ANL/ESD-19/8

Fuel Economy and Cost Estimates for Medium- and Heavy-Duty Trucks

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Energy Systems Division

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NOTATION

ACRONYMS AND INITIALISMS

21CTP	21st Century Truck Partnership
ARB	(California) Air Resources Board
Argonne	Argonne National Laboratory
BEV	battery electric vehicle
BTE	brake thermal efficiency
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency (United States)
FCHEV	fuel cell hybrid electric vehicle
FCTO	Fuel Cell Technologies Office
H_2	hydrogen
HD	heavy duty
HEV	hybrid electric vehicle
HFTO	Hydrogen and Fuel Cell Technologies Office
HR	high roof
ICCT	International Council on Clean Transportation
ISG	integrated starter/generator
LR	low roof
MR	mid roof
NHTSA	National Highway Transportation Safety Administration
NREL	National Renewable Energy Laboratory
PHEV	plug-in hybrid electric vehicle
PnD	pickup and delivery
OEM	original equipment manufacturer
R&D	research and development
U.S. DRIVE	United States Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability

VIUS	Vehicle Inventory and Use Survey
VMT	vehicle miles traveled
VTO	Vehicle Technologies Office

UNITS OF MEASURE

Cd	drag coefficient
DGE	diesel gallon equivalent
gal	gallon(s)
kg	kilogram(s)
kW	kilowatt
kWh	kilowatt-hour(s)
L	liter(s)
mi	mile(s)
mpg	mile(s) per gallon
Wh	watt-hour(s)

ACKNOWLEDGMENTS

Support and guidance from Vehicle Technologies Office (VTO) manager Jacob Ward and Hydrogen and Fuel Cell Technologies Office (HFTO) managers Fred Joseck and Neha Rustagi were essential for completing this analysis.

Technical targets and input for the Program Success cases came from the expert opinions of technology managers at the U.S. Department of Energy. Gurpreet Singh and Ken Howden gave input regarding the Advanced Combustion Engines and Fuels program. Brian Cunningham and Steven Boyd gave input for the Electrification program. Jerry Gibbs and Sarah Kleinbaum gave input related to the Materials Technology program. Jason Marcinkoski and Fred Joseck gave input related to HFTO targets.

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1 INTRODUCTION

The U.S. Department of Energy's (DOE's) Vehicle Technologies Office (VTO) and Hydrogen and Fuel Cell Technologies Office (HFTO) aim to develop sustainable, affordable and efficient technologies for transportation of goods and people. These offices seek to advance DOE investments in advanced transportation component technologies and powertrains that translate to the estimated potential vehicle-level fuel savings contained herein. As part of quantifying these benefits, we have been asked to take a three-decades-long view of the fuel-saving vehicle technologies that will likely be implemented in medium- and heavy-duty trucks. In this work, we focus on technologies funded by VTO and HFTO that we expect to see during this time frame. Simulation was carried out for more than 20 types of trucks, ranging from Class 2 (the smallest medium-duty trucks, which span from Class 2b–6) to Class 8 (the largest heavy-duty trucks, which span Classes 7 and 8). The output of this study provides the fuel consumption and estimated purchase prices for trucks that employ advanced technologies, where both types of output offer a vehicle-level perspective and estimated projections about the future of advanced-technology medium- and heavy-duty trucks, as well as cost and performance data pairs that can inform other advanced transportation studies.

The system modeling and control group at Argonne National Laboratory (Argonne) has developed a series of integrated tools and processes to quickly and efficiently evaluate the impact of advanced vehicle and transportation technologies from a mobility and energy point of view. Argonne's Autonomie is the primary tool for evaluating vehicle energy consumption levels. This tool resulted from collaborative efforts between Argonne and General Motors. This tool has the right level of fidelity required for analyzing the fuel economy benefits of vehicle technologies, and it provides unrestricted access to simulation models and calibration information. Autonomie has undergone extensive reviews from experts in the automotive industry, government, and academia as part of various projects and is widely used in these sectors.

This report quantifies the vehicle-level fuel consumption benefits and changes in vehicle manufacturing cost associated with the improvements in component technologies. We are likely to see these improvements make their way into trucks in the next few decades, and so the projections contained herein extend from 2025 to 2050. The report documents the assumptions and methods used in this analysis. Section 2 details the methodology followed for defining vehicles and estimating the cost and energy consumption rates. In Section 3, the results of vehicle-level modeling and analysis are discussed.

All details of vehicle assumptions and simulation results are available in the spreadsheets accompanying this report.

2 METHODOLOGY

This report covers the simulation techniques used for translating the component-level technology changes to vehicle-level fuel consumption or cost differences. Figure 2-1 illustrates the boundaries of the work described in this report.

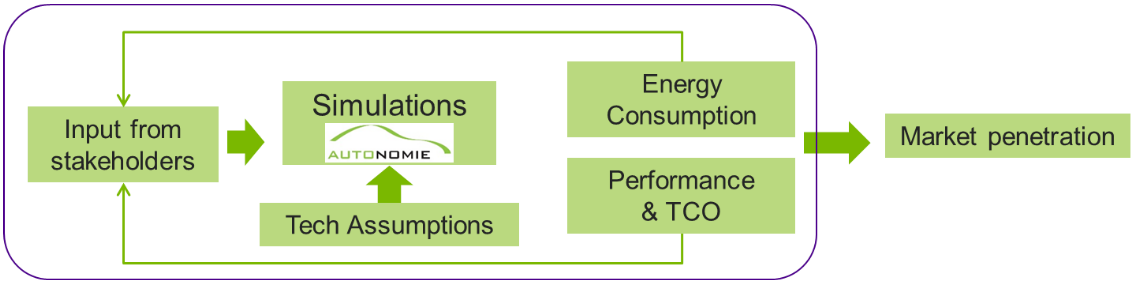

Figure 2-1 Scope of the work described in this report. (Note: TCO = total cost of ownership.)

The first step is the inputs we receive from stakeholders and our assumptions on technology progress levels. Technology managers at DOE, researchers at national laboratories, and other agencies that work on technology forecasts are the primary stakeholders for this effort. They provide us with guidance on the types of vehicles that are of interest. This effort is described in Section 2.1, which, at the end, also briefly explains the appropriateness of using Autonomie for this analysis.

Assumptions are the most important part of any study. We explain ours in Section 2.2, including those related to vehicle sizing, fuel economy estimation, powertrain choices, and technology progress.

2.1 VEHICLE SIZE CLASSES AND FLEET MARKET SEGMENTS

This section describes the process for determining vehicles' input assumptions and executing Autonomie model runs to estimate vehicle-level costs and energy consumption. After an overview of the types of trucks included and the models used, this section details vehicle specifications, drive cycles, and component technology assumptions.

Medium and heavy truck configurations are customized to suit their specific vocations or chief purposes, such that potentially innumerable types of these vehicles operate on America's roads today. This analysis examines a relatively smaller number of vehicle types. As of now, 26 truck types can be simulated using Autonomie. To keep this analysis tractable, only a subset of representative vehicles are modeled herein, as listed in Table 2-1.

Table 2-1 Summary of all types of trucks modeled in Autonomie.

Class	Purpose	U.S. Environmental Protection Agency/National Highway Transportation Safety Administration Regulatory Code
2[a]	*Van*	Light_HD
3	PnD[b]	Light_HD
3	*Van*	Light_HD
3	*School*	Light_HD
3	*Service*	Light_HD
4	PnD	Light_HD
4	*WalkIn*	Light_HD
5	*Utility*	Medium_HD
6	PnD	Medium_HD
6	*Construction*	Medium_HD
7	Tractor	DayCab_HR
7	Tractor	DayCab_LR
7	Tractor	DayCab_MR
7	Vocational	Medium_HD
7	*School*	Medium_HD
8	Tractor	DayCab_HR
8	Tractor	DayCab_LR
8	Tractor	DayCab_MR
8	Vocational	Heavy_HD
8	*Transit*	Heavy_HD
8	*Refuse*	Heavy_HD
8	Tractor	Sleeper_HR
8	BestInClass	Sleeper_HR
8	SuperTruck	Sleeper_HR
8	Tractor	Sleeper_LR
8	Tractor	Sleeper_MR

[a] Use of italics indicates specific makes and models with significant market share in their respective use cases.

[b] PnD = pickup and delivery. HD = heavy-duty; HR = high roof; MR = mid roof; and LR = low roof.

As Table 2-1 also shows, the U.S. Environmental Protection Agency (EPA)/National Highway Transportation Safety Administration (NHTSA) has proposed several regulatory codes for trucks for specifying regulatory fuel consumption analysis (EPA and NHTSA, 2016b): As each truck type has its own officially specified test procedure, this classification is also used in Autonomie to follow the test procedures specified by the EPA.

The list of vehicles in Table 2-1 represents a large segment of the trucks operating in the United States. Based on the information gathered in survey data by the National Renewable Energy Laboratory (NREL) and Vehicle Inventory and Use Survey (VIUS), these trucks cover about 59% of the truck population, 82% of the distance driven, and 85% of the fuel consumed by trucks driven throughout the United States. The class and vocation combinations in italics are modeled based on specific makes and models of trucks that have a significant market share in their respective use cases. The remaining vehicles do not represent a particular make and model but represent a generic truck for that class and vocation.

2.1.1 Models Overview

Autonomie is used to evaluate the energy consumption and cost of advanced powertrain technologies in this work. It has been validated for several powertrain configurations and vehicle classes using Argonne's Advanced Powertrain Research Facility (APRF) vehicle test data (Kim et al. 2009, 2012, 2013; Rousseau et al. 2006; Cao 2007; Rousseau 2000; Pasquier et al. 2001). As part of SuperTruck and various others of the numerous prototyping projects funded by DOE, Autonomie has been updated and validated for medium- and heavy-duty applications as well (Delorme et al. 2010; Karbowski et al. 2010; Zukouski 2015; Kresse 2017; Vijayagopal et al. 2018).

Autonomie has been used to execute multiple studies that guided various departments of the U.S. government in setting targets for future research. More than 175 companies and research entities, including major automotive companies and suppliers, use Autonomie to support their advanced vehicle development programs.

2.2 ASSUMPTIONS

2.2.1 Vehicle Specifications

Assumptions made in vehicle simulations were established with input from VTO and HFTO analysts and technology managers. Additional information and review of some assumptions were provided by industry experts, including industrial partners in the 21st Century Truck Partnership (21CTP), representatives from truck manufacturers, and fleet operators.

Each truck is unique in its functional requirements. The performance capabilities that determine the engine power requirements are rarely advertised for these types of vehicles. However, the engine power rating, transmission ratios, and curb weight are all available from original equipment manufacturers (OEMs). Performance capabilities were estimated through simulations for each category of vehicle. Based on feedback from many of the industry partners, we have identified the following parameters for enforcing performance parity between conventional and more advanced powertrains. They are (1) 0–30-mph acceleration time, (2) 0–60-mph acceleration time, (3) sustainable maximum speed at 6% grade, (4) driving range between refueling/recharging, (5) cargo mass, and (6) maximum cruising speed.

By simulating the conventional vehicle models over various test cycles, the performance requirements for various types of vehicles are determined, as shown in Table 2-2, which also indicates the various vehicle classes, applications, and performance requirements. Although the targets vary depending on size class, all powertrain variants of a given type of truck should meet or exceed these minimum requirements. Please see the EPA rulemaking documents (EPA and NHTSA, 2016a) for the cargo mass used for sizing and fuel economy evaluations.

Table 2-2 Summary of vehicle classes and vocations and their performance requirements considered in this work.

Class	Purpose	Regulatory Code	0–30 mph (s)	0–60 mph (s)	Speed at 6% Grade (mph)	Cruise. Speed (mph)	Daily Driving Range (miles)
2	Van	Light_HD	7	22	65	70	200
3	PnD[a]	Light_HD	9	30	50	70	150
3	Van	Light_HD	6	24	49	70	200
3	School	Light_HD	6	20	60	70	150
3	Service	Light_HD	6	18	65	70	150
4	PnD	Light_HD	9	30	50	70	150
4	WalkIn	Light_HD	8	35	40	70	150
5	Utility	Medium_HD	9	24	65	65	150
6	PnD	Medium_HD	14	50	37	70	150
6	Construction	Medium_HD	12	47	27	65	150
7	Tractor	DayCab_HR	18	66	31	65	250
7	Tractor	DayCab_LR	18	66	31	65	250
7	Tractor	DayCab_MR	18	66	31	65	250
7	Vocational	Medium_HD	18	66	25	60	200
7	School	Medium_HD	19	60	30	60	150
8	Tractor	DayCab_HR	18	66	31	65	250
8	Tractor	DayCab_LR	18	66	31	65	250
8	Tractor	DayCab_MR	18	66	31	65	250
8	Vocational	Heavy_HD	18	76	30	60	200
8	Transit	Heavy_HD	17	50	28	60	150
8	Refuse	Heavy_HD	20	100	24	50	150
8	Tractor	Sleeper_HR	18	60	32	65	500
8	BestInClass	Sleeper_HR	16	52	34	60	500
8	SuperTruck	Sleeper_HR	20	60	34	60	500
8	Tractor	Sleeper_LR	18	60	32	65	500
8	Tractor	Sleeper_MR	18	60	32	65	500

[a] PnD = pickup and delivery; HD = heavy-duty; HR = high roof; MR = mid roof; and LR = low roof.

Performance capabilities for vehicles were chosen to include both transient and continuous power requirements, as shown in Figure 2-2. While a motor might meet the acceleration requirement with its peak power rating, the motor power output over a prolonged grade will be reduced to roughly half of the peak power rating. This factor is important enough to be considered specifically while sizing the components for commercial trucks with electric drivetrains.

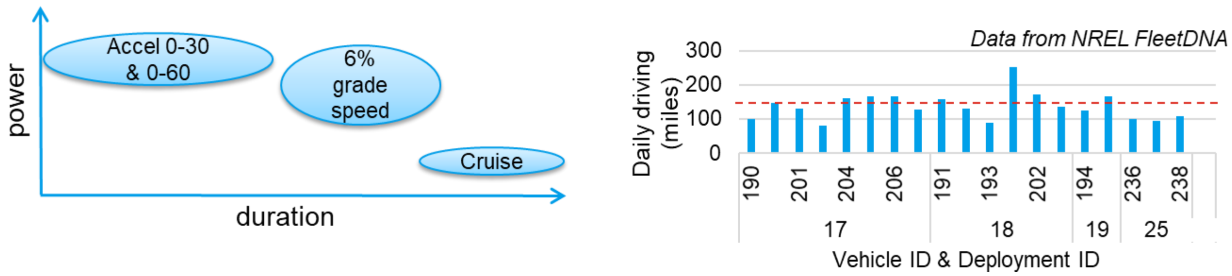

Figure 2-2 Overview of the performance parameters considered in this work.

2.2.2 Drive Cycles

The EPA and NHTSA have put forth compliance procedures for medium- and heavy-duty vehicles (EPA and NHTSA 2016a). This rule specifies the three drive cycles, shown in Figure 2-3, that are used to evaluate different operational conditions.

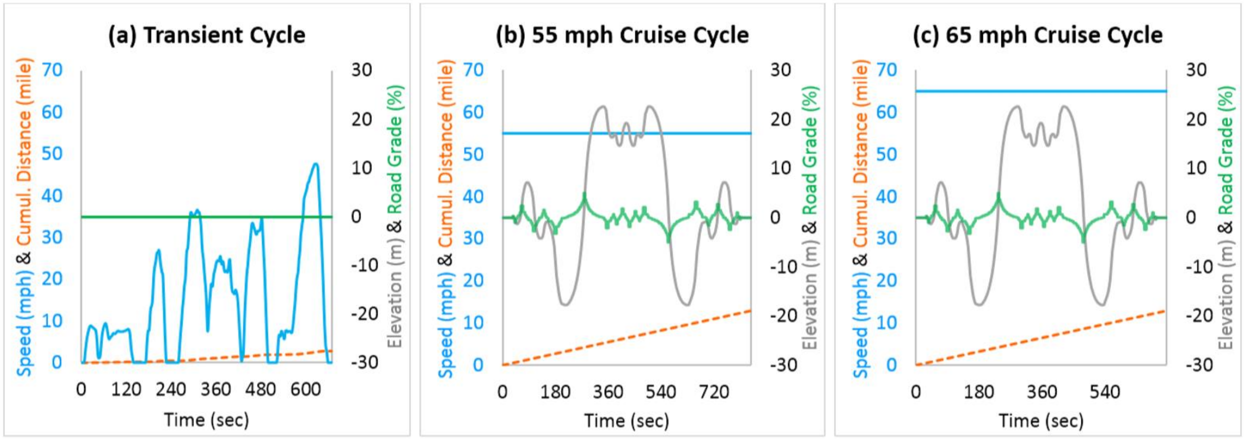

Figure 2-3 Drive cycles used for evaluating fuel consumption of medium- and heavy-duty cycles.

In addition to these cycles, other driving conditions were simulated for sizing tests. A grade test was simulated using a proxy of the Davis Dam grade in Arizona: an 11-mile-long drive with a steady 6% grade. The maximum sustainable speed was treated as the grade speed benchmark for the vehicle.

Acceleration tests were simulated to determine the time taken for the vehicle to achieve speeds of 30 and 60 mph. For heavy vehicles, acceleration times are much longer than those normally found in light-duty vehicles.

2.2.3 Powertrains

This work looked at five different powertrain configurations for trucks, with varying degrees of hybridization. The component layouts of those powertrains are shown in Figure 2-4. Conventional vehicles in this report are similar to today's diesel trucks. The mild hybrid (integrated starter/generator or ISG) adds start-stop functionality to avoid idling. Parallel pre-transmission architecture allows for more regenerative braking, effective assistance to the engine by motor, or even an electric-only launch or coast, if the battery and motor conditions permit.

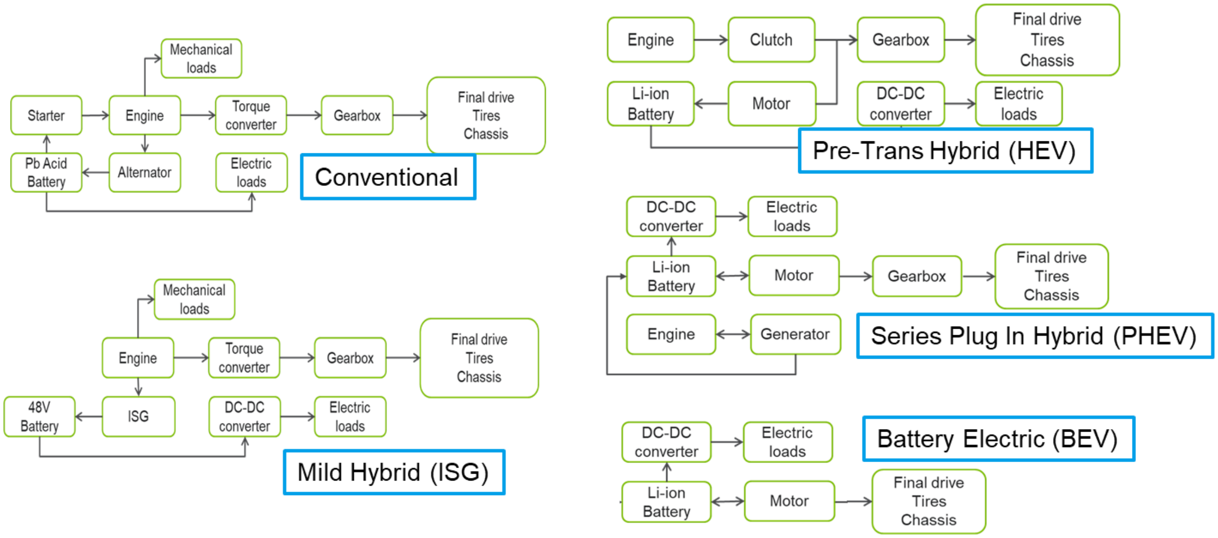

Figure 2-4 Component layout in powertrain architectures considered in this work

2.2.4 Component Technologies

Key performance parameters were identified for each component based on its impact on the overall energy consumption of the vehicle. These are summarized in Figure 2-5.

Technology managers at DOE who are responsible for specific research areas provided us their best estimates on how their respective technology areas will evolve over the next few decades. A "Business as Usual" (Low) scenario is provided where technology will progress at a pace seen from historic trends; and a program success case is provided to show the level of improvement targeted (High) by DOE through various research initiatives.

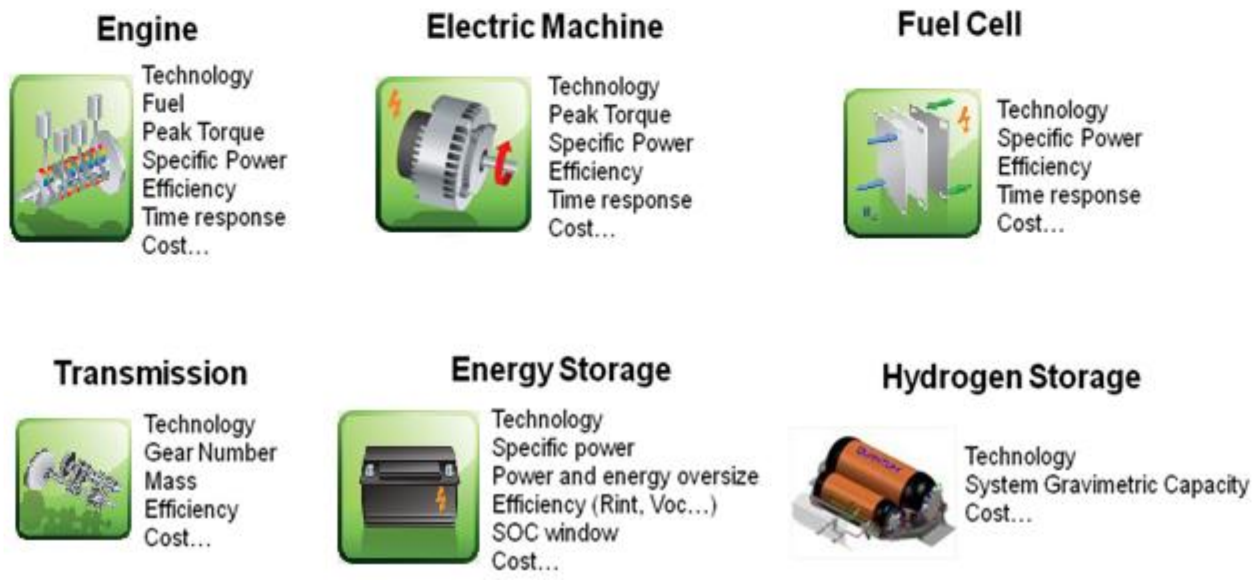

Figure 2-5 Component-specific parameters that affect energy consumption and operating cost estimation.

Although there are more than 25 types of trucks modeled in this work, the component assumptions are largely set using the regulatory code; for example, assumptions for improvements expected in light HD vehicles are used on vehicles that share that regulatory code, as shown in **Error! Reference source not found.**.

2.2.4.1 Engine

This study focuses on diesel engines, which is consistent with DOE's engine research program for heavy trucks and associated goals.

VTO research and development (R&D) helped demonstrate 50% brake thermal efficiency (BTE) on Class 8 trucks through the SuperTruck program. The goal for the SuperTruck II project is a 55% BTE engine at a 65-mph cruise point on a dynamometer (EERE-VTO 2016). DOE anticipates that close to 60% BTE is attainable by 2050, with continued R&D (Singh 2011).

We expect that the technologies developed to achieve these targets will help improve smaller engines, as well. Based on these targets, and the goals available for smaller diesel engines from the VTO's U.S. DRIVE Partnership (U.S DRIVE 2018), we developed assumptions for engines that are needed for different types of trucks. The assumed peak engine efficiencies and incremental engine costs are shown in Figure 2-6 for vehicles in each size class and application for the DOE target case shown as "High" and the business-as-usual case is shown as "Low.

Although the VTO targets do not define the costs associated with these technologies, an EPA and NHTSA (2016b) analysis of the cost implications of the Phase II rule making served as a guide to estimating the engine cost impact of achieving the efficiency targets.

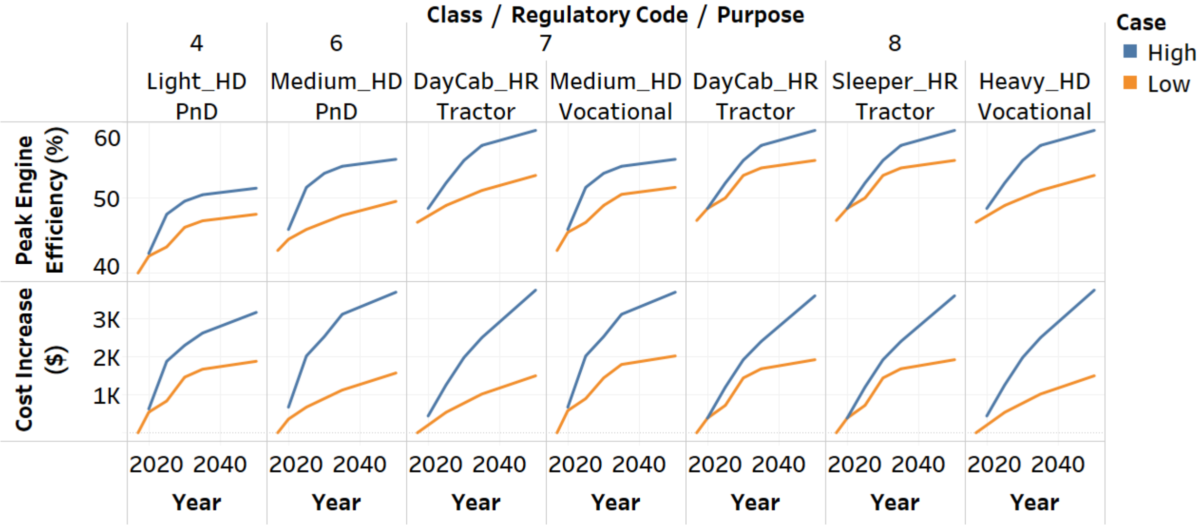

Figure 2-6 Efficiency and cost estimates for medium- and heavy-duty engines.

In addition to the cost increase due to increased efficiency, the cost of the engine itself would change with the size of engine needed in the future. The engine cost was estimated based on its peak power output. The International Council on Clean Transportation (ICCT) has carried out an analysis of the manufacturing cost of emission components (Posada et al. 2016), and Argonne has developed a cost estimation tool to support a VTO Co-Optima project. Based on the ICCT work and discussions with Argonne experts, the Argonne Autonomie team developed the cost assumptions shown in Figure 2-7.

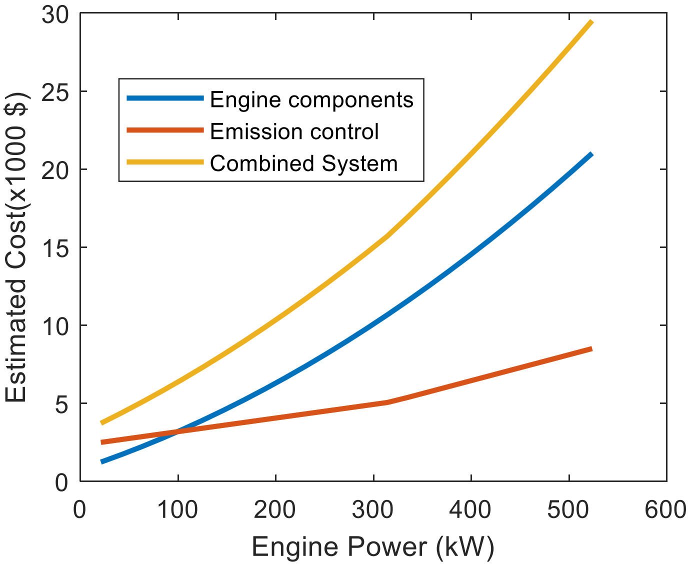

Figure 2-7 Estimated cost of diesel engine system as a function of engine power.

These estimates provide the base cost of engine manufacture. As technology improves, we expect to see higher costs associated with the devices and materials used to achieve higher efficiency. EPA and NHTSA (2016a) discuss several technologies and estimated costs in their regulatory impact analysis. These technologies fall within the region marked in green in Figure 2-8. For higher efficiency improvements, we assume the cost of manufacturing the engine to increase as shown in Figure 2-8.

The current peak efficiency of a large, commercially available diesel engine is about 47%. Efficiencies as high as 49% have already been demonstrated in vehicles, and 21CTP has a goal of demonstrating a path for 57% efficiency under laboratory conditions by 2025. VTO’s long-term expectation for engine efficiency is close to 60%. We estimate the manufacturing cost increase for the engine to be close to $5,000 as and when such high-efficiency targets are reached.

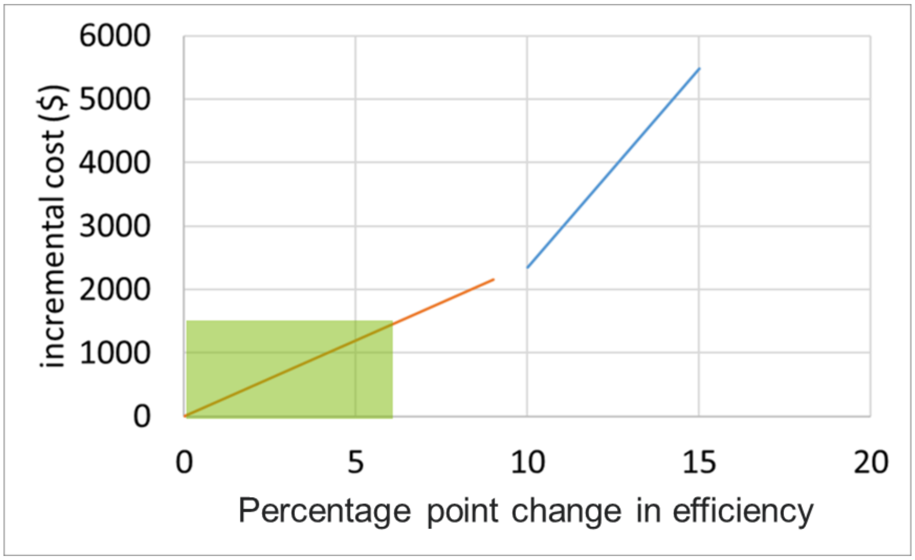

Figure 2-8 Estimated cost of diesel engine system as a function of percentage point improvement in engine efficiency.

2.2.4.2 Electric Machine

VTO has set goals for light-duty electric machine cost ($/kW) and volumetric power density (kW/L). Data from the A2Mac1 database (A2Mac1 2019) was used to estimate the current efficiency and power density (kW/kg) values. VTO targets were used for the future cost of electric machines, shown in Figure 2-9, and 1% year-over-year improvement was assumed for parameters where DOE has not set a development target.

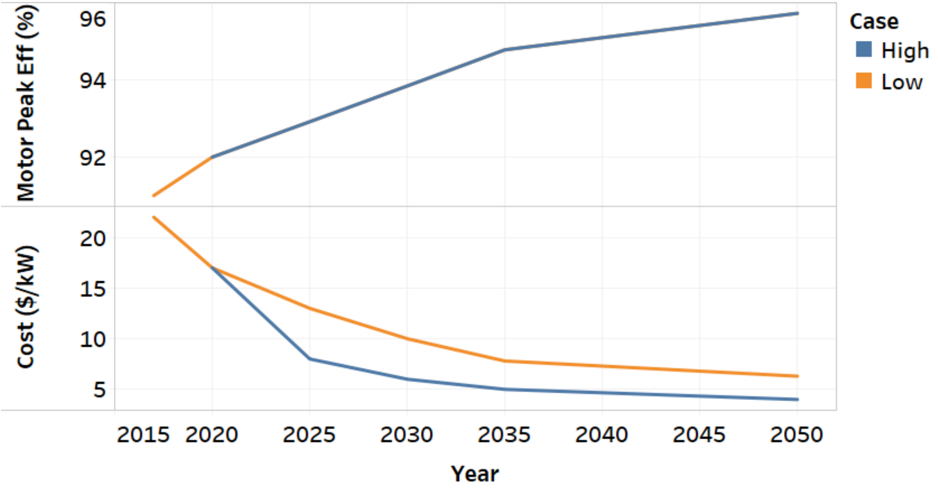

Figure 2-9 Cost estimates for electric machines based on VTO goals. (Both the High and Low cases assume the same efficiency improvements.)

2.2.4.3 Transmission

Such VTO-funded programs as SuperTruck have demonstrated the use of more efficient transmissions. Transmissions with more gears are expected in the Program Success (High) case. The overall efficiency of the gearbox is already high and is expected to remain high in the future. This study assumes that all of the trucks are using automated manual transmissions that will ensure consistent shift performance across different types of vehicles and powertrains. Figure 2-10 summarizes the number of gears used in each type of vehicle.

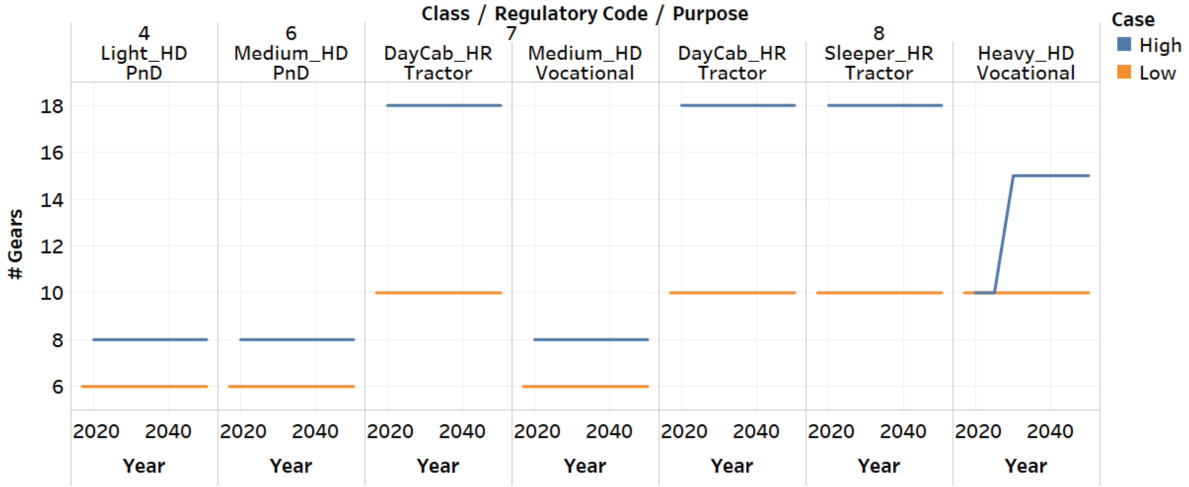

Figure 2-10 Assumed number of gears in truck transmissions.

2.2.4.4 Energy Storage

Research on batteries for light-duty vehicles is supported by VTO; however, no goals were established for medium- and heavy-duty vehicles at the time of this study. Similar battery technologies can be used for trucks as well, although higher levels of power and energy will be needed. Therefore, it is expected that the light-duty hybrid electric vehicle (HEV) battery goals will be applicable for ISG systems in the heavy-duty domain. HEV trucks will likely use technologies developed for light-duty plug-in HEVs (PHEVs). Trucks with plug-in and electric powertrains are assumed to use battery technologies developed for light-duty battery electric vehicles (BEVs).

Figure 2-11 summarizes the battery characteristics used for all trucks simulated. Battery packs for fuel cell hybrid electric vehicles (FCHEVs) were assumed to be very similar to HEV packs, so the same assumptions were made for both. Costs of PHEV and BEV battery packs were assumed to depend on energy, not power, and no power cost coefficient was used, so these values are shown as zero in these plots.

The battery cost values are higher than those of the light-duty vehicles, as we expect these packs to be redesigned to meet the tougher requirements for commercial trucks.

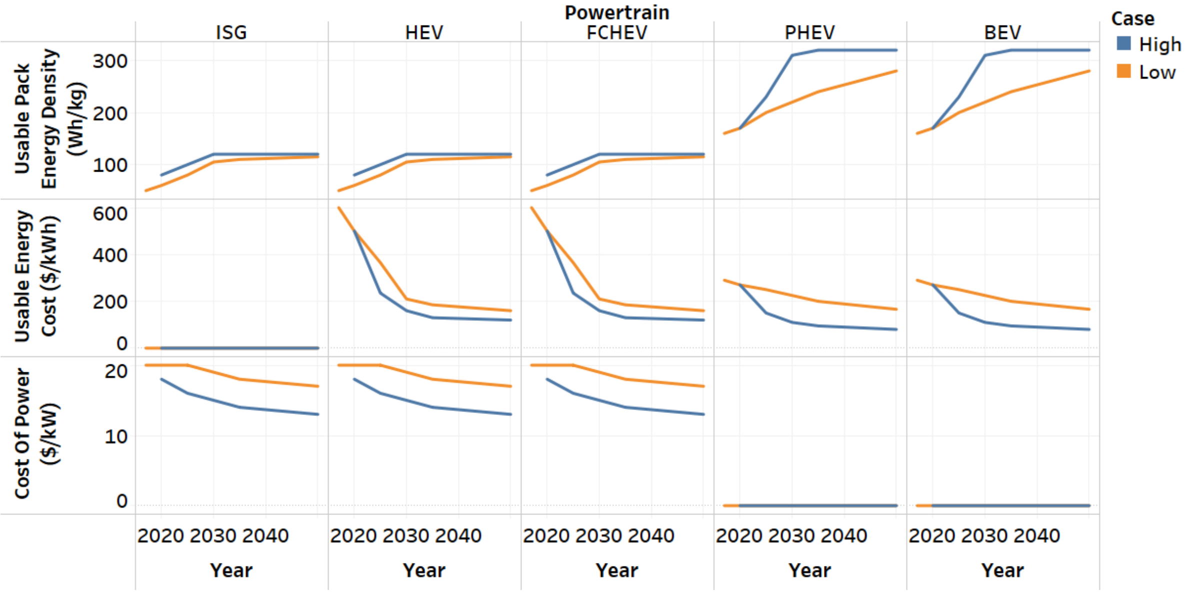

Figure 2-11 Battery assumptions for trucks.

2.2.4.5 Fuel Cells

HFTO efficiency goals for fuel cell systems for light-duty vehicles were assumed to apply to trucks, as well. As with battery packs, many factors that affect the fuel cell design could change in order to meet the rigorous requirements for trucks. Higher power, longer operating time, and durability requirements are expected to increase the cost of manufacturing fuel cells for trucks. HFTO provided updated cost targets for such fuel cells. Assumptions for fuel cells in medium- and heavy-duty FCHEVs are shown in Figure 2-12.

For Class 8 trucks, we considered a higher efficiency target (72%) for the fuel cells, as proposed by HFTO for HD applications.

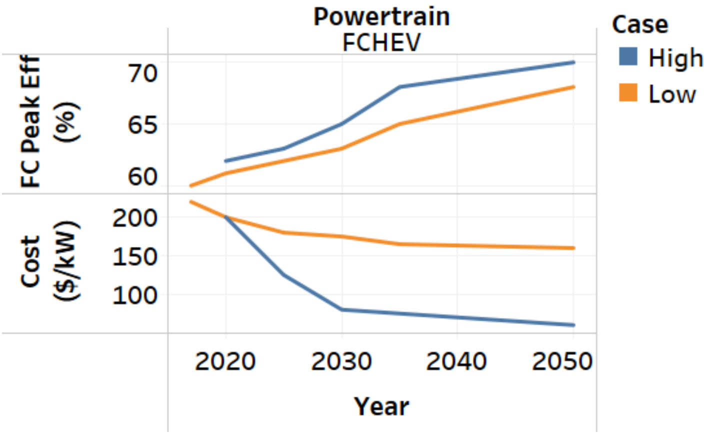

Figure 2-12 Fuel cell system efficiency and cost coefficients for trucks.

2.2.4.6 Hydrogen Storage

For onboard storage of hydrogen, the fuel tanks in medium- and heavy-duty fuel cell vehicles have a hydrogen density and potential for cost reduction similar to the hydrogen tanks in light-duty vehicles. The amount of hydrogen that can be stored in a given mass of tank is expected to increase with HFTO R&D, and costs will decrease, as shown in Figure 2-12. The cost of the tank involves a fixed cost as well as a cost component proportional to the size of the tank. However, for simplicity, Figure 2-13 displays the cost per kilogram of hydrogen for a tank rated to store 10 kg of hydrogen (H_2).

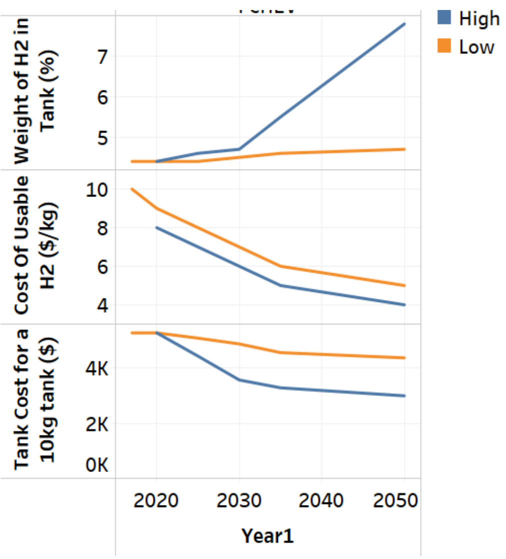

Figure 2-13 Hydrogen storage assumptions.

2.2.4.7 Lightweighting

Use of advanced materials and optimized design can lower the weight of trucks. A workshop conducted by DOE in 2013 provided estimates on how much weight savings can be achieved by 2050 and what cost is expected for every pound shaved from the truck (DOE-VTO, 2013). Since 2014, some of the lightweighting approaches mentioned in that report are already being deployed on trucks currently in the market, such as the use of fiber-reinforced plastics in Class 8 tractor bodies. Cost-effective technologies tend to be adopted quickly in this segment. Values assumed for future glider weight reductions and associated incremental costs are shown in Figure 2-14.

For commercial vehicles, reduction in curb weight offers two choices. One is to realize the fuel savings associated with this reduction in weight. The second option is to increase payload to compensate for the weight reduction in the glider. Although the second option may not reduce fuel consumption per vehicle-mile traveled, it provides potential operational cost savings. This savings was estimated to be $1.37 per pound saved for Class 8 sleeper cab trucks, based on estimated average operating cost per mile and the fraction of Class 8 trucks that operate at maximum payload. This savings is included in the incremental cost assumed for lightweighting.

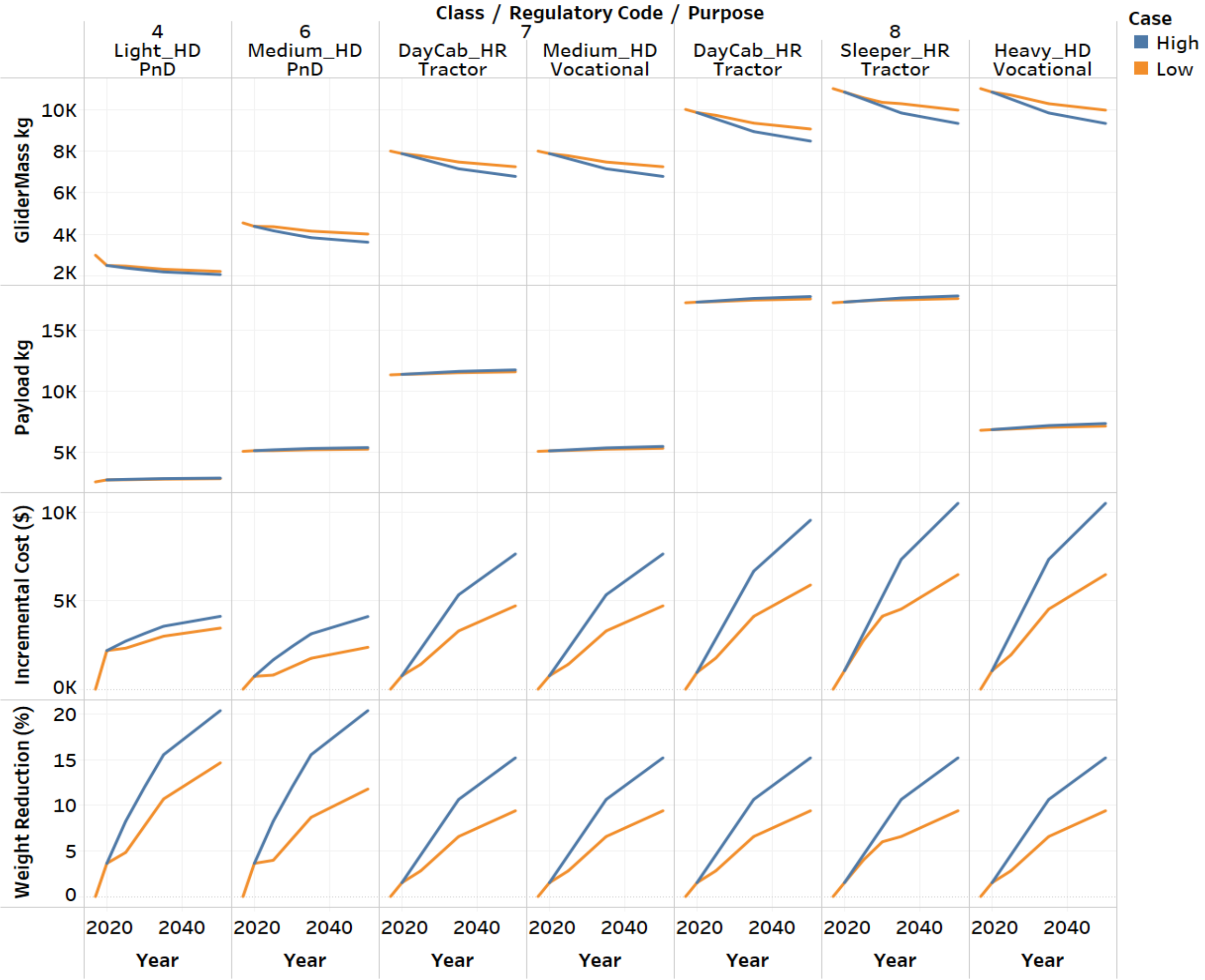

Figure 2-14 Weight reduction in trucks enabling increase in payload.

2.2.4.8 Aerodynamic Improvements

Aerodynamic improvements are among the most cost-effective technologies available for improving the fuel economy of vehicles operating at highway speeds. Consequently, side skirts, gap reducers, and similar aftermarket devices have already been widely adopted in line-haul vehicles. More improvement in the coefficient of drag can be expected in the future with improvements in vehicle design.

The SuperTruck I initiative demonstrated that Class 8 trucks can improve aerodynamics by another 20–30%. However, the powertrain-specific improvement could vary. The electric semi truck from Tesla claims an aerodynamic drag coefficient (Cd) as low as 0.3, comparable to that of passenger cars. Fuel-cell trucks may need a larger frontal area for effective cooling and may require further design improvements to achieve lower drag coefficients. To make comparisons across powertrain technologies consistent, this study assumed a retrofit approach for aerodynamic technology implementation. The body and chassis characteristics are assumed to remain the same as those of the conventional truck used as a baseline. Future work will explore varying such parameters based on powertrain, as well. The assumptions shown in Figure 2-15 were developed for conventional trucks, and these were applied to all other powertrains.

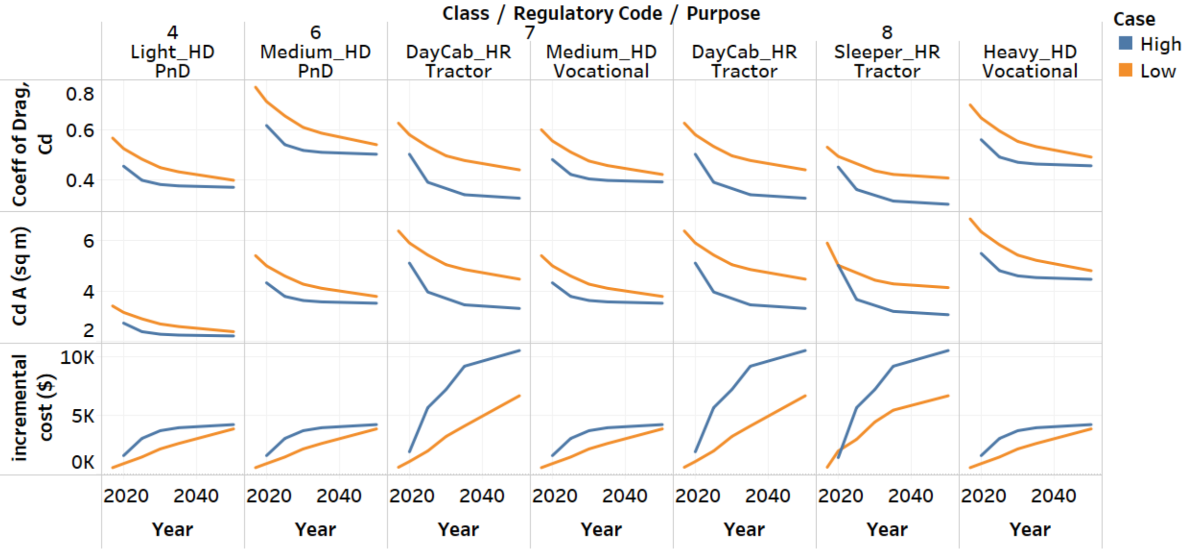

Figure 2-15 Aerodynamic improvement assumed in trucks.

2.2.4.9 Other Cost Assumptions

Technology-specific assumptions provided the direct manufacturing costs of improving technology over the years. DOE cost targets assume manufacturing of components at a high enough volume to achieve economies of scale. Using estimated technology costs as a function of production volume reported by Schubert et al. (2015) in a report prepared for NHTSA’s Phase 2 greenhouse gas and fuel economy standard regulatory analysis, cost adjustments were established for different technologies to account for production volume. Schubert et al. did not report costs for fuel cell or hydrogen storage technologies, but we assumed that these would scale similarly to battery costs. Costs for low (50,000 units) and higher cumulative production volumes were given in Schubert et al. (2015). Ratios of the costs of different technologies at the lowest and highest production volumes were used to determine direct cost multipliers.

In addition to direct manufacturing costs, there are indirect costs that depend on production volume and technology complexity/maturity. An indirect cost multiplier of 1.2 was assumed for 2035 and later, based on discussions with industry experts; however, higher factors would be more appropriate for earlier years. Schubert et al. provide suggested indirect cost multipliers for different technologies, depending on complexity. Combining (multiplying) the production-dependent cost multipliers produces the factors applied to the full-scale direct manufacturing costs of the components described in previous subsections of Section 2.2.4 to yield retail costs. These factors are shown by technology and year in Table 2-3.

Table 2-3 Manufacturing cost multiplier by component and year.

Component	2020 and Earlier	2025	2030	2035 and Later
Engines and emission control	1.49	1.32	1.20	1.20
Glider	1.36	1.26	1.20	1.20
Electric machines	1.95	1.55	1.29	1.20
Battery packs	2.18	1.76	1.48	1.20
Fuel cell system	2.18	1.76	1.48	1.20
Hydrogen storage	2.18	1.76	1.48	1.20
Other	1.20	1.20	1.20	1.20

Vehicle prices were estimated by summing the component costs after applying the factors shown in the above table to direct, full-scale manufacturing cost estimates. The price estimates from Autonomie for all conventional baseline trucks in 2017 align well with the advertised retail prices of production vehicles.

3 INDIVIDUAL VEHICLE TECHNOLOGY BENEFITS IN ENERGY CONSUMPTION

The simulation results for all vehicles are shared through the Excel spreadsheets associated with this document (Attachments A and B in the appendix). The detailed plots shown in this document focus on the vehicle classes and vocations used for the benefit analysis.

3.1 FUEL CONSUMPTION BENEFITS

Sleeper trucks constitute about 45% of the overall fuel usage by trucks in the United States. These trucks are designed to maximize their fuel economy on steady highway driving conditions. The EPA 65 cycle is one of the good representative cycles for this scenario. In this study, fuel consumption was estimated from simulations over three drive cycles identified in Section 2.2.2 — the (California) Air Resource Board (ARB) Transient, EPA 55 mph, and EPA 65 mph). Interestingly, such highway driving is particularly challenging for many advanced powertrains as it requires sustained high power output and offers very little opportunity to reduce fuel consumption. Because of this challenge, the EPA 65 is used in this study for estimating the driving range of FCHEV, PHEV, and BEV variants. A summary of the fuel consumption of present-day trucks on the EPA 65 cycle is shown in Figure 3-1.

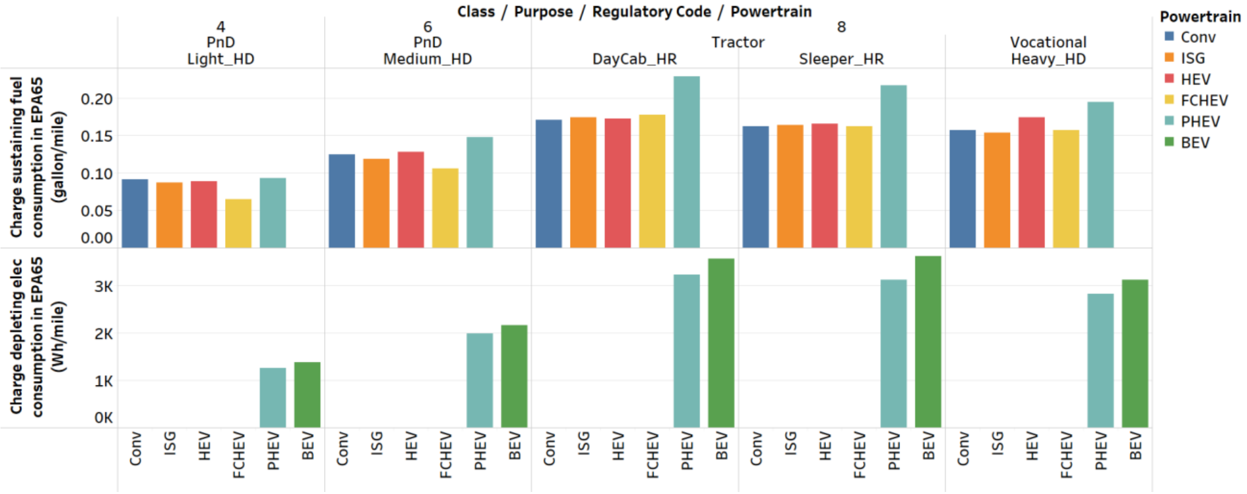

Figure 3-1 Overview of energy consumption of trucks for highway driving.

Figure 3-1 shows that the start-stop (ISG) systems and HEV systems do not provide large fuel savings during highway driving, where there is no idling and only limited opportunity for regenerative braking. For heavy trucks, hybrid powertrains might even result in increased fuel consumption during highway driving resulting from the additional weight of hybrid components. PHEVs have two sources for propulsion energy. The fuel consumption in charge-sustaining operation is shown in the top part of the plot. It is nearly always the highest among the various powertrains owing to the additional weight and inefficiencies in the series hybrid powertrain. The electrical energy consumption levels for the charge-depleting operation of a PHEV and BEV are shown in the lower part of the figure. In that area, the additional energy consumed by the BEV attributable to the increase in vehicle weight is evident.

The potential to downsize the engine varies with the class and vocation of the truck. The electrical energy consumption of the PHEVs and BEVs observed here is likely to be higher than what is claimed by some of the manufacturers. This result is attributable to two factors. The first is the choice of drive cycle in this case. In the simulations shown here, the vehicle maintains a speed of 65 mph on varying grades. Most manufacturers, however, state their energy consumption for an optimum steady speed on a flat road. The second reason is that the aerodynamic improvements and chassis weight assumptions for the BEVs in this study come from baseline conventional vehicles; that is, the same chassis and body were assumed for all powertrains. Truck manufacturers building a new vehicle have the option to design a body and chassis specifically suited to their powertrain. This factor is being updated in Autonomie for future simulations for VTO benefit analyses.

Each vehicle is sized for a specific application. Class 8 sleeper trucks are sized to drive 500 miles without refueling or recharging. Similarly, Class 4 and 6 trucks are sized to drive 150 miles before stopping for fuel. PHEVs are sized to drive half of the daily driving distance with stored energy in the battery pack. When comparing the fuel displacement potential of these powertrains, we assume a scenario in which these vehicles are driven for their full daily driving range. This assumption forces all powertrains, including PHEVs, to use all types of onboard energy storage. ISGs, HEVs, FCHEVs, and PHEVs will achieve a charge-sustaining condition. PHEVs and BEVs will deplete the battery, thereby maximizing the petroleum displacement potential of each powertrain. Energy consumption is converted to diesel gallon equivalent (DGE) values for comparison purposes.

Figure **3-2** indicates that the BEVs show more promise (up to 70% reduction) in energy consumption for small trucks over ARB transient cycles. For larger trucks, the BEVs still save a significant amount of energy; however, for line-haul trucks on highways, the net savings from BEVs might be only about 40%.

The percentage of fuel savings realized by each powertrain for various types of trucks is shown in Figure **3-2**. It displays estimated savings for present-day vehicles under the three regulatory drive cycles. About 70% savings in fuel savings is observed for small trucks in the ARB transient cycle. The savings are lower for larger trucks on highway driving. This figure does not show the petroleum savings. Although BEVs displace 100% of the petroleum consumption, they still consume energy from the electric grid.

Although future improvements in powertrain components will slightly alter the relative advantages of each powertrain, the overall trend will remain similar. This result is shown in Figure 3-3, which compares daily fuel requirements for future vehicles with different powertrains for each of the three drive cycles. A more complete set of results for all vehicles considered in this work is provided in the Excel spreadsheets accompanying this report (Attachments A and B).

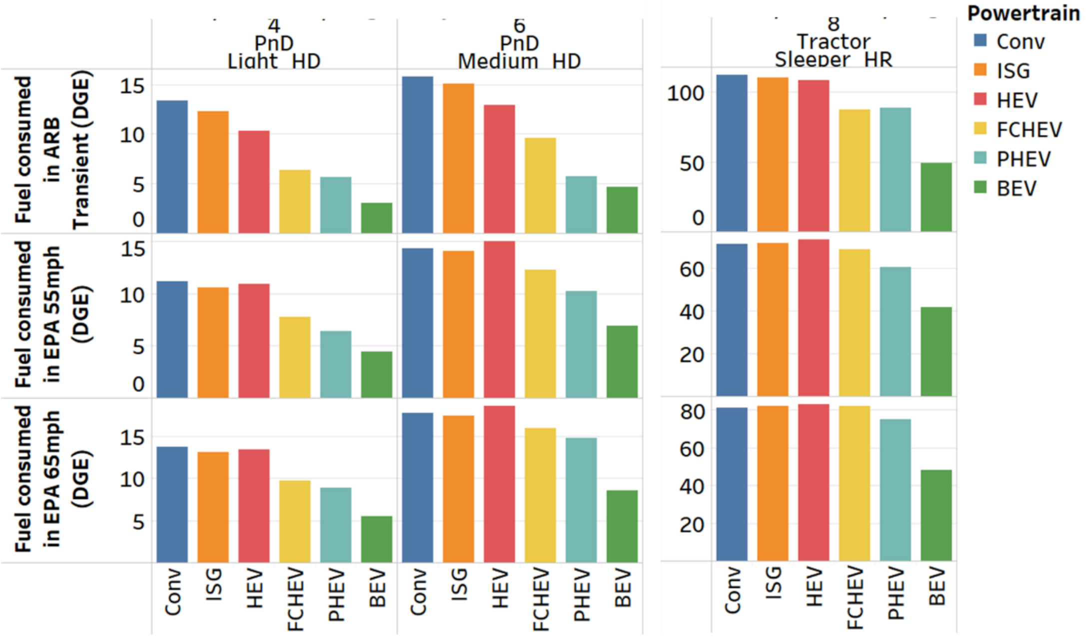

Figure 3-2 Comparison of diesel equivalent fuel consumption for various powertrains.

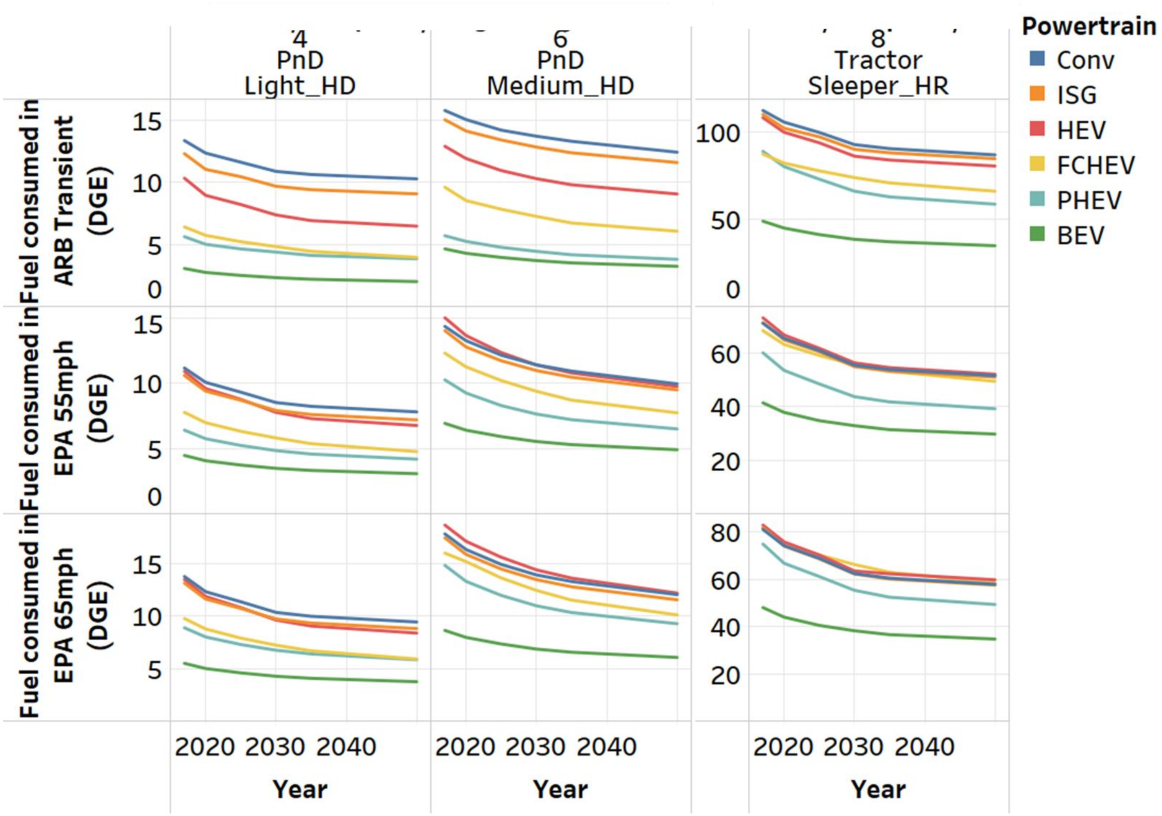

Figure 3-3 Daily fuel requirements in terms of diesel gallon equivalent values.

4 TOTAL COST OF OWNERSHIP ANALYSIS

For the Benefits and Scenario (BaSce) analysis, the total cost of ownership (TCO) estimation and its influence on consumer decisions is determined by agencies carrying out market penetration analysis. Market penetration analysis is beyond the scope for this report. Autonomie has a built-in method for estimating total cost of ownership. This section specifies the way TCO analysis is carried out in Autonomie. Some TCO factors, such as driver wages, registrations costs, tolls, etc., are assumed to be identical across vehicle designs and are not relevant for powertrains comparisons. The two main factors considered in this analysis are:

1. Initial purchase price
2. Fuel/energy cost spread over the service period of the truck

4.1 ANNUAL VEHICLE MILES TRAVELED (VMT) ASSUMPTION

The designed driving range and miles traveled (VMT) per year for these vehicles were determined based of the VIUS survey, NREL's FleetDNA data, and feedback from OEMs and industry partners. We assume the same VMT for the entire service period. The vehicle use case scenario needs to be better understood. Recently, VTO has set up a working group to determine the most appropriate assumptions for TCO calculations. Future work in this topic will use the feedback from that working group. VMT estimates used for this work are shown in Table 4-1. It is assumed that battery replacement will not be needed during the service period of the vehicle.

4.2 VEHICLE SERVICE PERIOD ASSUMPTION

The service period differs for different types of trucks. The vehicle lifetime is expected to be 15 years for all trucks except Class 8 sleepers. Typical sleeper trucks are used for long haul for less than five years. After the initial five years, they are used in regional or short-haul operations. We assume the sleeper trucks to have a residual value of 45% of their purchase price when the fleets dispose of them at the end of five years. If trucks are used for their full lifetime of 15 years, there is no residual value expected at the end of their service period. The variation in residual values as a function of the service time is shown in Figure 4-1.

With the assumptions shown in Table 4-1, and today's diesel costs, Autonomie estimates that the sum of purchase price and fuel costs over the service period for a Class 8 sleeper is \$0.62 per mile. This result is similar to the estimate made by the American Transportation Research Institute (Hooper and Murray 2018).

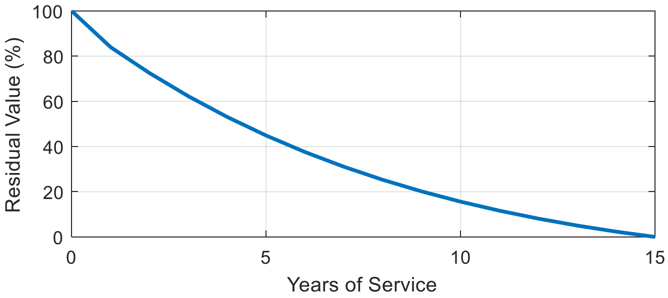

Figure 4-1 Variation of assumed residual value of a truck as a percentage of purchase price by years of service.

Table 4-1 Assumptions for TCO calculation.

Class	Purpose	VMT	Service period (years)	Discount rate (%)	Battery Cost	Electricity Cost	Diesel Cost
4	Delivery	18,000	15	7	$350/kWh to $80/kWh	10c.kWh to 30c/kWh	$2.5/gallon to $4/gallon
6	Delivery	18,000					
8	Sleeper	120,000	5				
8	DayCab	30,000	15				
8	Vocational	24,000					

Exploratory work was carried out to examine the economic viability of electric trucks and how that viability will be influenced by battery cost targets set by DOE and other factors that are not under the purview of technology targets. The range considered for each parameter in this work will help account for variations that we cannot predict now. A conference paper on this topic has been written and already accepted for publication at EVS 33.

Some of the interesting insights from the TCO analysis are mentioned here. Sensitivity related to battery and energy cost, daily trip distance, and associated electric range were considered as part of this work. Based on Figure 4-2, we can infer that among the vehicles considered, the most promising candidate to achieve purchase price parity with diesel trucks is the Light HD (Classes 2 to 5) electric delivery truck. Medium HD (Classes 6 and 7) and larger trucks face a tougher challenge because of their need for larger battery packs.

Figure 4-2 shows the difference in purchase price between diesel and electric trucks. Values under zero show that EVs are more expensive than diesel trucks. Light HD trucks could see purchase price parity when the battery pack cost is around $80/kWh. Light HD trucks can achieve TCO parity with diesels even with costlier battery packs, as shown in Figure 4-.

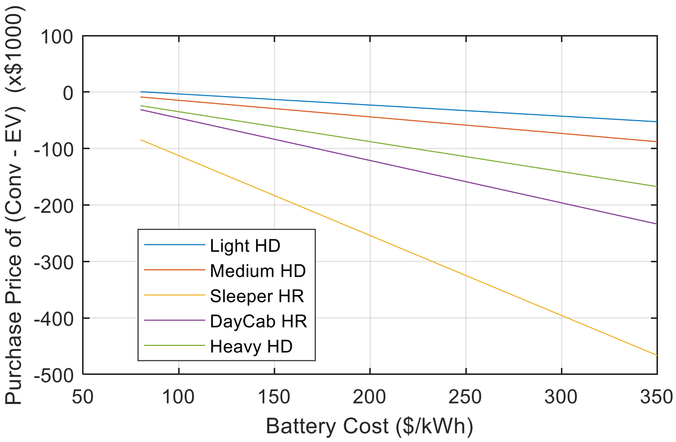

Figure 4-2 Purchase price parity comparison of all vehicles considered in this study.

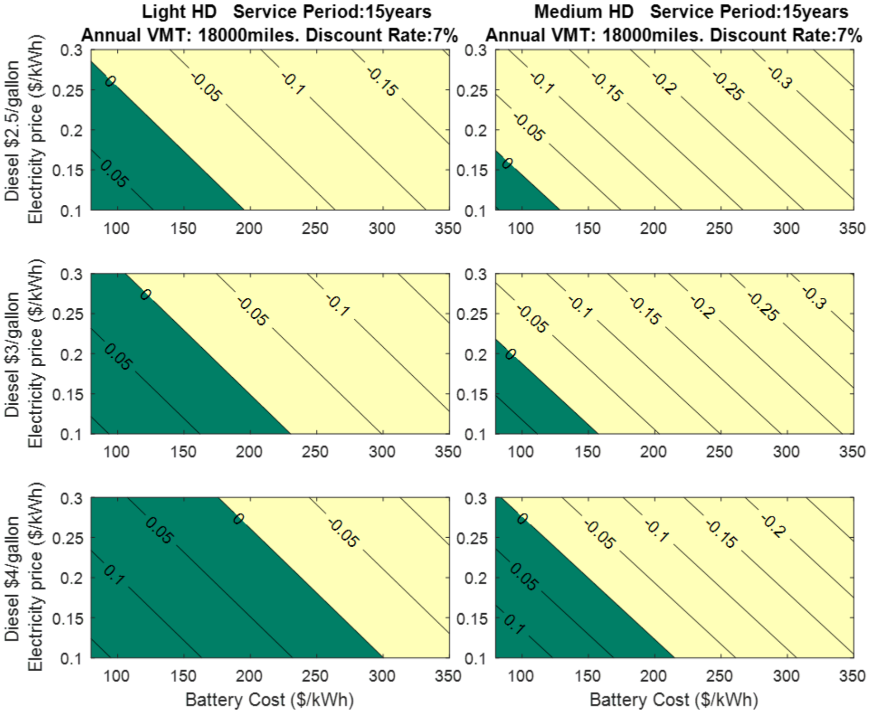

Figure 4-3 Difference in TCO in using an electric truck over a diesel truck for parcel delivery operations in urban centers.

The profit or loss associated with operating an electric delivery truck is quantified in terms of $/mile in this figure. The green region indicates conditions where the electric truck is profitable. With present diesel prices at $3/gallon, Class 4 (Light HD) delivery trucks could see TCO parity if the battery pack cost is at $225/kWh. Light-duty battery packs are expected to be at this price point now; however. the truck battery packs are expected to be more expensive as they have to survive more charge-discharge cycles and work for longer hours. In this work, we assume the truck battery pack costs around $270/kWh in 2020.

5 CONCLUSIONS

This study details the assumed inputs and modeling processes (including assumed performance requirements and official operational constraints) used to estimate future vehicle-level fuel economies and associated costs for medium and heavy trucks. Fuel economy, vehicle purchase price, and energy consumption estimates were made for more than 20 class-vocation combinations, five different powertrains, and six time frames with upper and lower limits for two technology progress scenarios. Detailed results are reported in the complementary Excel worksheets (Attachments A and B). These results inform the BaSce analysis, lifecycle cost analysis, and market penetration analysis work carried out by various agencies including other national laboratories.

New technologies being developed under VTO and HFTO R&D programs are shown to improve the cost effectiveness and fuel economy of medium- and heavy-duty vehicles. TCO analysis shows that achieving the targets set by DOE can make BEV variants of Class 4 delivery trucks an economically attractive choice over conventional diesel trucks. Similar analysis is proposed for all other powertrains and vehicle classes as well, to identify market segments where such trucks can be introduced.

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APPENDIX

ATTACHMENT A: AUTONOMIE SIMULATION INPUTS

ANL - MDHD -
VTO_FCTO - Autono

ATTACHMENT B: AUTONOMIE SIMULATION RESULTS

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