains to become more efficient in the near-term[15].

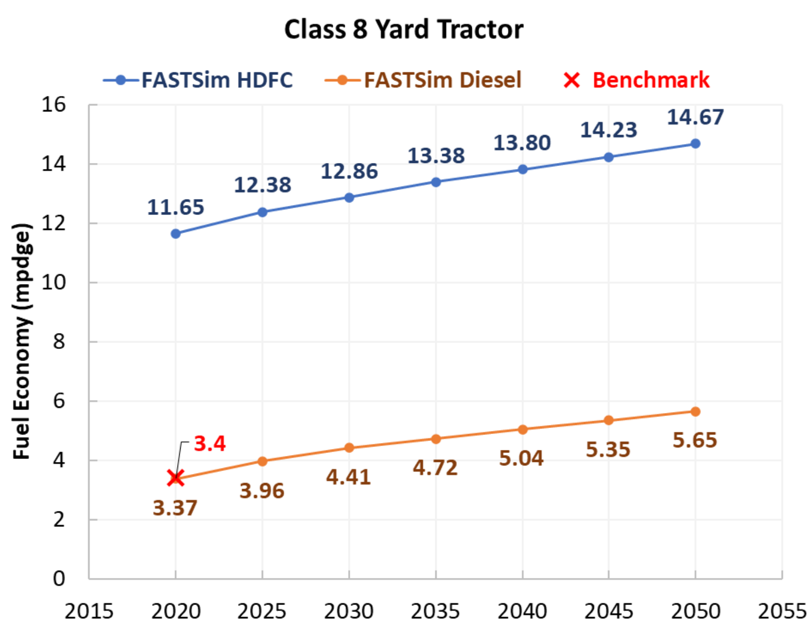


**Figure 19. Fuel economy projections out to 2050 for Class 8 Yard Tractors (200-mile range) for conventional diesel and HDFC powertrains.**

Figure 20 shows the FASTSim-projected fuel economies for the conventional diesel, CNG, and HDFC Class 8 refuse truck with a 190-mile range and payload capacity of approximately 17,000 lbs. A benchmark diesel fuel economy for real-world refuse trucks was set at approximately 2-3[16] mpdge in

[14] Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan
[15] Diesel Fuel Standards and Rulemakings
[16] Alternative Fuels Data Center: Average Fuel Economy by Major Vehicle Category

2020 to validate the FASTSim model. Our 2020 diesel refuse truck (Figure 20) fuel economy is between 2-3 mpdge, confirming our vehicle model and model inputs. As was seen with the yard tractors, HDFC refuse truck projects to have a fuel economy of approximately three times that of the conventional diesel. Again, this is due to the fuel cells powertrain efficiency (refer to

Table 12 for average engine efficiencies) during the duty cycle of the refuse truck, which includes numerous starts and stops and idling times during trash collection; a major component of the truck's cycle. CNG realizes a slightly higher fuel economy relative to diesel during the timeframe between 2020 and 2030 as CNG engines operate more efficiently than diesel engines. But the two come to near parity in 2030 and 2035 as projected improvements in diesel engines outpace improvements in CNG technology. Diesel becomes more efficient beyond 2035 as diesel engines are projected to continue to become more efficient in future technology years.

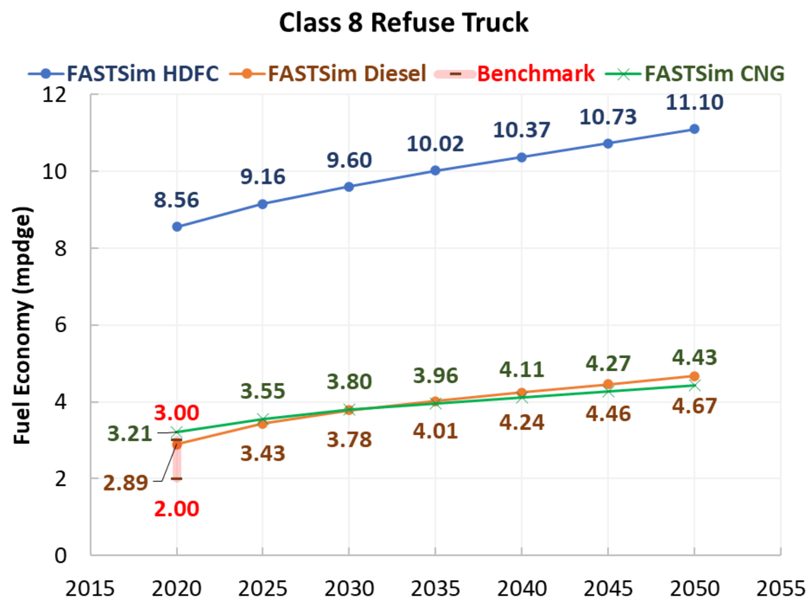


**Figure 20. Fuel economy projections out to 2050 for Class 8 Refuse Trucks (200-mile range) for conventional diesel, CNG, and HDFC powertrains.**

The modeled fuel economies shown in Figure 19 and Figure 20 were used to approximate the fuel consumption for each vehicle and therefore helps determine the projected fuel expense component to the TCO analysis.

### 3.1.4 Vehicle MSRP

The cost projections in Table 13 and the size requirements set for the powertrain components are used to help determine the baseline cost of each vehicle and powertrain option. FASTSim uses the default cost markup factor of 1.5x and purchase tax to project an estimated MSRP. The component cost breakdown can be referenced at the beginning of Section 3.1. Figure 21 shows the projected MSRP for the conventional diesel and HDFC Class 8 yard tractor. During the timeframe of 2020 through 2030, the hydrogen fuel cell and fuel storage adds significant cost to the MSRP, making the HDFC yard tractor more expensive up front versus the conventional diesel option. As HDFC powertrain costs are assumed to approach DOE tech targets, the projected MSRP of the HDFC yard tractor reduces and approaches cost parity with conventional diesel yard tractors.

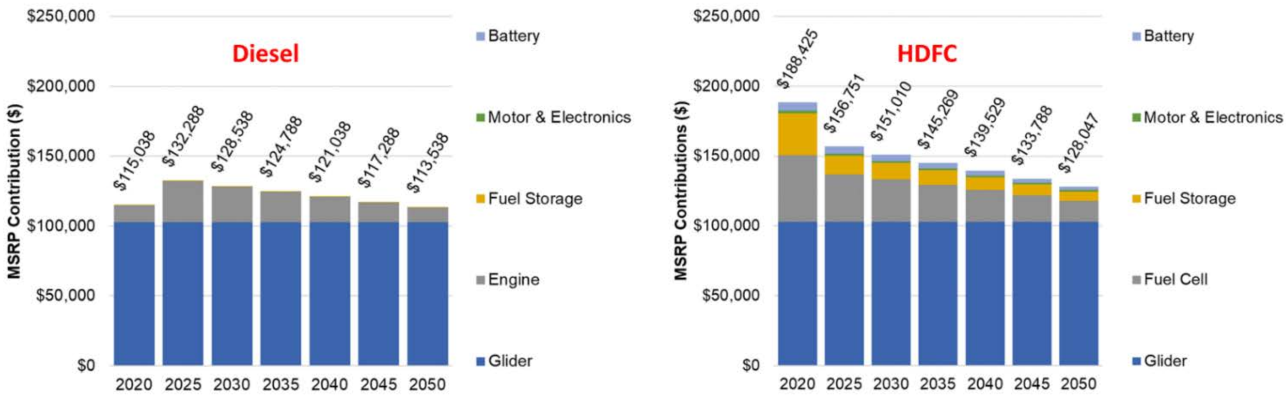


**Figure 21. MSRP projections for conventional diesel and HDFC Class 8 yard tractors from 2020 to 2050.**

Figure 22 displays the projected MSRP breakdown for the conventional diesel, CNG, and HDFC Class 8 refuse truck. Again, the high cost of fuel cells and fuel storage in the early years of the projection make the MSRP of the HDFC option much more expensive versus the conventional diesel and CNG option for refuse trucks. As these component costs are also assumed to come down over time, however, the HDFC refuse truck trends down towards cost parity with the other two powertrains. The CNG refuse truck tracks nearly identically with the conventional diesel for the glider plus engine cost, but the advanced storage needed for the fuel adds a significant cost to the CNG refuse truck MSRP; making it more expensive than the diesel refuse truck over the entire modeled time series.

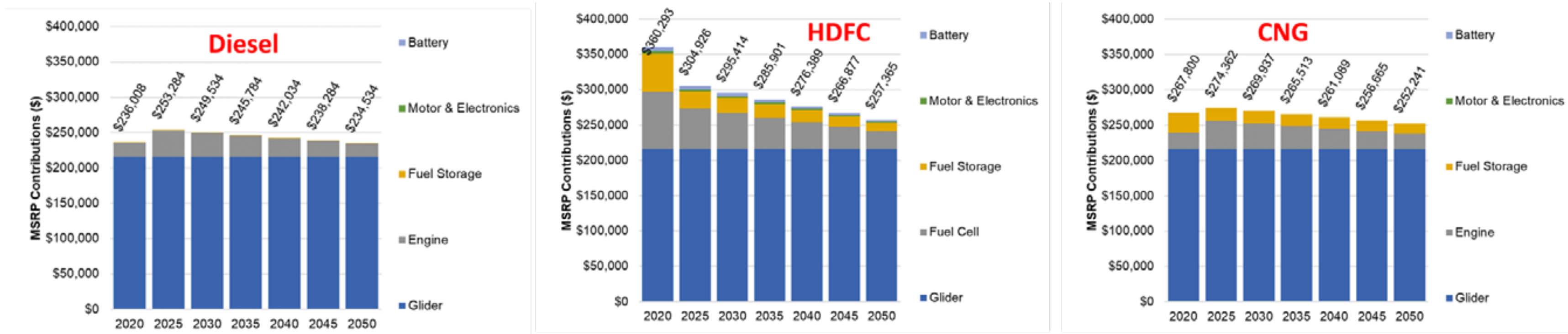


**Figure 22. MSRP projections for conventional diesel, CNG, and HDFC Class 8 refuse trucks from 2020 to 2050.**

For the diesel scenario presented in Figure 21 and both the diesel and CNG scenarios presented in Figure 22, the engine cost experiences an uptick in total cost between 2020 and 2025. This is driven by assumed powertrain efficiency improvements (e.g., increased production costs and performance enhancements) expected to be made in the near-term to meet emissions and fuel economy regulations[17].

These projections suggest that, in the near-term, relatively high costs of hydrogen fuel cell power components may continue to be a barrier for HDFC vehicle adoption in each of these segments. Progress towards achieving DOE component cost targets, greater fuel cell market adoption across all sectors, and increased manufacturing economies of scale will help drive hydrogen-related costs down. But costs will need to decrease at an accelerated rate, relative to the projected costs assumed in this analysis, to have a competitive MSRP in the near future. However, as we discuss in the next section, cost savings in other areas may lead to lower near-term TCO for HDFC vehicles relative to their conventional counterparts for some applications, despite the higher upfront purchase costs we present in this section.

## 3.2 Total Cost of Ownership

Section 3.2 describes the results of the TCO analysis for both the Class 8 yard tractor and Class 8 refuse truck. TCO results presented in this section are comprised of the total MSRP (shown in Section 3.1.4), the projected O&M cost, and the fuel price (determined by fuel consumption combined with fuel prices referenced in Table 14).

### *3.2.1 TCO Projections: Class 8 Yard Tractors*

For Class 8 yard tractors, the model assumes a 10-year operating life at 16,000 miles per year. Our FASTSim modeling assumes a discount rate of 4.1% for the purposes of this study; a default discount rate used in this version of FASTSim. Figure 23 presents the projected total cost of ownership of both the conventional diesel and HDFC Class 8 yard tractors in thousands of dollars (USD).

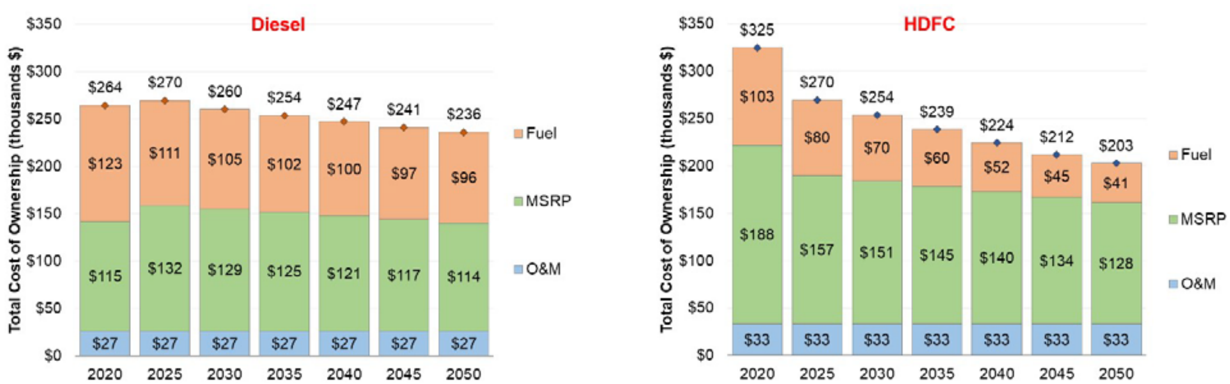


**Figure 23. Total cost of ownership (TCO) projections for conventional diesel and HDFC Class 8 yard tractors projected from 2020 to 2050.**

Because of the lower powertrain efficiency and expected fuel economy for conventional diesel, projected diesel fuel costs are greater than the fuel costs for the HDFC yard tractor. This gap grows over time in favor of HDFC TCO as the assumed cost of hydrogen and efficiency of fuel cells both improve. While the modeled 2020 HDFC yard tractor achieves only a $20,000 fuel cost savings relative to its

[17] Diesel Fuel Standards and Rulemakings

diesel equivalent, the modeled 2030 HDFC achieves a $35,000 savings. This projected advantage grows to $55,000 by 2050. These results demonstrate that, if hydrogen fuel prices continue to decline as they have in recent years, and meet future DOE targets, the drop in hydrogen fuel costs would be significant. This would greatly influence TCO for a HDFC yard tractor, leading to nearer-term TCO parity with the conventional diesel tractor.

2020 MSRP estimates for HDFCs see a roughly a $30,000 decrease heading towards 2025 as manufacturing rates and end use applications for hydrogen fuel cells increase. However, cost drops from 2025 to 2050 level off to approximately $6,000 per 5-year increment as market adoption settles in and manufacturing trends towards production capacity. 2025 diesel MSRP estimates realize an increase from 2020 MSRP projections, which again is a result of anticipated powertrain improvements needed to adhere to EPA emission standards and regulations.

Both diesel and HDFC O&M cost projections remain static throughout this simplified TCO calculation as future O&M projections for these vehicle types are not readily available. Understanding improvements around HDFC reliability could help lower O&M costs, further reducing the estimated TCO.

Figure 24 summarizes the TCO of the two yard tractor powertrain options to demonstrate the potential tech year in which the HDFC yard tractor can become cost competitive with the conventional diesel tractor. Based on our estimations, HDFC yard tractors have the potential to achieve cost parity with diesel yard tractors as early as 2025. Beyond 2025, we project that HDFC yard tractor will continue to see a reduction in overall TCO, ultimately reaching approximately a $33,000 total cost advantage over diesel yard tractors.

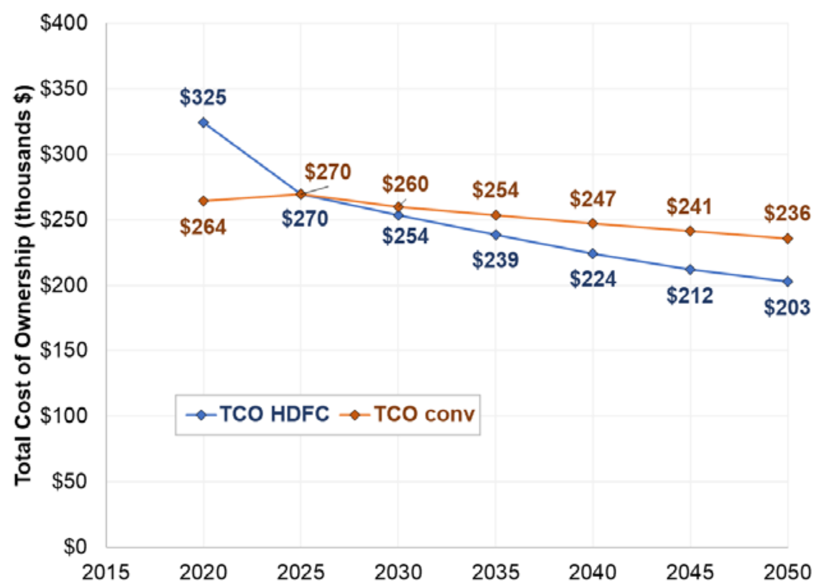


**Figure 24. Total cost of ownership comparison for the conventional diesel and HDFC Class 8 yard tractor.**

### 3.2.2 TCO Projection: Class 8 Refuse Trucks

For Class 8 refuse trucks, the model assumes a 10-year operation at 25,000 miles per year. The same FASTSim default discount rate of 4.1% is assumed again as an input for the model. Figure 25 presents the projected total cost of ownership for the conventional diesel, CNG, and HDFC Class 8 refuse truck in thousands of dollars (USD).

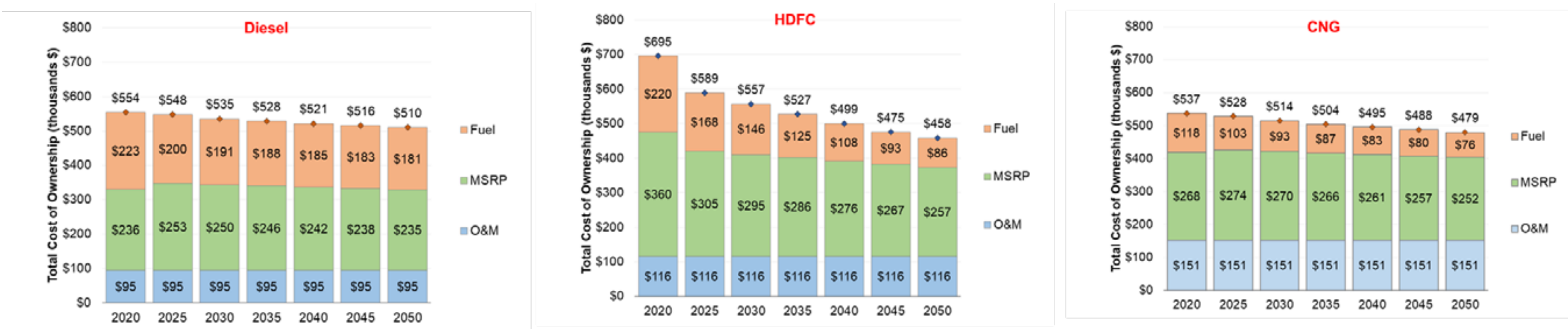


**Figure 25. Total cost of ownership (TCO) projections for conventional diesel, CNG, and HDFC Class 8 refuse trucks projected out to 2050 (ultimate).**

As was seen for the Class 8 yard tractors, the more efficient hydrogen fuel cell helps yield a lower fuel consumption and therefore a lower relative fuel cost basis for the HDFC refuse truck compared to diesel. This fuel cost advantage over diesel continues to become more pronounced for HDFCs beyond 2020 as hydrogen production and end-uses increases. The projected diesel refuse truck MSRP and O&M cost are modeled to remain lower than HDFC throughout the model timeframe, but the fuel savings observed with hydrogen fuel are significant enough to allow HDFCs the potential to achieve cost parity with diesel in the mid- to long-term future.

CNG trucks project to have fuel costs approximately $100,000 less than diesel, but the higher projected MSRP and O&M cost of the CNG trucks cause the CNG trucks to only have a TCO roughly $20,000-30,000 less than its diesel counterpart. Similarly, the CNG truck has lower MSRP, and fuel costs compared to HDFCs, but the higher O&M costs give the HDFC an opportunity to achieve a lower TCO in the long-term.

As with yard tractors, diesel, HDFC, and CNG O&M cost projections remain static throughout this simplified TCO calculation as future O&M projections for these vehicle types are not readily available. Understanding improvements around HDFC reliability could help lower O&M costs, further reducing the estimated TCO.

Figure 26 summarizes and highlights the projected TCO for each of the three powertrain options as well as indicates the potential tech year in which the HDFC could realize cost parity with the conventional diesel and CNG powertrains. Our models estimate that HDFC refuse trucks could achieve cost parity with the conventional diesel and CNG truck around the years 2035 and 2040, respectively. CNG trucks are projected to have a lower overall TCO compared to diesel throughout all analysis years. Both powertrains have a similar cost basis, but CNG takes advantage of the significantly lower fuel costs. Improvements around O&M data for each vehicle type can help aid this TCO analysis and provide further understanding about near-term projections for HDFCs in the refuse truck sector.

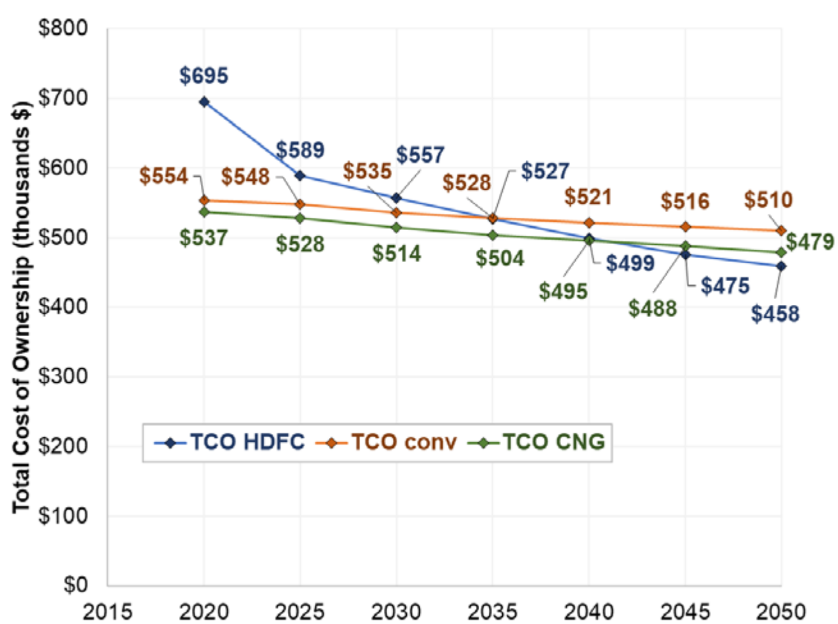


**Figure 26. Total cost of ownership comparison for the conventional diesel, CNG, and HDFC Class 8 refuse trucks.**

# 4 Discussion

This report presents scoping-level vehicle performance and TCO results for two Class 8 vocational vehicles: a Class 8 U.S. port-side yard tractor and a Class 8 U.S.-based refuse truck. This completed work can serve as a complementary extension to other TCO work performed by NREL within the medium- and heavy-duty vehicle segments (Hunter et al. 2021; Hunter and Laboratory 2019; Brooker et al. 2021). The goal of this analysis was to help direct future analytical approaches and to identify opportunities for advanced powertrains within the selected Class 8 vocational segments. In this section, we summarize and discuss the key findings within this report can be found in the subsequent sections.

## Vehicle Performance and Modeling

Results for vehicle modeling include design (e.g., component sizing), weight, duty cycle characteristics, fuel economy, and upfront purchase price. The MSRP results presented in Section 3 and discussed here do not necessarily represent cost and pricing strategies that may be employed by OEMs, nor do they necessarily cover potential sales mandates or other technology-forcing policies which may be issued by governments for the vehicle segments discussed in this report (our results do however consider current federal emissions and fuel economy standards for these vehicles). These results offer beneficial insights into the relative costs associated with each powertrain type for both the Class 8 yard tractor and Class 8 refuse truck.

- **Yard Tractor MSRP:** In the 2020 timeframe, our results project the HDFC yard tractor to be approximately 64% more expensive than the conventional diesel tractor. This drops steadily to approximately 13% in the ultimate tech year of 2050. This is largely due to the expected cost decrease in fuel cells and hydrogen fuel storage systems caused by increased hydrogen market adoption and increased manufacturing of hydrogen fuel cell systems. For yard tractor applications, the fuel cell and fuel storage system are the largest contributors to the observed price premium. Therefore, the MSRP is highly dependent on the powertrain component sizing. Our MSRP results are based on a generalized set of yard tractor assumptions and duty cycle. Other niche use cases and vehicle performance metrics for yard tractors could vary the powertrain sizing significantly, resulting in a decrease or increase in MSRP. For example, duty cycles requiring fewer starts and stops, minimal idling, higher VMTs, or towing above average cargo loads may result in a larger fuel cell system needed to achieve the overall duty cycle, yielding a higher MSRP projection. Conversely, reducing the fuel cell system for yard tractors requiring a less demanding duty cycle could further decrease the MSRP compared to diesel MSRP. To fully understand the magnitude of the effects performance requirements has on powertrain sizing and MSRP, a future sensitivity analysis could be added as an extension of this analysis.
- **Refuse Truck MSRP:** In the 2020 timeframe, our results project the HDFC refuse truck to be approximately 53% more expensive than the conventional diesel truck and 35% more expensive than the CNG truck. The CNG truck is approximately 14% more expensive than the conventional diesel truck in 2020 as well. By 2050, the projected upfront price premium drops for the HDFC truck and is approximately only 10% more expensive than the conventional diesel truck and 2% more expensive than the CNG truck. As with yard tractors, the cause for this decrease in MSRP for the HDFC is related to the projected reductions in component costs, driven by increased market adoption, technological learning, and production economies of scale for hydrogen fuel cells and hydrogen-related systems. The CNG truck projects to always be slightly

more expensive than the diesel truck. This is likely due to the fact that CNG engines tend to have cost parity with diesel engines, but CNG storage systems will likely always be more intricate systems requiring higher-end materials and designs. Again, similar to the yard tractors, the modeled results are based on generalized, representative duty cycles that can't fully capture all operational use cases for refuse trucks. Other duty cycles and performance characteristics could change the resulting MSRP for each powertrain type. More demanding duty cycles and performance for refuse trucks (e.g., more rural applications or higher average cargo loads) could be a disadvantage for fuel cells, resulting in larger powertrain requirements and increasing MSRP. Less demanding applications (e.g., urban settings with more starts and stops or higher idling times) could help reduce fuel cell system requirements and sizing, which could aid in decreasing the HDFC refuse truck MSRP compared to the diesel truck. An in depth duty sensitivity analysis could be added to this analysis to further understand the full effects both duty cycle and vehicle performance requirements have on powertrain sizing and the resulting MSRP.

- **Yard Tractor Duty Cycle:** The representative yard tractor duty cycle used in this study demonstrates that average yard tractors have high idle times, numerous starts/stops, operate at relatively low power outputs, don't experience significant gradients, and aren't required to achieve high acceleration. These operational characteristics are favorable for HDFCs as fuel cells typically achieve peak efficiency at lower percentages of total power output. Like battery electric vehicles, when the HDFC tractor idles or comes to a complete stop, the fuel cell consumes little to no energy; therefore, preserving fuel reserves (assuming insignificant amounts are used for power take-off or auxiliary power such as air conditioning). Conversely, diesel powertrains achieve higher efficiencies at higher percentages of total power output. Since yard tractors don't operate for long durations at maximum power output potential, diesel powertrains may not be the best option for operators and fleet owners. Yard tractors have relatively low VMTs compared to other segments in the heavy-duty space, further yielding an overall low fuel consumption and fuel cost potential for HDFCs. Additionally, yard tractors are centralized, off-road fleets that can take advantage of centralized, on-site refueling with minimal interruptions. This can allow HDFC yard tractors to reduce and optimize powertrain sizing while still meeting operation requirements. Centralized refueling can also capture refueling for other on-site vehicles, which ultimately helps drive infrastructure, fuel, and vehicle costs down. Further investigation into infrastructure planning and development can be added to this analysis to go beyond a simplified TCO for yard tractors.
- **Refuse Truck Duty Cycle:** Similar to yard tractors, the representative refuse truck duty cycle observed in this study demonstrates that refuse trucks can also have higher than average idle times, numerous starts/stops (during trash collection), and spend a relatively large amount of time at lower power outputs. However, since refuse trucks are on-road vehicles, these trucks can experience variable road gradients and need to meet the acceleration needs of on-road driving. The operational characteristics during trash collection are favorable for fuel cells for the same reasons mentioned in the previous bullet point for yard tractors. Highway driving and times when trucks need to operate at higher power outputs could favor the diesel and CNG powertrains more than the HDFCs. CNG trucks are starting to gain significant market share within the refuse truck segment because CNG engines offer similar advantages to diesel engines with lower fuel prices and slightly better fuel economy. Refuse trucks may not be as flexible as yard tractor with regards to powertrain size optimization as individual refuse trucks may experience a wide variety of duty cycles day-to-day. However, like yard tractors, refuse trucks are typically centralized fleets that can take advantage of centralized refueling depots, a beneficial trait for hydrogen

refueling infrastructure. These fleets could allow other vehicles (vocational or retail) have access to hydrogen refueling, which could further decrease the overall fuel prices within refuse truck TCO. Again, further investigation is needed to understand how infrastructure affects refuse truck TCO to a full extent.

- **Yard Tractor Fuel Economy:** Our results project that HDFC yard tractors would achieve a fuel economy approximately 3.5x that of their diesel equivalent in the year 2020, under the conditions we assumed, and approximately 2.6x greater in the ultimate year 2050. This slight decline in fuel economy edge is likely due to the expected increases in diesel fuel economy projected in the near future with new rule making and advancements in diesel engines. Varying the yard tractor duty cycle and assumed cargo load could greatly affect the overall fuel economy. For example, increasing average cargo weight would require the yard tractor to experience a higher average power output, which could cause the HDFC to be less efficient and the diesel powertrain more efficient. As a result, this would reduce the gap between the HDFC and diesel powertrain projected fuel economies. Conversely, decreasing average cargo weight could push the HDFC to higher overall efficiency; giving the HDFC an even greater fuel economy advantage over the diesel powertrain. As HDFC yard tractors make their way into port fleets, operators could focus on optimizing cargo loads and duty cycles to capture a best-case fuel economy, which helps lower the overall TCO for these fleets.
- **Refuse Truck Fuel Economy:** In 2020, HDFC refuse trucks have a fuel economy that is approximately 3x greater than diesel and 2.6x greater than CNG. By 2050, the fuel economy for HDFC trucks could be approximately 2.4x greater and 2.5x greater than diesel and CNG trucks, respectively. The lower magnitude of the fuel economy increase for HDFCs over diesel and CNG with respect to yard tractors is because of the operational characteristics mentioned above in the previous bullet about the refuse truck duty cycle. The highway driving and higher power output instances refuse trucks experience allow for diesel powertrains to realize moments of higher efficiencies relative to fuel cell performance. Refuse trucks experience a wide variety of cargo weights, which can give way to highly variable fuel economies. Similar to yard tractors, increasing cargo weight would require higher power outputs (advantage diesel powertrains) and decreasing cargo weight would require lower power outputs (advantage HDFC). Better capturing these characteristics on a fleet-by-fleet basis could help determine fuel economies and TCO results for individual fleets and fleet operators. Urban and rural duty cycles can affect fuel economy. Urban fleets may never experience highway driving and have lower average speeds, power output, and starts and stops. These attributes would further lean in favor of HDFC refuse trucks. Conversely, rural fleets may experience even greater amounts of highway driving times with higher average speeds, power output, and less starts and stops, which could increase diesel and CNG powertrain fuel economy and incentive fleet owners to opt for these powertrains for their fleets.

## Total Cost of Ownership Modeling

A summary of the T3CO and total cost of ownership modeling results include the following:

- HDFC yard tractors could be cost competitive and economically viable with diesel tractors potentially as early as 2025 and beyond if hydrogen fuel price, fuel cell, and fuel storage cost targets are achieved.

- HDFC refuse trucks could be cost competitive and economically viable with diesel trucks in the year 2035 and with CNG trucks in the year 2040 if hydrogen fuel price, fuel cell, and fuel storage cost targets are achieved.
- Cost reductions for dispensed hydrogen and fuel cell systems play an important role in HDFC market adoption within the heavy-duty sector as well as decreasing TCO. These cost reductions should be a major focus area for research and development.
- For both HDFC yard tractors and refuse trucks, the fuel cell and fuel storage dominate the MSRP component of the TCO.
- Until HDFCs are widely available on various vehicle types, maintenance for HDFCs will be higher than the diesel counterparts due to the fuel cell's complexity and lower technology readiness.
- Glider and chassis modifications for HDFCs could add more cost implications for each vehicle type studied.

Overall, these results successfully indicate that HDFC applications within the yard tractor and refuse truck segments are viable in terms of both performance and TCO. Fuel cell efficiency maps continue to demonstrate that vehicles with lower average power outputs can reach peak fuel cell efficiency and achieve higher fuel economy projections over more conventional powertrains. We find that yard tractor and refuse truck average duty cycles favor fuel cell performance in large part because their duty cycles share these characteristics. We expect investigations into other vehicle segments with similar duty cycle characteristics should yield similar results and advantages. These types of vocational markets may be optimal early points of entry for HDFCs and fuel cells in general. Coupling these vehicle-specific advantages with potential for centralized refueling for each segment is another promising feature as this promotes lower fuel cost potential and other on- or near-site hydrogen applications; further growing the hydrogen market.

However, this analysis lays out only a simplified TCO analysis and needs to be modified and enhanced to deliver a more in depth analysis for each vehicle. The overarching trend pointing towards cost competitiveness for yard tractors and refuse trucks is promising, but more precise cost data (e.g., O&M, glider) and regionally specific information (e.g., fleet specific duty cycles, climate, VMTs) could help this analysis narrow in on cost figures that fleet operators can realistically expect for their fleets. Other data inputs such as rolling resistance and wheel inertia are defaults for Class 8 long-haul trucks as this type of specific data is not available for either yard tractors or refuse trucks. Obtaining vehicle specific data in these areas could help this analysis produce a more accurate vehicle model for both yard tractors and refuse trucks. Also, for real-world applications of HDFCs for these vehicles, chassis modifications and light-weighting is almost certainly going to be needed for full build outs, which will likely require higher glider and overall MSRP costs for these advanced powertrains. This is not captured in this study at this time as it goes beyond the scope of the funded work.

## Real-World Considerations

The work performed in this analysis is a scoping-level approach to estimate the TCO of each of the studied segments. It is based on a bottom-up approach and does not necessarily reflect the strategies potentially implemented by OEMs. Select representative duty cycles for each vehicle do not encompass all duty cycle types or edge-cases that these vehicles may experience in different locations or under extreme duty cycle circumstances (e.g., extreme climate conditions or rural examples for refuse trucks). The duty cycles for each vehicle are also subject to operator preferences based on specific fleet characteristics or economical decisions that best suit the fleet operation. The transportation energy sector is constantly changing; therefore, logistics and strategies around fleet operation are likely to continue to evolve and adapt quickly. This analysis lays a foundation for TCO assessments based on real-world data and future iterations of this work will depends on future duty cycle considerations and technological advancements within each segment.

# 5 Conclusion

A scoping-level TCO assessment was performed for a U.S.-based Class 8 yard tractor and a U.S.-based Class 8 refuse truck. The assessment includes direct costs (e.g., operation & maintenance, MSRP, and fuel costs) for each vehicle application. The analysis does not include indirect costs such as dwell time cost implications and payload opportunity.

The drive/duty cycles for each of these vehicles aims to represent typical operational characteristics experienced. Favorable operational characteristics for each vehicle could allow for HDFCs to gain significant market share in the near future. Results from the TCO indicate that heavy-duty fuel cells within these segments have the opportunity to achieve cost parity with conventional diesel and CNG (refuse only) powertrains if interim and ultimate targets are achieved.

Both Class 8 yard tractors and refuse trucks have opportunities for centralized refueling, which could present an advantage for electrifying these segments sooner than other segments. U.S. ports specifically could see significant future on-site hydrogen demand, further making HDFC yard tractors a viable vehicle choice at ports.

To continue to complement this analysis, more extensive literature reviews and on-board vehicle data could help fill in data gaps seen in this report.

# 6 Future Work

Since this report presents a scoping-level TCO assessment, many details and facets were either condensed and summarized and/or beyond the scope of this analysis. Future iterations of this work may include:

- Assessment of additional heavy-duty vocational vehicles with similar operation characteristics
- Inclusion of the effects of a centralized refueling infrastructure and fuel demand analysis
- Extreme climate impacts and powertrain power control strategy and optimization
- Further development of representative duty cycles for yard tractors and refuse trucks to encompass greater detail around operation characteristics
- Investigation into fleet regionality and how fleet location and specific operation characteristics can affect performance and TCO for individual fleets
- Varying cargo load characteristics to account for extreme cases
- Capture regenerative breaking and how this affects overall fuel economy for HDFC yard tractors and refuse trucks
- Implication of power take-off and onboard auxiliary power requirements for each vehicle type
- Sensitivity analysis to identify key major contributors to yard tractor and refuse truck TCO
- Real-world, higher fidelity operating and maintenance data specifically for HDFCs within each of these segments

- Obtaining vehicle specific attributes such as wheel inertia, rolling resistance, and frontal area estimations
- Inclusion of dwell time cost implications and payload opportunity
- Inclusion of other financial incentive and policies centered around advance powertrain technologies, Low Carbon Fuel Standards, and zero emission vehicle mandates
- Evaluation beyond expected vehicle lifetime (e.g., resale and salvage value) and other durability assessments

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