ANL/ESD-21/10

A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050

Energy Systems Division

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A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050

by
Ehsan Sabri Islam, Ram Vijayagopal, Ayman Moawad, Namdoo Kim, Benjamin Dupont, Daniela Nieto Prada, Aymeric Rousseau
Energy Systems Division, Argonne National Laboratory

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NOTATION

ACRONYMS AND ABBREVIATIONS

21CTP	21st Century Track Partnership
AER	All Electric Range
AMTL	Advanced Mobility Technology Laboratory
ARB	(California) Air Resources Board
Argonne	Argonne National Laboratory
BEV	battery-powered electric vehicle
BEV200	BEV with 200 mi of all-electric range (end-of-life) on the combined driving cycle (adjusted)
BEV300	BEV with 300 mi of all-electric range (end-of-life) on the combined driving cycle (adjusted)
BEV400	BEV with 400 mi of all-electric range (end-of-life) on the combined driving cycle (adjusted)
BEV500	BEV with 500 mi of all-electric range (end-of-life) on the combined driving cycle (adjusted)
BISG	belt-integrated starter generator (mild hybrid vehicle)
BTE	brake thermal efficiency
CI	compression ignition
CNG	compressed natural gas
CO_2	carbon dioxide
CVT	continuously variable transmission
DCT	dual-clutch transmission
DM	discrete manual transmission
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DRIVE	U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability
EDV	electric drive vehicle
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
E-REV	extended-range electric vehicle
EV	electric vehicle
FCHEV	fuel cell hybrid electric vehicle
FCET	fuel cell powered electric truck(s)
FCEV	fuel cell dominant electric vehicle
FTP	Federal Test Procedure

GPRA	Government Performance and Results Act
H_2	hydrogen
HD	heavy duty
HEV	hybrid electric vehicle
HFTO	Hydrogen & Fuel Cell Technologies Office
HR	high roof
HWFET	Highway Federal Emissions Test
ICE	internal combustion engine
ICCT	International Council on Clean Transportation
ISG	integrated starter/generator
IVM	initial vehicle movement
Li-ion	lithium ion
LCOD	Levelized Cost of Driving
MY	model year
NEMS	National Energy Mobility System
NHSTA	National Highway Safety Transportation Administration
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PARHEV	Parallel Hybrid Electric Vehicle
PEV	pure electric vehicle
PHEV	plug-in hybrid electric vehicle
PHEV20	PHEV with 20 mi of all-electric range (end-of-life) on combined driving cycle (adjusted)
PHEV50	PHEV with 50 mi of all-electric range (end-of-life) on combined driving cycle (adjusted)
PnD	pickup and delivery
SAE	Society of Automotive Engineers
SEDS	State Energy Data System
SI	spark ignition
SOC	state of charge
SUV	sport utility vehicle
UDDS	Urban Dynamometer Driving Schedule
U.S. DRIVE	United States Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability
USD	U.S. dollars

US06	EPA US06 cycle
VCR	variable compression ratio
VIUS	Vehicle Inventory and Use Survey
VMT	vehicle miles traveled
VTO	Vehicle Technologies Office
VTS	vehicle technical specifications
VVL	variable valve lift
VVT	variable valve timing

UNITS OF MEASURE

Cd	coefficient of drag
DGE	diesel gallon equivalent
gal	gallon(s)
kg	kilogram(s)
km	kilometer(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
L	liter(s)
m	meter(s)
m^2	square meter(s)
mi	mile(s)
mph	mile(s) per hour
sec	second(s)
V	volt(s)
W	watt(s)
Wh	watt hour(s)

PREFACE

This report is the seventh revision of a continuous-improvement scenario-based study on program benefits from the U.S. Department of Energy Vehicle Technologies Office and Hydrogen and Fuel Cell Technologies Office. Past reports are as follows:

1. Islam, E., A. Moawad, N. Kim, and A. Rousseau, 2020a. *Energy Consumption and Cost Reduction of Future Light-Duty Vehicles through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050*, Report No. ANL/ESD-19/10, Argonne National Laboratory, Lemont, Ill., June 2019.

2. Vijayagopal R., Nieto Prada D., Rousseau A., "Fuel Economy and Cost Estimates for *Medium-and Heavy-Duty Trucks"*, Report to the US Department of Energy, ANL/ESD-19/8, December 2019

3. Islam, E., A. Moawad, N. Kim, and A. Rousseau, 2018a. *An Extensive Study on Vehicle Sizing, Energy Consumption and Cost of Advance Vehicle Technologies*, Report No. ANL/ESD-17/17, Argonne National Laboratory, Lemont, Ill., Oct.

4. Moawad, A., N. Kim, N. Shidore, and A. Rousseau, 2015. *Assessment of Vehicle Sizing, Energy Consumption and Cost through Large-Scale Simulation of Advanced Vehicle Technologies*, Report No. ANL/ESD 15/28, Argonne National Laboratory, Argonne, Ill., March.

5. Moawad, A., and A. Rousseau, 2014. *Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045*, Report No. ANL/ESD-14/4, Argonne National Laboratory, Argonne, Ill., April.

6. Moawad, A., P. Sharer, and A. Rousseau, 2011. *Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045*, Report No. ANL/ESD-11/4, Argonne National Laboratory, Argonne, Ill., July.

Links to these reports and the accompanying datasets are on the Argonne Autonomie webpage at http://www.autonomie.net/publications/fuel_economy_report.html. The webpage also contains a link to the Main Assumptions and Results per component and Results per vehicle for each revision.

With each revision of the study, improvements were made to the assumptions, control strategies at the vehicle level, methodologies, and powertrain selections and the number of vehicles analyzed. In 2019, separate reports were published on the analysis of light duty and heavy duty vehicles. This year an attempt is made to consolidate both this work into one report. The first part of the report covers the impact of technology progress on light duty vehicles and the later part of the report is devoted to the technology progress assumed for medium and heavy duty trucks.

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PART ONE. Analysis of Light Duty Vehicles

1 INTRODUCTION

The U.S. Department of Energy (DOE) 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. Translating investments in advanced transportation component technologies and powertrains to estimate vehicle-level fuel savings potential is critical for understanding DOE's impact. In this work, we simulated technologies funded by VTO and HFTO for light duty vehicles. The simulations were performed across:

- Multiple powertrain configurations (conventional, power-split, extended-range electric vehicle, battery electric drive, and fuel-cell vehicles).
- Vehicle classes (compact car, midsize car, small sport utility vehicle [SUV], midsize SUV, and pickup trucks).
- Fuels (gasoline, diesel, natural gas, hydrogen, and battery electricity).

These various technologies are assessed for six different timeframes: laboratory years 2015 (reference), 2020, 2025, 2030, and 2045. A delay of five years is assumed between laboratory year and model year (the year the technology is introduced into production). Finally, uncertainties are included for both technology performance and cost aspects by considering two cases:

- *Low case*, aligned with DOE technology manager estimates of expected original equipment manufacturer improvements based on regulations, business as usual.
- *High case*, aligned with aggressive technology advancements based on R&D targets developed through support by VTO & HFTO.

These scenarios are not intended as predictions of future performances. The energy and cost impact of different technologies were estimated using Autonomie (www.autonomie.net), the Argonne vehicle system simulation tool. Autonomie is a state-of-the-art vehicle system simulation tool used to assess the energy consumption, performance and cost of multiple advanced vehicle technologies across classes (from light to heavy duty), powertrains (from conventional to HEVs, FCEVs, PHEVs, and BEVs), components, and control strategies. Autonomie is packaged with a complete set of vehicle models for a wide range of vehicle classes, powertrain configurations, and component technologies, including vehicle level and component level controls. These controls were developed and calibrated using dynamometer test data. Autonomie has been used to support a wide range of studies including analyzing various component technologies, sizing powertrains components for different vehicle requirements, comparing the benefits of powertrain configurations, optimizing both heuristic and route based vehicle energy control, and predicting transportation energy use when paired with a traffic modeling tool such as POLARIS.

This report documents the assumptions and estimates the vehicle-level energy consumption benefits and associated technology costs for the various types of light duty vehicles. All details of vehicle assumptions and simulation results are available in the spreadsheets accompanying this report.

2 METHODOLOGY

2.1 VEHICLE CLASSES AND POWERTRAINS

To enable detailed assessment of the benefits of future technologies, the following options are considered:

- *Five vehicle classes*: compact, midsize car, small SUV, midsize SUV, and pickup truck.

- *Two performance categories*: base (non-performance) and premium (performance).

- *Six timeframes*: 2015 (reference), 2020, 2025, 2030, and 2045. All years considered are laboratory years with a 5-year delay to production year.

- *Five powertrain configurations*: conventional, hybrid electric vehicle (HEVs), plug-in hybrid electric vehicle (PHEVs) - split HEV, split PHEV, extended-range PHEV, fuel cell electric vehicles (FCEV), and battery electric vehicle (BEV).

- *Two technology progress uncertainty levels*: low and high cases. These correspond to low uncertainty (aligned with original equipment manufacturer improvements based on regulations), average uncertainty, and high uncertainty (aligned with aggressive technology advancement based on DOE VTO & HFTO programs). Low-technology progress represents very small uncertainty in achieving the target; that is, the manufacturers would achieve this target without the advancement of DOE VTO & HFTO programs. High-technology progress represents very high uncertainty in manufacturers achieving the target as they respond to DOE VTO & HFTO targets for the corresponding technology and laboratory year. These uncertainties do not necessarily lead to predicting future performance. In addition to the two main uncertainty levels, an additional high-technology case except for lightweighting is simulated to quantify the benefits without additional lightweighting costs.

Figure 1-1 displays the simulation options for the vehicles defined and simulated in Autonomie.

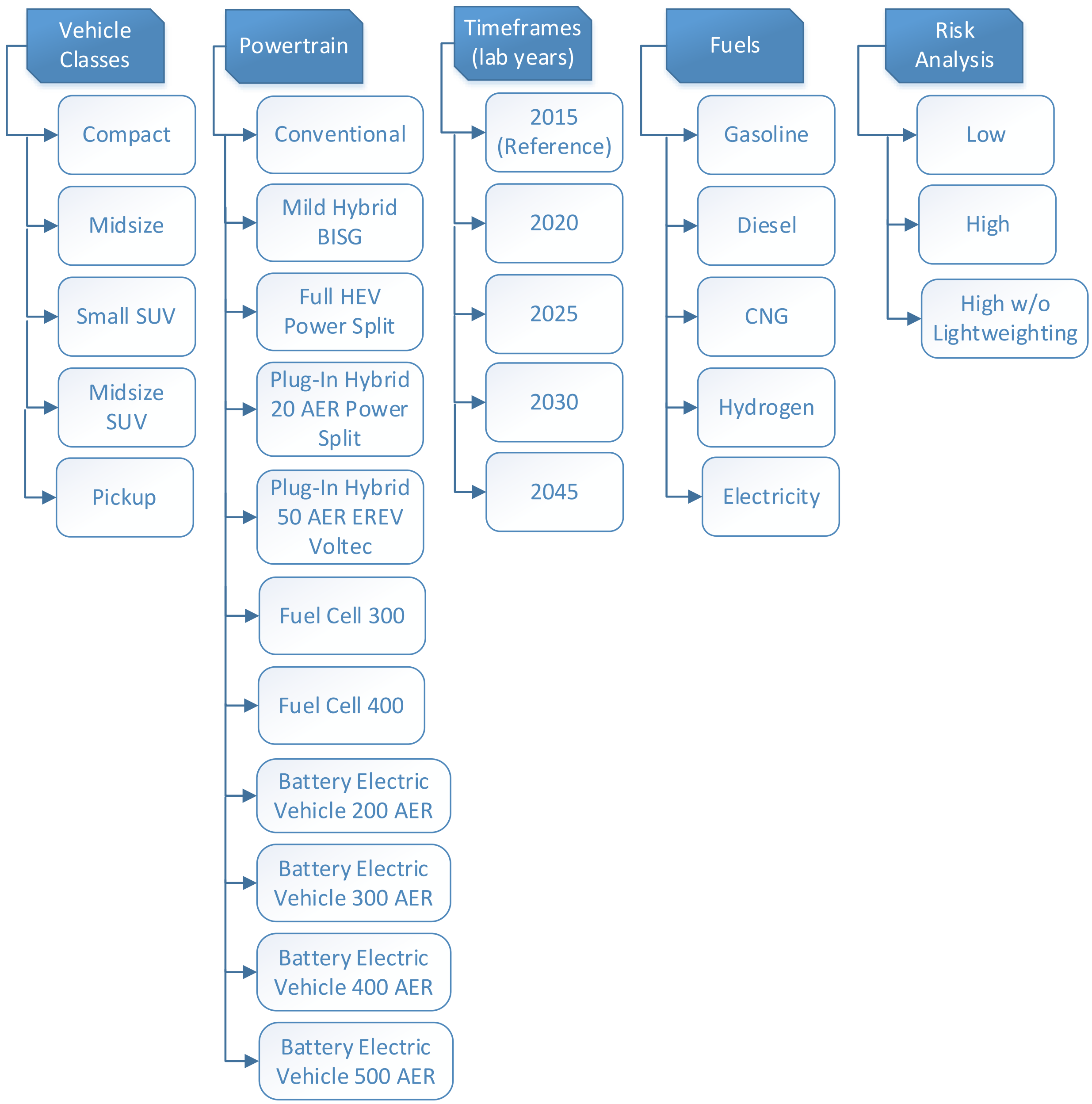

FIGURE 1-1 Vehicle classes, timeframes, configurations, fuels, and technology progress level

2.2 AUTONOMIE OVERVIEW

Autonomie is a Mathworks®-based software environment and framework for automotive control-system design, simulation, and analysis. The tool, sponsored by the DOE Vehicle Technologies Office (VTO), is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity), abstraction (from subsystems to systems to entire architectures), and processes (e.g., calibration, validation). Developed by Argonne in collaboration with General Motors, Autonomie was designed to serve as a single tool that can be used to meet the requirements of automotive engineers throughout the development process—

from modeling to control. Autonomie was built to:

- Estimate the energy, performance, and cost impact of advanced vehicle and powertrain technologies.
- Support proper methods, from model-in-the-loop, software-in-the-loop (SIL), and hardware-in-the-loop (HIL) to rapid-control prototyping (RCP).
- Integrate math-based engineering activities through all stages of development—from feasibility studies to production release.
- Promote re-use and exchange of models industrywide through its modeling architecture and framework.
- Support users' customization of the entire software package, including system architecture, processes, and post-processing.
- Mix and match models with different levels of abstraction to facilitate execution efficiency with higher-fidelity models, for which analysis and high-detail understanding are critical.
- Link with commercial off-the-shelf software applications, including GT-POWER, AMESim™, and CarSim®, for detailed, physically based models.
- Protect proprietary models and processes.

Autonomie allows the quick simulation of a very large number of component technologies and powertrain configurations. Autonomie can do the following:

- Simulate subsystems, systems, or entire vehicles.
- Predict and analyze fuel efficiency and cost.
- Perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms.
- Support system hardware and software requirements.
- Link to optimization algorithms.
- Supply libraries of models for propulsion architectures of conventional powertrains as well as electric drive vehicles (EDVs).

Autonomie is used to evaluate the energy consumption and cost of advanced powertrain technologies. It has been validated for several powertrain configurations and vehicle classes using the Argonne Advanced Mobility Technology Laboratory (AMTL) vehicle test data (Kim et al. 2013; Kim et al. 2012; Kim et al. 2009; Rousseau et al. 2006; Cao 2007; Rousseau 2000; Pasquier et al. 2001).

2.3 TEST PROCEDURE

Energy consumption was simulated using the Urban Dynamometer Driving Schedule (UDDS) and Highway Federal Emissions Test (HWFET) (U.S. EPA, 2021), a combination which will herein be referred to as “the combined driving cycle.” The vehicle costs are calculated from individual component characteristics (e.g., power, energy, weight).

3 ASSUMPTIONS

Individual vehicle component target assumptions have been determined in collaboration with experts from DOE, while various vehicle assumptions are based on consultation with other national laboratories, industry, and academia. Each vehicle simulation utilizes a number of component assumptions.

3.1 ENGINE

The latest designs of internal combustion engines (ICEs) with current state-of-the-art technologies are selected as the baseline for the different types of fuel considered: gasoline (spark ignition [SI]) and diesel (compression ignition [CI]). The engines used for HEVs and PHEVs are based on Atkinson cycles generated from test data of a 2010 Toyota Prius collected at the Argonne dynamometer testing facility, and the efficiency maps are scaled in order to meet DOE targets.

A wide range of technologies has been designed to increase engine efficiencies, including

- Low-friction lubricants.
- Reduced engine friction losses.
- Cylinder deactivation.
- Advanced cylinder deactivation with dynamic skip-firing.
- Variable valve timing (VVT) and variable valve lift (VVL).
- Turbocharging and downsizing.
- Variable compression ratio (VCR).
- Stoichiometric and lean-burn gasoline direct injection.

Instead of analyzing individual engine technologies, the approach is to consider baskets of advanced technologies consistent with expectations of engine performance over time. The peak and part-load efficiencies have been selected for each fuel type and timeframe after discussions with experts and review of the available literature. The different part-load operations ensure different operating regions of the engines correspond to coupling with advanced transmissions. These areas determine the vehicle operations in standard U.S. regulatory cycles to determine the fuel economy of the vehicles. Table 1-1 illustrates the engine peak and part-load efficiencies for a conventional powertrain across the different laboratory years. The low and high labels correspond to the different technology performance cases.

TABLE 1-1 Engine peak and part-load efficiency assumptions

Lab Year	Model Year	Technology Progress Case	Engine Type	Fuel	Peak Eff (%)	Engine eff at 2bar at 2000rpm (%)	Engine eff at 20% at 2000rpm (%)	Engine eff at 3bar at 1300rpm (%)
2015	2020	Low	Naturally Aspirated	Gasoline	36.0%	24.0%	24.0%	
2020	2025	Low	Naturally Aspirated	Gasoline	38.0%	25.0%	25.0%	
2020	2025	High	Naturally Aspirated	Gasoline	43.0%	29.0%	29.0%	33.0%
2025	2030	Low	Naturally Aspirated	Gasoline	40.0%	26.0%	26.0%	31.0%
2025	2030	High	Naturally Aspirated	Gasoline	43.0%	30.0%	30.0%	35.0%
2030	2035	Low	Naturally Aspirated	Gasoline	42.0%	29.0%	29.0%	34.0%
2030	2035	High	Naturally Aspirated	Gasoline	45.0%	32.0%	32.0%	37.0%
2045	2050	Low	Naturally Aspirated	Gasoline	44.0%	31.0%	31.0%	36.0%
2045	2050	High	Naturally Aspirated	Gasoline	47.0%	35.0%	35.0%	39.0%
2015	2020	Low	Diesel	Diesel	44.0%	28.0%	35.0%	
2020	2025	Low	Diesel	Diesel	45.0%	28.0%	35.0%	
2020	2025	High	Diesel	Diesel	50.0%	31.0%	40.0%	36.0%
2025	2030	Low	Diesel	Diesel	46.0%	29.0%	37.0%	35.0%
2025	2030	High	Diesel	Diesel	50.0%		42.0%	39.0%
2030	2035	Low	Diesel	Diesel	47.0%		39.0%	37.0%
2030	2035	High	Diesel	Diesel	51.0%		44.0%	41.0%
2045	2050	Low	Diesel	Diesel	48.0%		41.0%	39.0%
2045	2050	High	Diesel	Diesel	52.0%		46.0%	43.0%
2015	2020	Low	Turbo	Gasoline	35.9%	24.0%	29.1%	27.0%
2020	2025	Low	Turbo	Gasoline	39.0%	25.0%	30.0%	28.0%
2020	2025	High	Turbo	Gasoline	43.0%	26.0%	36.0%	38.0%
2025	2030	Low	Turbo	Gasoline	39.0%	25.0%	32.0%	29.0%
2025	2030	High	Turbo	Gasoline	43.0%	28.0%	36.0%	38.0%
2030	2035	Low	Turbo	Gasoline	40.0%	26.0%	34.0%	32.0%
2030	2035	High	Turbo	Gasoline	44.0%	32.0%	39.0%	38.0%
2045	2050	Low	Turbo	Gasoline	42.0%	28.0%	36.0%	34.0%
2045	2050	High	Turbo	Gasoline	46.0%	34.0%	41.0%	40.0%
2015	2020	Low	HEV	Gasoline	40.0%	25.1%	24.0%	
2020	2025	Low	HEV	Gasoline	40.0%	26.0%	25.0%	
2020	2025	High	HEV	Gasoline	46.0%	30.0%	29.0%	33.0%
2025	2030	Low	HEV	Gasoline	41.0%	27.0%	26.0%	31.0%
2025	2030	High	HEV	Gasoline	46.0%	31.0%	30.0%	35.0%
2030	2035	Low	HEV	Gasoline	41.0%	29.5%	29.5%	34.0%
2030	2035	High	HEV	Gasoline	48.0%	33.0%	32.0%	37.0%
2045	2050	Low	HEV	Gasoline	43.0%	31.6%	31.0%	36.0%
2045	2050	High	HEV	Gasoline	50.0%	35.5%	35.0%	39.0%
2015	2020	Low	Naturally Aspirated	CNG	36.0%			
2020	2025	Low	Naturally Aspirated	CNG	39.9%			
2020	2025	High	Naturally Aspirated	CNG	44.7%			
2025	2030	Low	Naturally Aspirated	CNG	42.0%			
2025	2030	High	Naturally Aspirated	CNG	44.7%			
2030	2035	Low	Naturally Aspirated	CNG	44.1%			
2030	2035	High	Naturally Aspirated	CNG	46.8%			
2045	2050	Low	Naturally Aspirated	CNG	46.2%			
2045	2050	High	Naturally Aspirated	CNG	48.9%			

3.2 FUEL CELL & HYDROGEN STORAGE TANK SYSTEM

Table 1-2 illustrates the power density of fuel cell systems and shows that, between the reference case of laboratory years 2015 and 2045, the power density increases from 650 W/kg for the low scenario to up to 1,000 W/kg for the high scenario. The low and high labels correspond to the two different technology performance cases considered in the study. Along with the various assumed characteristics the fuel cell system, the different parameters of the hydrogen storage tank system are also specified.

TABLE 1-2 Fuel cell and hydrogen storage tank system assumptions

Lab Year	Model Year	Technology Progress Case	FC Peak Eff (%)	FC specific power (W/kg)	FC cost ($/kw)	H2 slope (kg tank/ kg H2)	Tank Cost slope ($/usable kg of H2)	Tank Cost (fixed) ($)
2015	2020	Low	61%	650	165	22.7	352	1946
2020	2025	Low	64%	860	111	22.7	352	1946
2020	2025	High	64%	860	111	22.7	352	1946
2025	2030	Low	64%	860	77	22.7	352	1946
2025	2030	High	65%	900	66	22.7	236	1849
2030	2035	Low	64%	860	64	22.7	352	1946
2030	2035	High	67%	900	52	22.7	191	981
2045	2050	Low	64%	860	40	22.7	352	1946
2045	2050	High	68%	1000	30	22.7	145	679

The hydrogen tank weight is measured using the equation:

$$H_2\ storage\ mass\ (kg) = H_2\ fuel\ mass\ (kg)\ \times H_2\ slope\ \left(\frac{kg\ tank}{kg\ H_2}\right)$$

The hydrogen tank cost is calculated using the equation:

$$H_2\ storage\ cost\ (\$) = fixed\ tank\ cost\ (\$) + H_2 fuel\ mass (kg) \times tank\ cost\ slope\ \left(\frac{kg\ tank}{kg\ H_2}\right)$$

The fuel cell system simulated has been sized to various ranges on the adjusted combined cycles. In addition, 100% of the hydrogen present in the tank is referred to as usable. The fuel cell peak efficiency is assumed to be at 61% for reference laboratory year 2015, which increases to 68% for laboratory year 2045.

3.3 ELECTRIC MACHINE

Two electric machines are used as references in this study:

- Power-split vehicles use a permanent magnet electric machine (similar to the Toyota Camry).
- Series configuration (fuel cells) and electric vehicles (EVs) use an induction primary electric machine.

The efficiency maps were measured under normal temperature operating conditions and include the inverter losses. The electric machine power, similar to the engine, is sized for each individual vehicle. Table 1-3 details the electric machine efficiency map sources for the different powertrain configurations.

TABLE 1-3 Electric machine efficiency map sources for different powertrain configurations

Powertrain Type	Source of Efficiency Map for Motor1 (Traction Motor) + Inverter	Source of Efficiency Map for Motor 2 (Motor/Generator) + Inverter
Mild-hybrid BISG	Toyota Camry EM1 data from Oak Ridge National Laboratory (ORNL) (Burress et al. 2008)	
Parallel HEV	Hyundai Sonata HEV data from ORNL (Olszewski 2011)	
Split HEV and blended PHEV	Toyota Camry EM1 data from ORNL (Burress et al. 2008)	Toyota Camry EM2 Data from ORNL (Burress et al. 2008)
EREV PHEV	Toyota Camry EM1 data from ORNL (Burress et al. 2008)	Hyundai Sonata HEV Data from ORNL (Olszewski 2011)
BEV and FCV	Chevrolet Bolt EM data (Momen 2018)	

For the study, the peak efficiency of electric machines for the different powertrains was scaled, as shown in Table 1-4. Please note that this is the peak efficiency value for the electric machine, the average operational efficiency will depend on the drive cycle and vehicle characteristics.

TABLE 1-4 Efficiency scaling of electric machines

Vehicle Powertrain	Peak Efficiency Scaled (%)
Micro-HEV / mid-hybrid BISG	96
Power-split HEV / Parallel HEV	96
Blended PHEV20 AER / E-REV PHEV50 AER	96
BEV and FCV	98

3.4 ENERGY STORAGE SYSTEM

Battery performance data used in the study are provided by Argonne, Idaho National Laboratory, and major battery suppliers (Francfort 2014). Argonne developed the scaling algorithm used for high-energy cases (Nelson et al. 2007). The scaling algorithm is used to scale the battery cell capacity as well as number of cells.

Based on the performance data provided by Argonne, the HEV, PHEV, and BEV applications use a lithium-ion (Li-ion) battery. Table 1-5 summarizes the battery characteristics.

TABLE 1-5 Battery assumptions

Lab Year	Model Year	Technology Progress Case	Vehicle Powertrain	Specific Power @ 70% SOC (W/kg)	Total Pack Energy Density (Wh/kg)	Cost of Power ($/kW)	Total Pack Energy Cost ($/kWh)
2015	2020	Low	BEV	2750	189		170
2020	2025	Low	BEV	3000	189		128
2020	2025	High	BEV	4000	256		100
2025	2030	Low	BEV	4000	256		100
2025	2030	High	BEV	5000	344		70
2030	2035	Low	BEV	4500	255		80
2030	2035	High	BEV	5500	340		60
2045	2050	Low	BEV	5000	298		50
2045	2050	High	BEV	6000	340		40
2015	2020	Low	HEV	2750		20	
2020	2025	Low	HEV	3000		20	
2020	2025	High	HEV	4000		16	
2025	2030	Low	HEV	4000		19	
2025	2030	High	HEV	5000		15	
2030	2035	Low	HEV	4500		18	
2030	2035	High	HEV	5500		14	
2045	2050	Low	HEV	5000		17	
2045	2050	High	HEV	6000		13	
2015	2020	Low	PHEV	2750	100	20	200
2020	2025	Low	PHEV	3000	136	20	150
2020	2025	High	PHEV	4000	140	16	110
2025	2030	Low	PHEV	4000	140	19	110
2025	2030	High	PHEV	5000	147	15	90
2030	2035	Low	PHEV	4500	147	18	90
2030	2035	High	PHEV	5500	165	14	70
2045	2050	Low	PHEV	5000	144	17	70
2045	2050	High	PHEV	6000	189	13	50

3.5 LIGHTWEIGHTING

Table 1-6 details the lightweighting assumptions on the glider mass across vehicle classes and laboratory years. Low and high cases illustrate the different technology performance cases. Glider mass reduction varies across vehicle classes, though lightweighting cost ($/kg-saved) assumptions over time are similar among similarly sized vehicles. The assumption of reduction can be explained by the use of better materials and technologies in the future, such as aluminum unibody structures.

TABLE 1-6 Lightweighting across vehicle classes and laboratory years

Lab Year	Model Year	Technology Progress Case	Class	Glider % Reduction	Cost of lightweighting ($/kg-saved)
2020	2025	Low	Midsize	8.0%	1.3
2020	2025	High	Midsize	16.0%	7.3
2025	2030	Low	Midsize	10.0%	7.3
2025	2030	High	Midsize	25.0%	17
2030	2035	Low	Midsize	10.0%	7.3
2030	2035	High	Midsize	30.0%	14.7
2045	2050	Low	Midsize	10.0%	6.7
2045	2050	High	Midsize	32.0%	10.7
2020	2025	Low	Small SUV	6.8%	1.3
2020	2025	High	Small SUV	12.3%	7.3
2025	2030	Low	Small SUV	9.5%	1.3
2025	2030	High	Small SUV	17.7%	6.2
2030	2035	Low	Small SUV	13.6%	7.3
2030	2035	High	Small SUV	22.0%	14.7
2045	2050	Low	Small SUV	17.6%	6.7
2045	2050	High	Small SUV	28.2%	10.7
2020	2025	Low	Compact	4.1%	1.3
2020	2025	High	Compact	10.8%	7.3
2025	2030	Low	Compact	5.4%	1.3
2025	2030	High	Compact	17.6%	6.2
2030	2035	Low	Compact	5.4%	1.3
2030	2035	High	Compact	18.9%	5
2045	2050	Low	Compact	5.4%	1.3
2045	2050	High	Compact	18.9%	2.7
2020	2025	Low	Midsize SUV	11.2%	7.3
2020	2025	High	Midsize SUV	13.0%	7.3
2025	2030	Low	Midsize SUV	12.5%	7.3
2025	2030	High	Midsize SUV	20.0%	17
2030	2035	Low	Midsize SUV	16.7%	7.3
2030	2035	High	Midsize SUV	24.1%	14.7
2045	2050	Low	Midsize SUV	20.9%	17.3
2045	2050	High	Midsize SUV	30.1%	10.7
2020	2025	Low	Pickup	11.6%	7.3
2020	2025	High	Pickup	11.6%	7.3
2025	2030	Low	Pickup	14.5%	7.3
2025	2030	High	Pickup	20.9%	17
2030	2035	Low	Pickup	17.3%	7.3
2030	2035	High	Pickup	24.0%	14.7
2045	2050	Low	Pickup	21.7%	17.3
2045	2050	High	Pickup	28.3%	10.7

3.6 VEHICLE ASSUMPTIONS

Table 1-7 summarizes values defined for the frontal area of the reference vehicles for the different vehicle classes and performance categories.

TABLE 1-7 Frontal area summary

Vehicle Class	Performance Category	Reference value (m^2)
Compact	Base/Premium	2.3
Midsize	Base/Premium	2.35
Small SUV	Base/Premium	2.65
Midsize SUV	Base/Premium	2.85
Pickup	Base/Premium	3.25

The fixed rolling resistance coefficient is set at 0.0006 for all vehicle classes and performance categories as the reference value. Table 1-8 details the rolling resistance coefficient reductions for all vehicle classes and performance categories across all laboratory years and technology progresses.

TABLE 1-8 Rolling resistance coefficient reductions for reference vehicles by laboratory year and technology progress

Model Year:		MY2020	MY2025		MY2030		MY2035		MY2050	
Lab Year:		2015	2020		2025		2030		2045	
Technology Progress:		Low	Low	High	Low	High	Low	High	Low	High
Rolling Resistance Reduction	%	0	5	10	5	10	10	25	15	30

Table 1-9 summarizes the reference drag coefficient assumptions for different vehicle classes.

TABLE 1-9 Reference drag coefficient assumptions

Vehicle Class	Performance Category	Reference Value
Compact	Base/premium	0.31
Midsize	Base/premium	0.30
Small SUV	Base/premium	0.36
Midsize SUV	Base/premium	0.38
Pickup	Base/premium	0.42

Table 1-10 details the drag coefficient reductions for all vehicle classes and performance categories across laboratory years and technology progress.

TABLE 1-10 Drag coefficients reductions for reference vehicles by laboratory year and technology progress

Model Year:		MY2020	MY2025		MY2030		MY2035		MY2050	
Lab Year:		2015	2020		2025		2030		2045	
Technology Progress		Low	Low	High	Low	High	Low	High	Low	High
Drag Coefficient Reduction	%	0	5	10	5	10	10	25	15	30

4 VEHICLE POWERTRAIN SIZING

4.1 VEHICLE TECHNICAL SPECIFICATION (VTS)

The first step in sizing individual powertrain components is to define the vehicle technical specifications (e.g., maximum speed, 0-60mph, gradeability, etc.). Minimum requirements were developed based on an in-depth analysis of current vehicles in the market.

Table 1-11 provides the 0-60mph minimum requirements across vehicle classes and categories.

TABLE 1-11 Vehicle classification and performance categories

Vehicle Class	Performance Category	0–60 mph time (s)
Compact	Base	9
	Premium	7
Midsize	Base	8
	Premium	6
Small SUV	Base	8
	Premium	6
Midsize SUV	Base	9
	Premium	7
Pickup	Base	7
	Premium	7

Additional performance metrics include:

- Gradeability, 6% grade at 65 mph.
- Payload, 900 kg (pickup base/premium only).
- Towing, 3,000 kg (pickup base) and 4,350 kg (pickup premium).

4.2 POWERTRAIN SIZING ALGORITHMS

Sizing each component for each vehicle is an iterative process. Using a battery electric vehicle as an example: increasing the required battery energy would increase the vehicle weight, which would then result in an increase in electric machine power. Considering the large number of vehicles to be simulated, we used several automated sizing algorithms to provide a fair comparison among technologies.

All sizing algorithms follow the same concept: the vehicle is built from the bottom up, meaning each component assumption (specific power, efficiency, and so on) is taken into account to define the entire set of vehicle attributes (vehicle curb weight and so forth). The process is recursive in the sense that the main component characteristics (maximum power, vehicle weight, and so on) are influenced accordingly until all specifications are met. On average, the sizing algorithm takes between 5 and 10 iterations to converge to a solution. Specific algorithms have been developed for each powertrain (i.e., conventional, power-split, series, electric) and application (i.e., HEV, PHEV) combination.

Figure 1-2 illustrates the different processes involved in sizing a conventional vehicle.

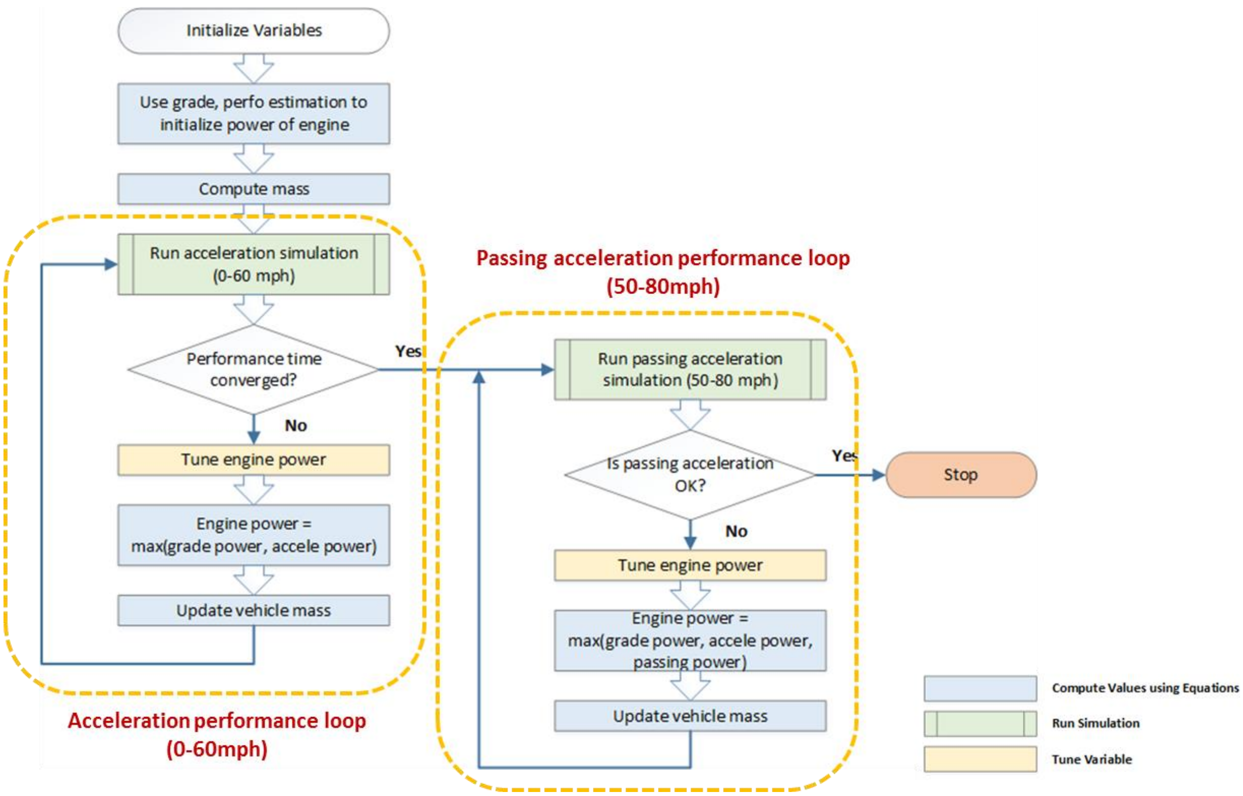

FIGURE 1-2 Conventional powertrain sizing algorithm

- For HEVs, the electric machine and battery power levels are determined to capture all the regenerative energy from a UDDS cycle. The engine and the generator are then sized to meet the gradeability and performance requirements.

- For PHEV20s, the electric machine and battery power levels are sized to be able to follow the UDDS cycle in electric-only mode. (This control is used only for sizing; a blended approach is used to evaluate consumption.) The battery-usable energy is defined to follow the combined drive cycle for 20 mi (with EPA adjusted, sticker values). The engine is then sized to meet both performance and gradeability requirements.

- For PHEV50s, the main electric machine and battery power levels are sized to be able to follow the aggressive EPA US06 drive cycle (US06, duty cycle with aggressive highway driving) in electric-only mode. The battery-usable energy is defined to follow the combined drive cycle for 50 mi (adjusted), depending on the requirements. The genset (engine plus generator) or the fuel cell systems are sized to meet the gradeability requirements.

4.3 POWERTRAIN SIZING RESULTS

This section provides examples of maximum power, energy, and weight for the base midsize vehicle across several powertrain configurations.

4.3.1 Conventional Vehicles

Figure 1-3 illustrates the evolution in engine peak power for conventional vehicles across different laboratory years and technology progress cases for the different performance categories. Driven by lightweighting and aerodynamic improvements, the engine peak power decreases over time. The different transmission penetration of different lab years has an effect in the performance sizing.

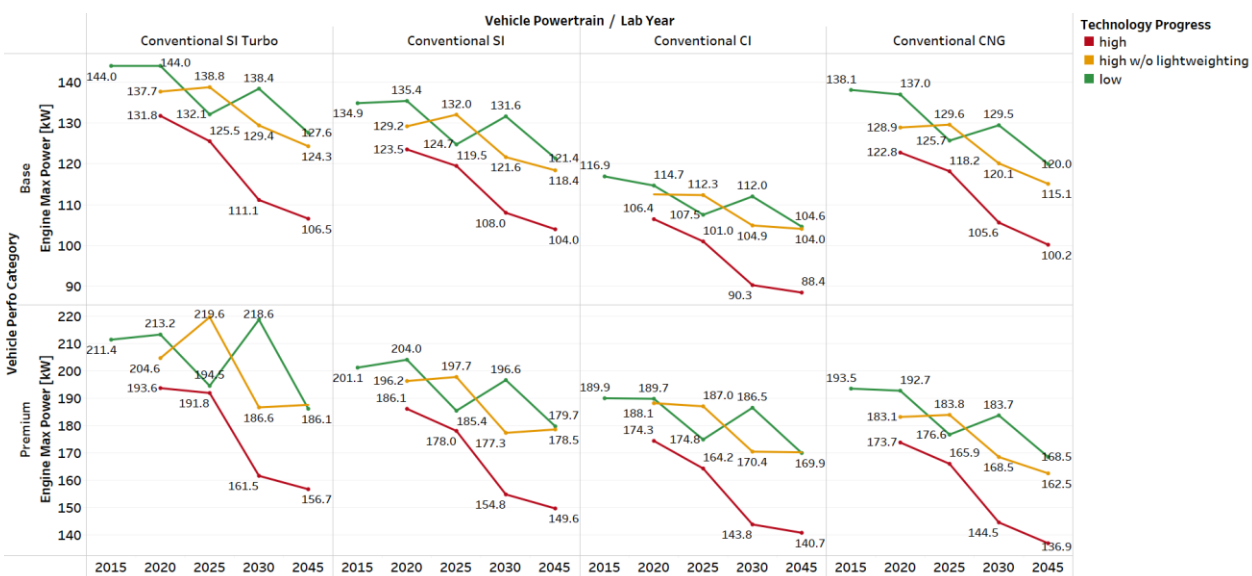

FIGURE 1-3 Engine maximum power for conventional midsize vehicles

Figure 1-4 illustrates the vehicle test weight for conventional vehicles across different laboratory years and technology progress cases for the different performance categories.

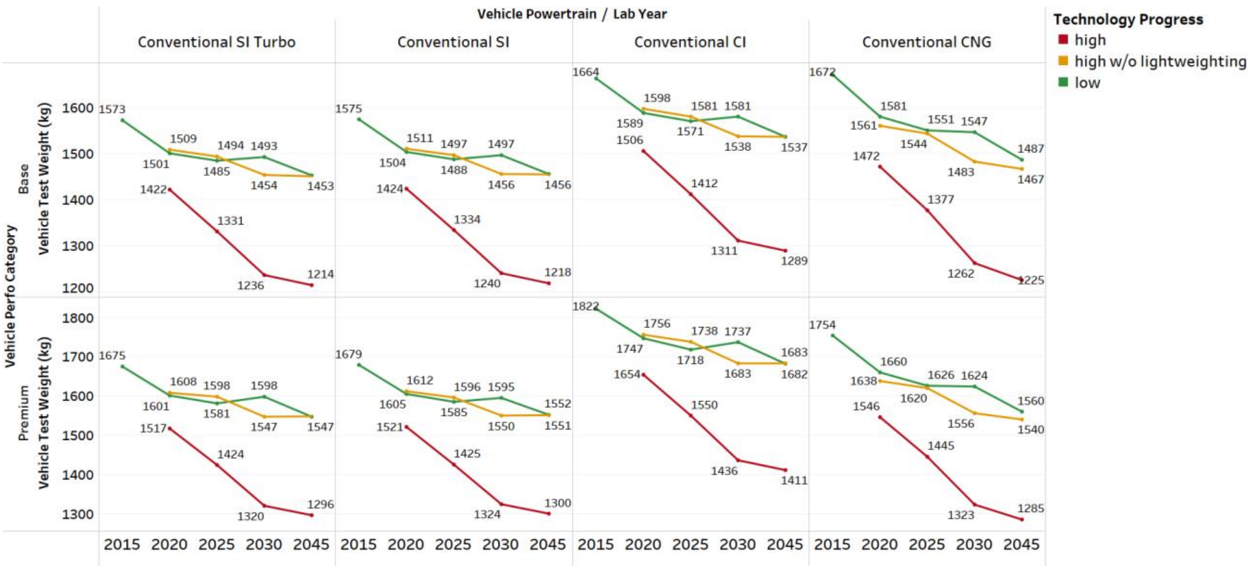

FIGURE 1-4 Vehicle test weight of conventional midsize vehicles

Over time, the vehicle test weight of conventional vehicles decrease by about 22 – 25% across the different fuel types, technology progress cases as well as performance categories. The main reason of the vehicle weight decrease is due to vehicle lightweighting in the future.

4.3.2 Power Split HEVs

Figure 1-5 illustrates the engine peak power for midsize HEVs. The engine power for HEVs is determined by both performance and gradeability requirements. While performance is the primary factor for current technologies, future lightweighting means that gradeability requirements will be critical in some cases. The engine peak power requirement decreases by about 22% - 25% across the different technology progress cases over time.

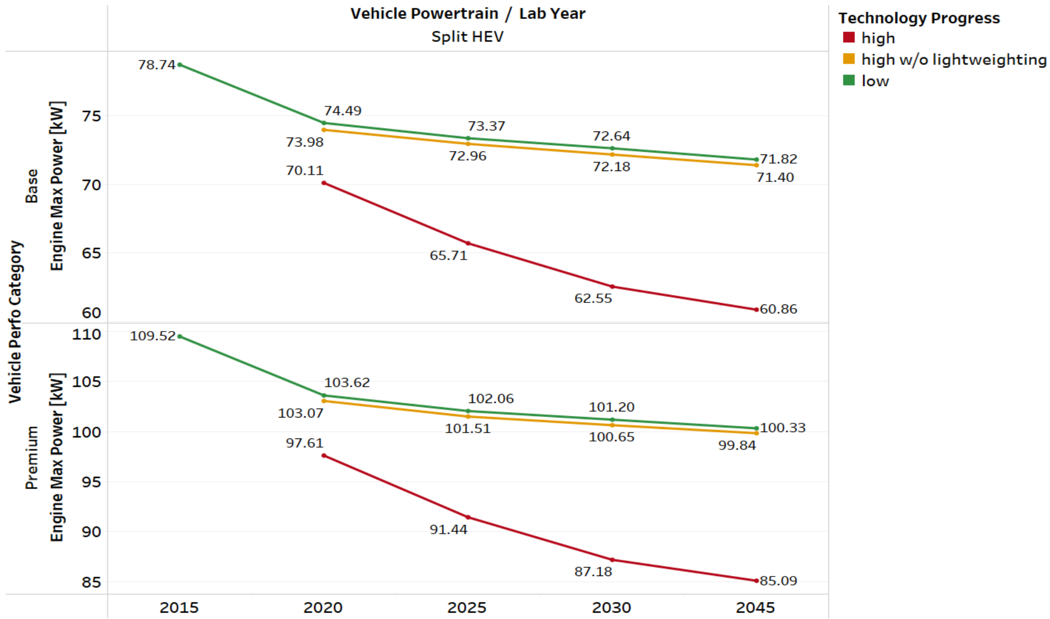

FIGURE 1-5 Engine peak power for split HEV for conventional powertrains

Figure 1-6 illustrates the evolution of electric machine peak power for HEVs with different performance categories. Electric machine peak power decreases in the future due to the effects of lightweighting and, to a lesser extent, other VTO technology advances (battery power density, etc.).

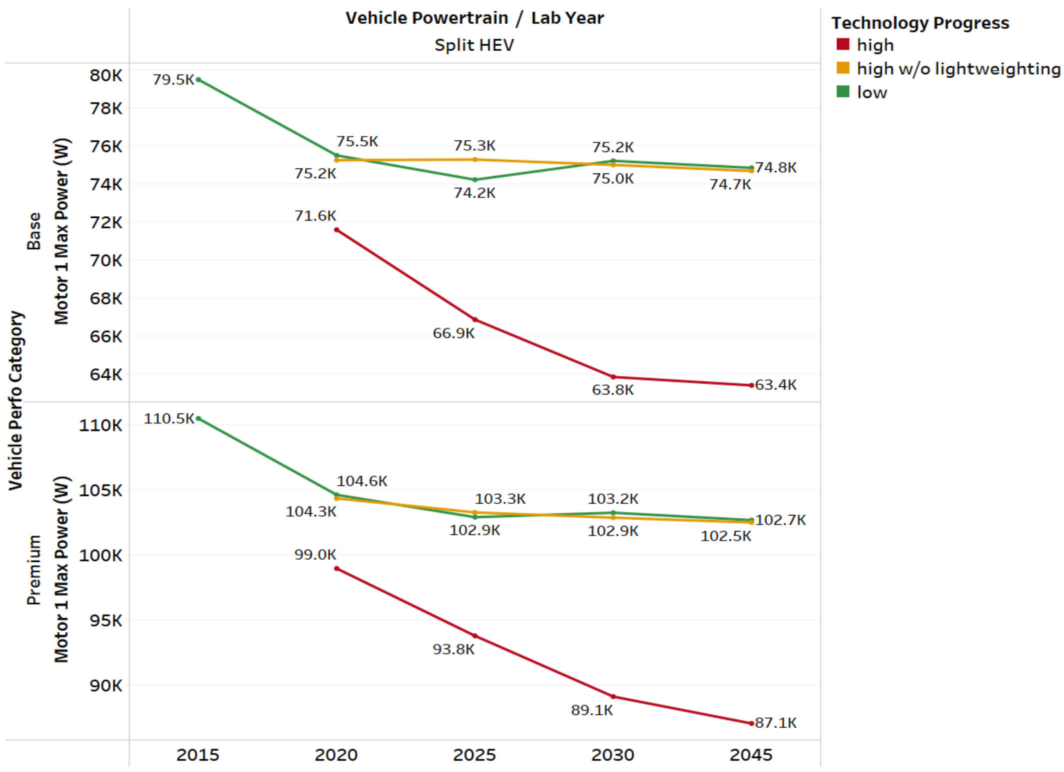

FIGURE 1-6 Electric machine peak power for midsize split HEVs

The electric machine peak power requirement decreases by about 5% - 20% across the different technology progress cases and the different performance categories.

4.3.3 Fuel Cell Electric Vehicles

Figure 1-7 illustrates the fuel cell peak power for midsize vehicles. Fuel cell systems show a decrease in fuel cell peak power over time, owing to vehicle lightweighting and improved component efficiency. The total decrease from the reference case to the 2045 case ranges between 14% and 45% for fuel cell electric vehicles in the base category.

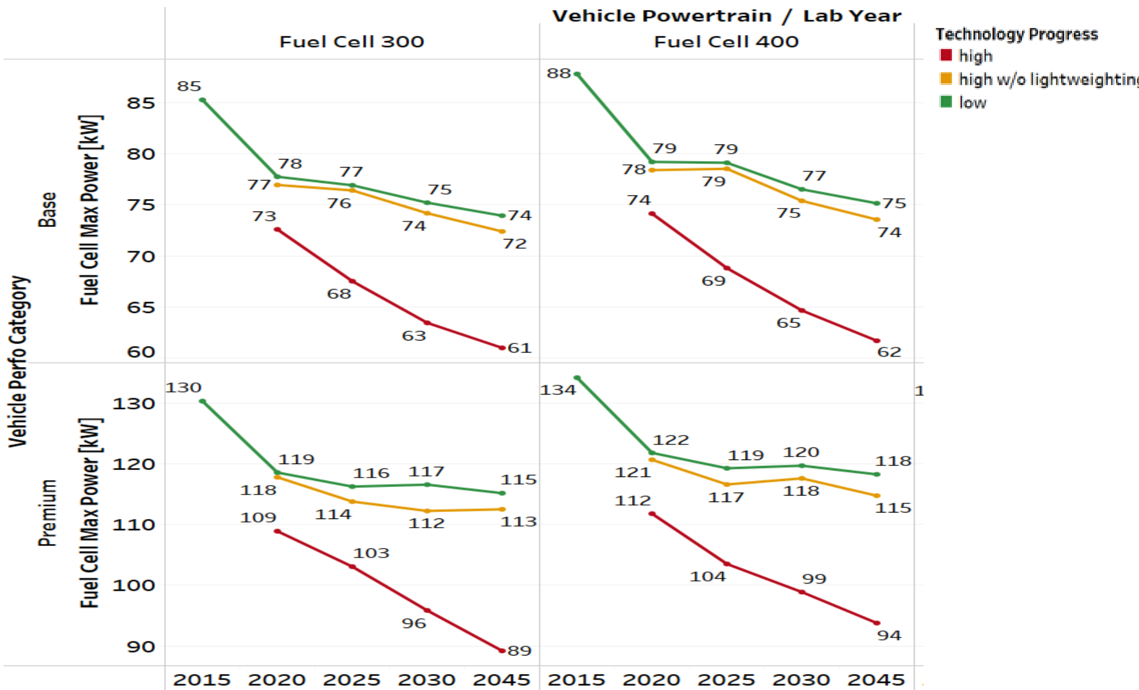

FIGURE 1-7 Fuel cell system power for midsize fuel cell electric vehicles

4.3.4 Battery Electric Vehicles

Figure 1-8 shows the electric machine peak power for the different BEVs of the midsize vehicle class. Electric machine peak power requirements decrease over time, owing to lightweighting and assumptions in electric machine efficiency improvements. The decrease ranges between 16% and 30% for a BEV with 200 mi of AER (beginning-of-life) on the combined driving cycle (adjusted) (BEV200), between 16% and 32% for a BEV with 300 mi of AER (beginning-of-life) on the combined driving cycle (adjusted) (BEV300), between 20% and 35% for a BEV with 400 mi of AER (beginning-of-life) on the combined driving cycle (adjusted) (BEV400), and between 25% and 40% for a BEV with 500 mi of AER (beginning-of-life) on the combined driving cycle (adjusted)(BEV500).

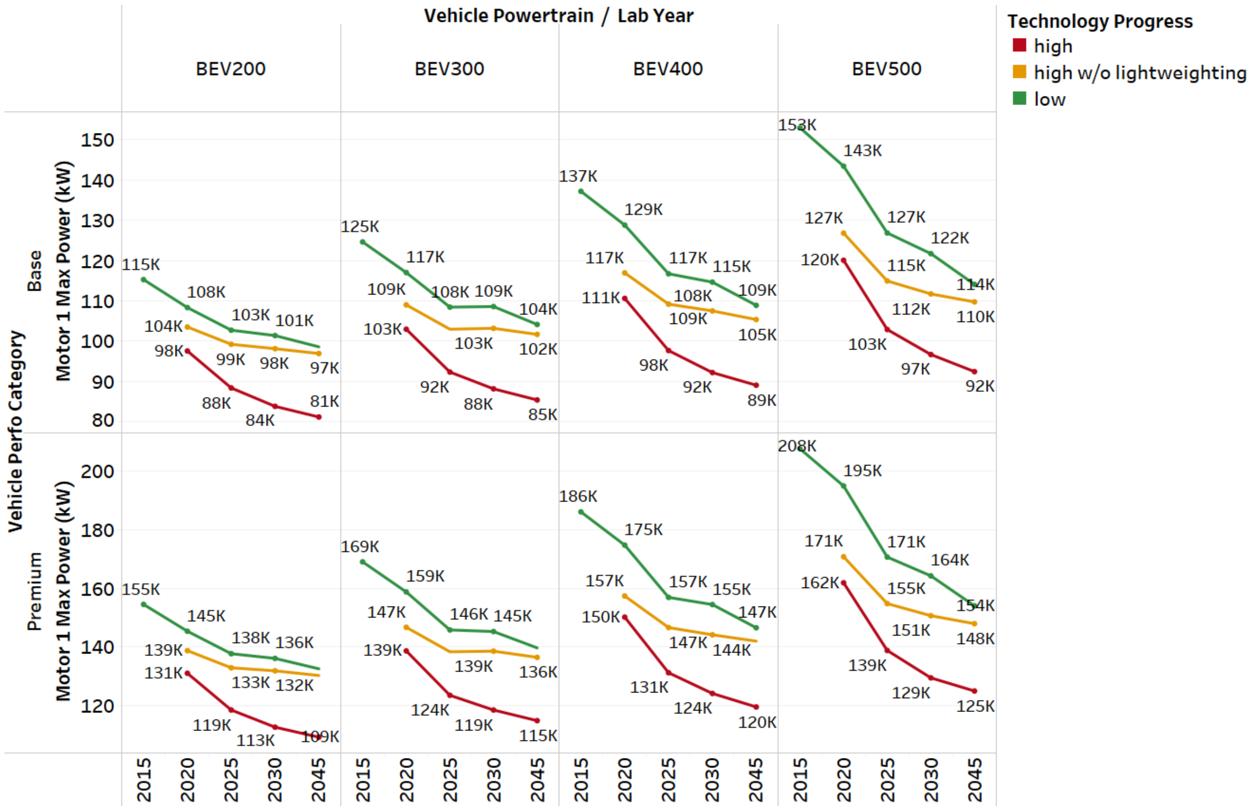

FIGURE 1-8 Electric machine power for midsize BEVs across powertrains

Figure 1-9 shows the battery pack peak power for different midsize BEV powertrains across the timeframes. Both the electric machine and the battery are close to 50% less powerful by 2045 compared with the reference case in 2015 for BEV200, a number that reaches almost 70% less powerful for the BEV400. This can be explained by the impact of lightweighting as well as the combined effect of several improved vehicle component assumptions. With lightweighting and technology advances, the same performance could be achieved with a much smaller battery size; hence, the sizing logic results in less powerful electric machines and batteries in the future when compared to the reference case in 2015. BEVs with higher ranges and bigger battery and motor sizes result in higher reductions because of the advancement in vehicle technologies.

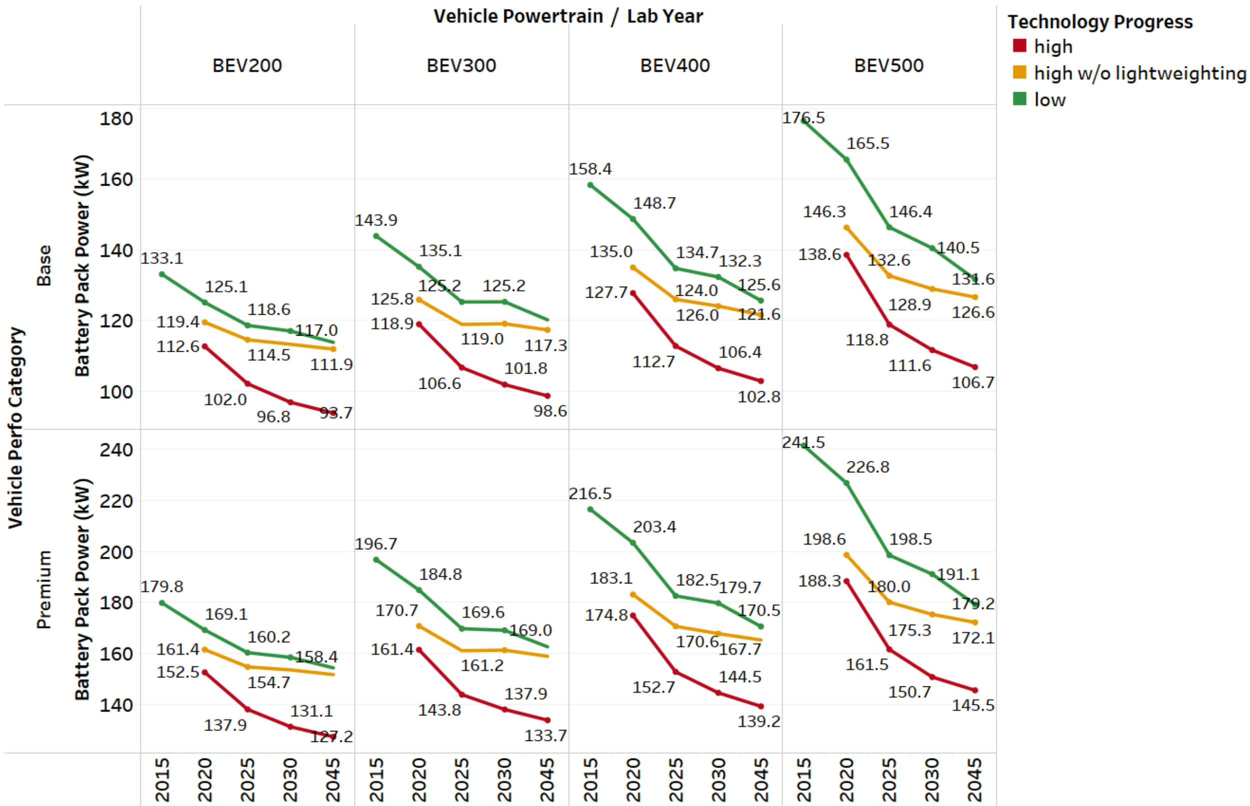

FIGURE 1-9 Battery pack power for midsize BEVs across powertrains

Figure 1-10 shows the battery pack total energy for the different midsize BEV powertrains across the timeframes. Following the trend line observed for motor and battery pack power sizes, the battery total energy requirement also decreases similarly over time. For the BEV200, the battery pack total energy decreases by 57% for 2045 compared to 2015. This reduction reaches almost 80% in total battery pack energy for the BEV400. With higher-range BEVs, the reduction observed is much greater because of the combined effects of advances in vehicle technology.

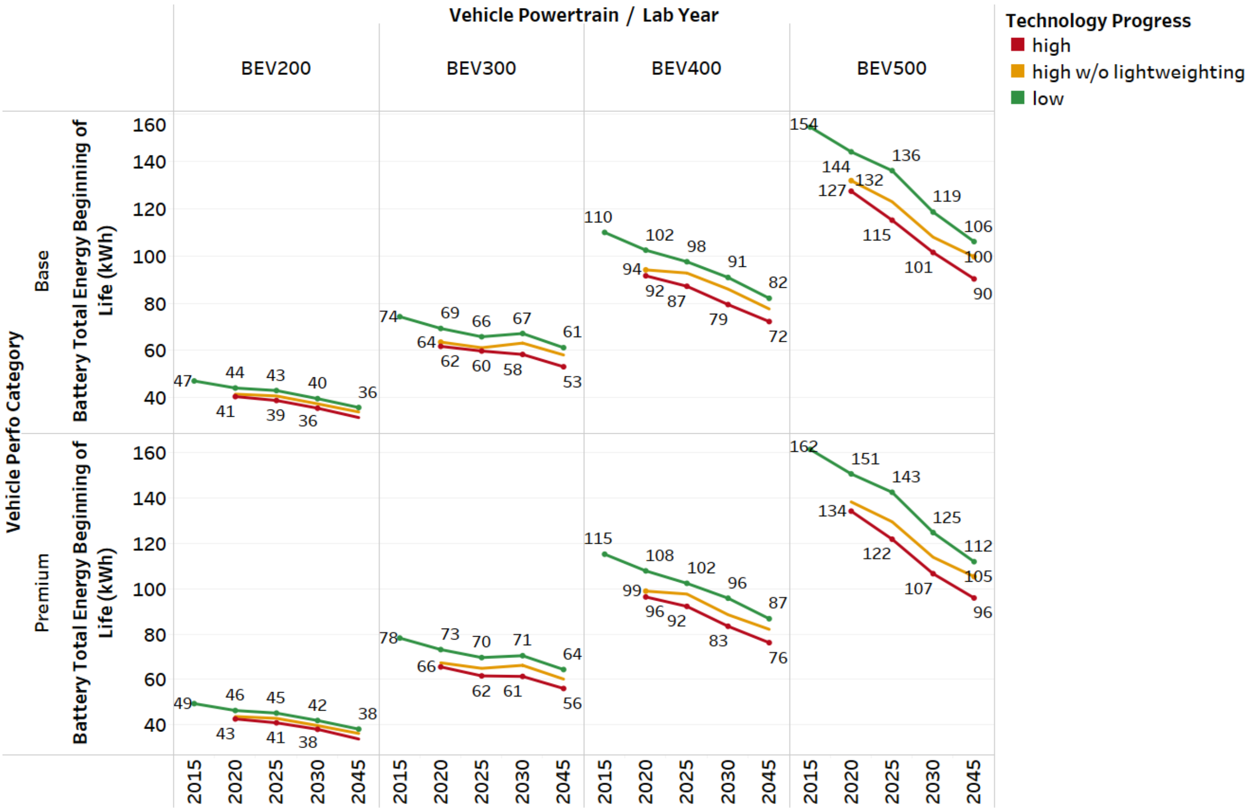

FIGURE 1-10 Battery pack total energy requirements for midsize BEVs across powertrains

5 ENERGY CONSUMPTION RESULTS

Unless otherwise specified, all fuel consumption results are for the US combined drive cycle using unadjusted values based on gasoline equivalent. The results in this section represent the midsize vehicle class only (full results available in the supplementary data).

5.1 CONVENTIONAL VEHICLES

The evolution of fuel consumption for the midsize conventional powertrain for gasoline and diesel fuel types is shown in Figure 1-11.

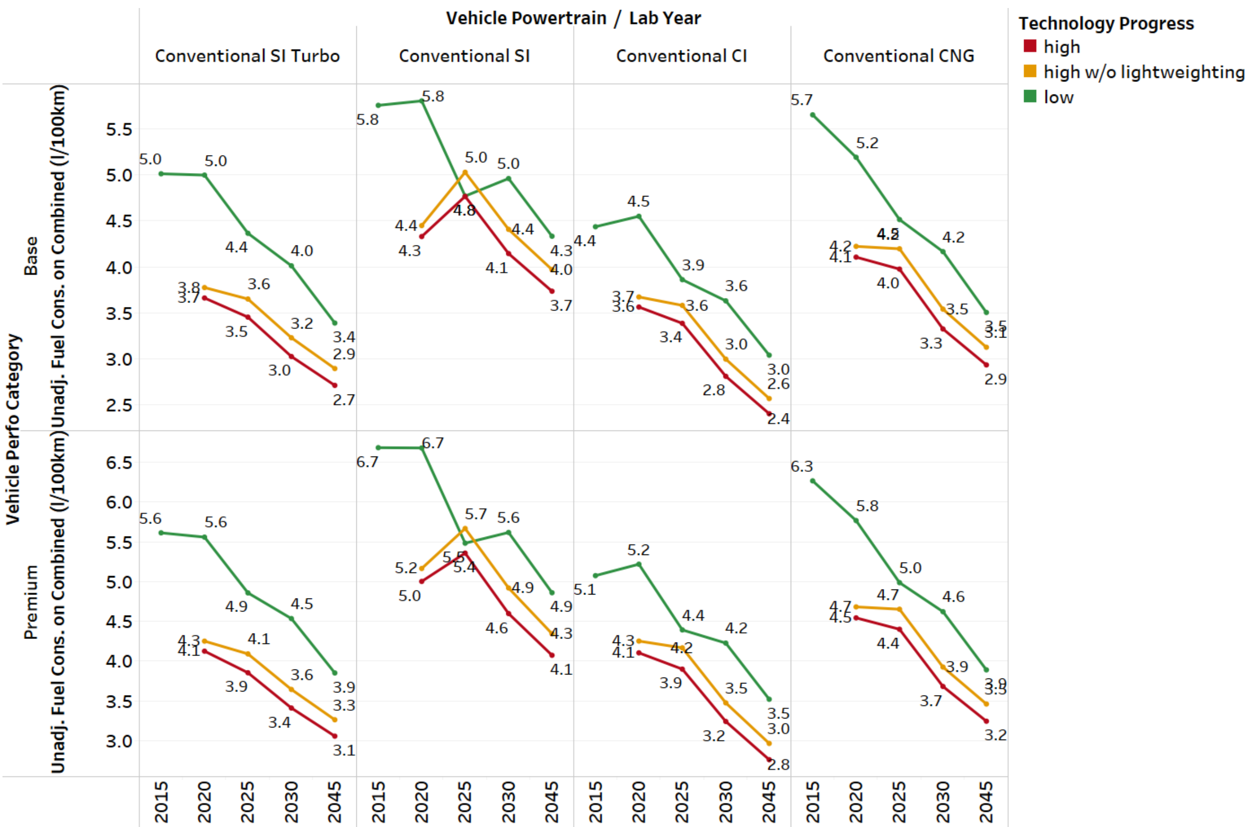

FIGURE 1-11 Unadjusted fuel consumption for conventional midsize vehicles

Fuel consumption decreases over time across fuels. Gasoline conventional vehicles consume from 40% to 54% less fuel by 2045 compared with the reference (2015) laboratory year. Diesel powertrains evolve somewhat differently, with decreases ranging from 41% to 57% for the base performance category. The improvement in fuel consumption varies slightly across the different performance categories.

5.2 POWER SPLIT HEVs

The evolution in fuel consumption for midsize split HEVs is shown in Figure 1-12. Similar to the conventional powertrain, the fuel consumption for HEVs is expected to decrease significantly over time. With reference to laboratory year 2015, the fuel consumption for gasoline HEVs decreases by 30% to 48% in laboratory year 2045 for the base performance category. The improvement in fuel consumption varies slightly across the different performance categories.

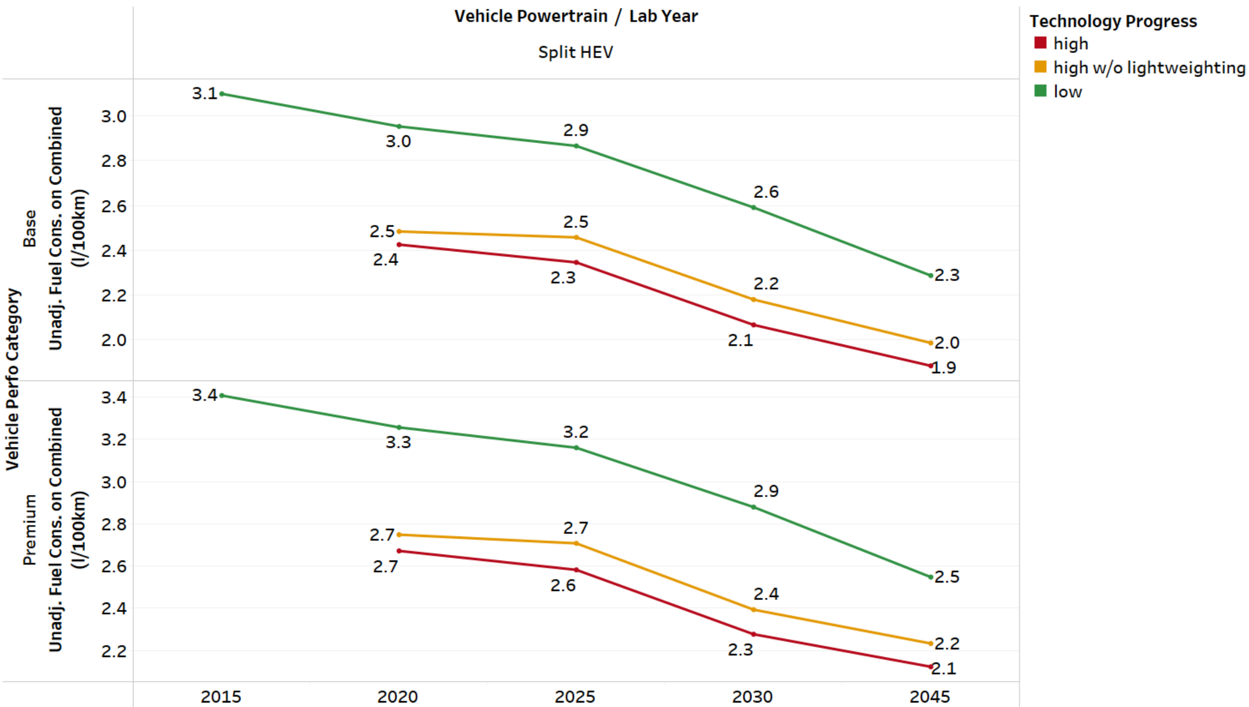

FIGURE 1-12 Unadjusted fuel consumption for midsize power-split HEVs

5.3 FUEL CELL ELECTRIC VEHICLES

The evolution in unadjusted fuel consumption for fuel cell vehicles is illustrated in Figure 1-13. Fuel consumption in 2045 is about 37% to 43% lower than the reference case of laboratory year 2015. This decrease is due to advances in technology and better component efficiencies over time.

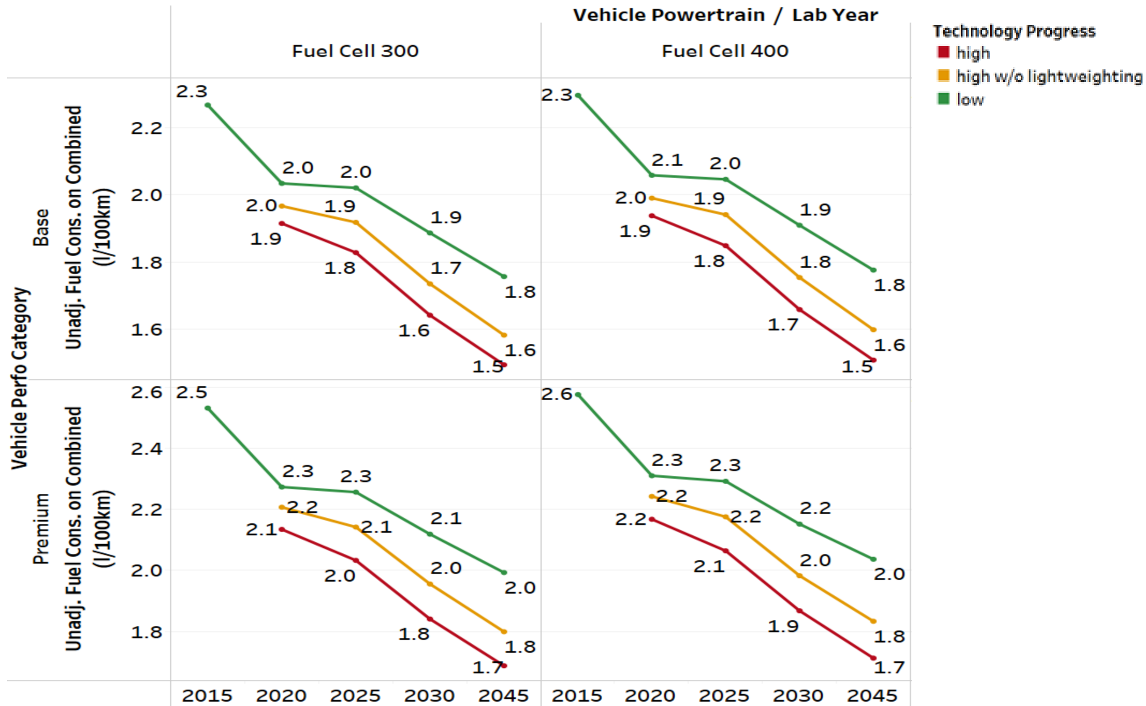

FIGURE 1-13 Unadjusted fuel consumption for midsize fuel cell electric vehicles

5.4 BATTERY ELECTRIC VEHICLES

Results for BEVs are presented in terms of electrical consumption for the two drive cycles used in the simulations: UDDS and HWFET. Improvements in lightweighting and component sizing in future years lead to a significant decrease in electrical consumption over time.

Figure 1-14 illustrates the electrical consumption for midsize BEVs. The values, expressed in Wh/mi, represent the average energy provided by the battery to drive the vehicle for 1 mi. The labels "low" and "high" represent the technology performance cases. The unadjusted electrical energy consumption in HWFET cycles tends to be consistently higher than that in the UDDS cycles for the corresponding cases. The trend is explained by examining the two drive-cycle curves and the energy recoverable by regenerative braking. The UDDS cycle consists of many strong and steep braking periods, which allow a great deal of the energy to be recovered. However, the HWFET cycle consists of stable speeds and limited braking. Hence, the battery recovers more energy through regenerative braking during a UDDS cycle than during a HWFET cycle. HWFET cycles also consist of higher speeds, which affect energy consumption.

FIGURE 1-14 Unadjusted electrical energy consumption by midsize BEVs for combined cycle

6 VEHICLE-MANUFACTURING COSTS

In addition to the two levels of technology performance uncertainties, the study computes two levels of technology cost uncertainty cases (low and high). In other words, the technology performance/technology cost uncertainty levels are illustrated according to technology progress cases low (low-technology performance/high-technology cost case) and high (high-technology performance/low-technology cost case). All costs reported in this section are in 2020 U.S. dollars (USD). The cost values in this section represent manufacturing costs, not sale prices. As mentioned earlier, along with the two main technology progress levels, an additional uncertainty level of high-technology progress case without lightweighting targets is also simulated.

6.1 CONVENTIONAL VEHICLES

Figure 1-15 illustrates manufacturing costs for conventional midsize vehicles. The labels “high” and “low” represent the different technology progress uncertainty cases. Vehicle prices increase from laboratory years 2015 to 2030 and then decrease by 2045. The increase in costs compared to the reference 2015 laboratory year can be explained by several factors, including the cost of lightweighting; the decrease in vehicle weight is accompanied by an increase in material cost brought about by escalating use of aluminum or carbon fiber and advanced component technologies. The eventual drop in vehicle manufacturing cost is driven by decrease in engine (due to lower displacements from sizing), transmission costs as well other accessory costs that achieve year over year improvements due to economies of scale. The difference in manufacturing costs between the diesel, CNG and gasoline vehicles can be explained by the differences in engine cost: CNG and diesel engine costs are much higher than gasoline vehicle engine costs, driving the difference in manufacturing costs.

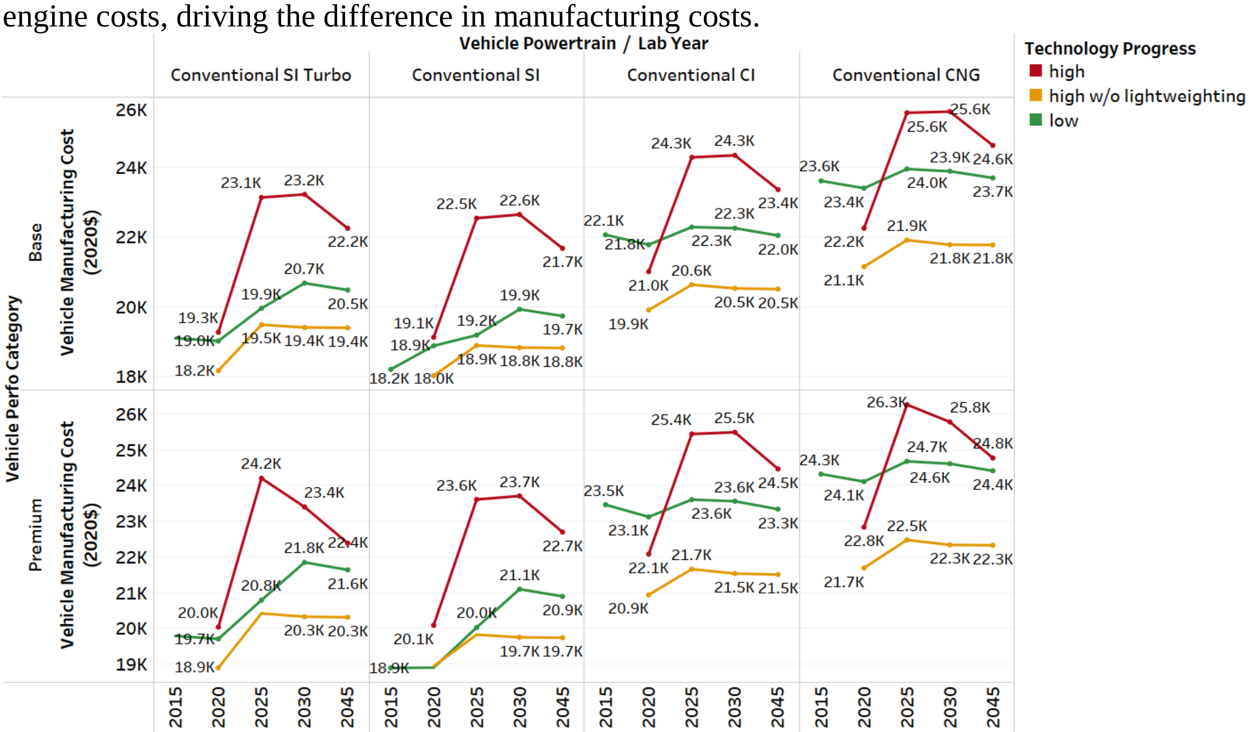

FIGURE 1-15 Manufacturing cost (2020 USD) of conventional vehicles

6.2 POWER SPLIT HEVs

Figure 1-16 shows the vehicle-manufacturing costs for power-split HEVs. Over time, manufacturing costs decrease for power-split HEVs because energy storage and electric machine costs decrease in the future. Although the glider cost increases over time, the overall effect on the manufacturing cost follows a downward trend.

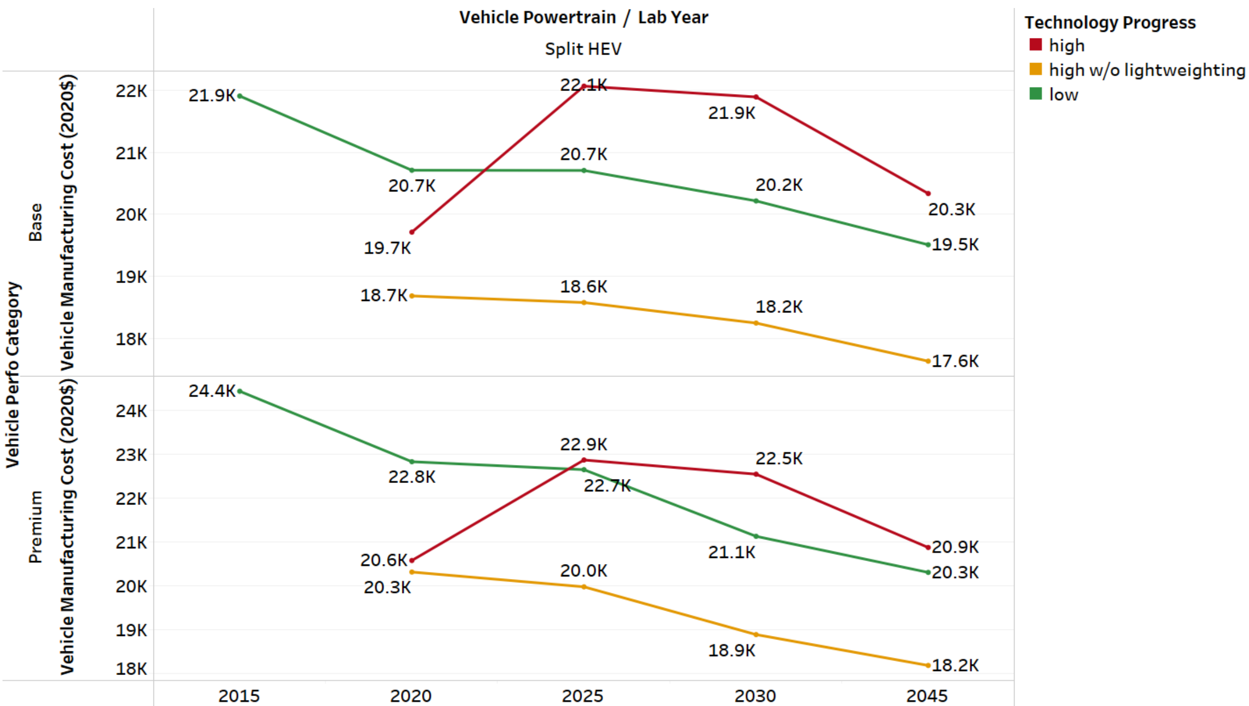

FIGURE 1-16 Manufacturing cost of midsize power-split HEVs

6.3 FUEL CELL ELECTRIC VEHICLES

Manufacturing costs of fuel cell vehicles are shown in Figure 1-17. As can be seen from the figure, over time, the difference in manufacturing costs steadily decreases. Compared to laboratory year 2015, the manufacturing cost of midsize vehicles is assumed to decrease by 10% to 15% by laboratory year 2045.

It is important to note that these estimates assume that fuel cells are manufactured at economies of scale in all years. This assumption was made for consistency with assumptions being made in other powertrains. However, fuel cells are not currently manufactured at high volume. As a result, the manufacturing costs and retail prices of fuel cell vehicles today are substantially higher than those in the projections below, and this difference will hold until production levels rise substantially.

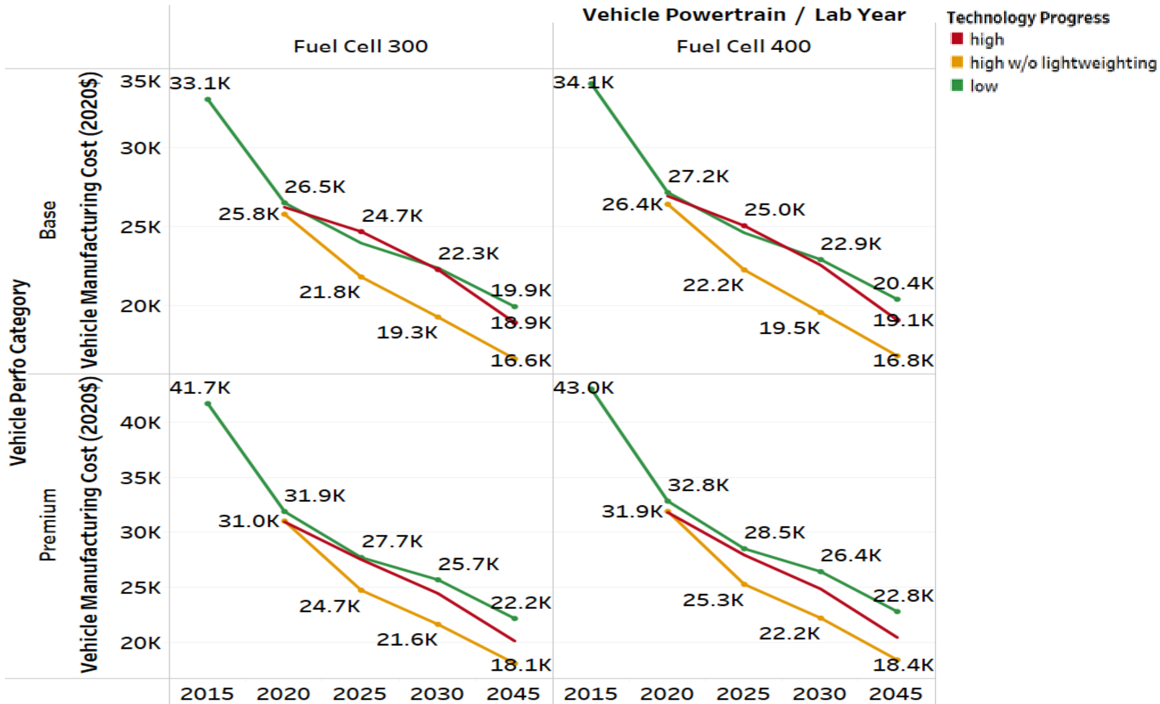

FIGURE 1-17 Manufacturing cost of midsize fuel cell electric vehicles

6.4 BATTERY ELECTRIC VEHICLES

Figure 1-18 illustrates the evolution of BEVs in terms of manufacturing cost. Lightweighting has an effect on battery sizes and hence decreases battery costs in future years. Battery size in turn affects the major manufacturing cost of BEVs. Higher-range BEVs have a greater impact on manufacturing costs in future years.

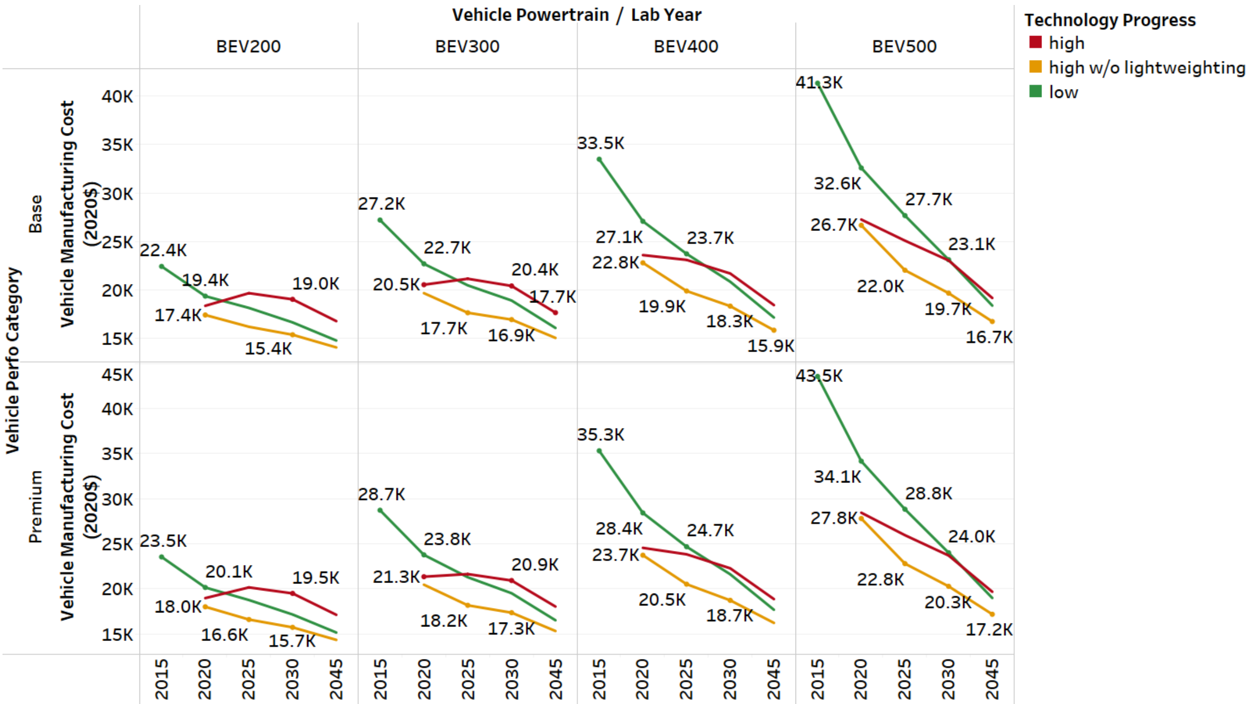

FIGURE 1-18 Manufacturing cost of midsize BEVs

7 VEHICLE FUEL CONSUMPTION VERSUS VEHICLE-MANUFACTURING COSTS

This section discusses the evolution of fuel consumption with respect to vehicle-manufacturing costs for the low- and high-technology progress cases discussed in Section 6.

7.1 CONVENTIONAL VEHICLES

Figure 1-19 illustrates the comparison of vehicle-manufacturing cost versus fuel consumption for conventional vehicles across multiple vehicle classes. The different-colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different vehicle classes. A key observation is that diesel vehicles have relatively higher manufacturing costs than gasoline vehicles. In addition, the figure shows the relative position of the different vehicle classes in terms of fuel consumption and manufacturing costs: midsize vehicles, small SUVs, and midsize SUVs cluster closely to each other, while compact and pickup classes lie on the two extremes. The trend line in the plot also confirms this observation.

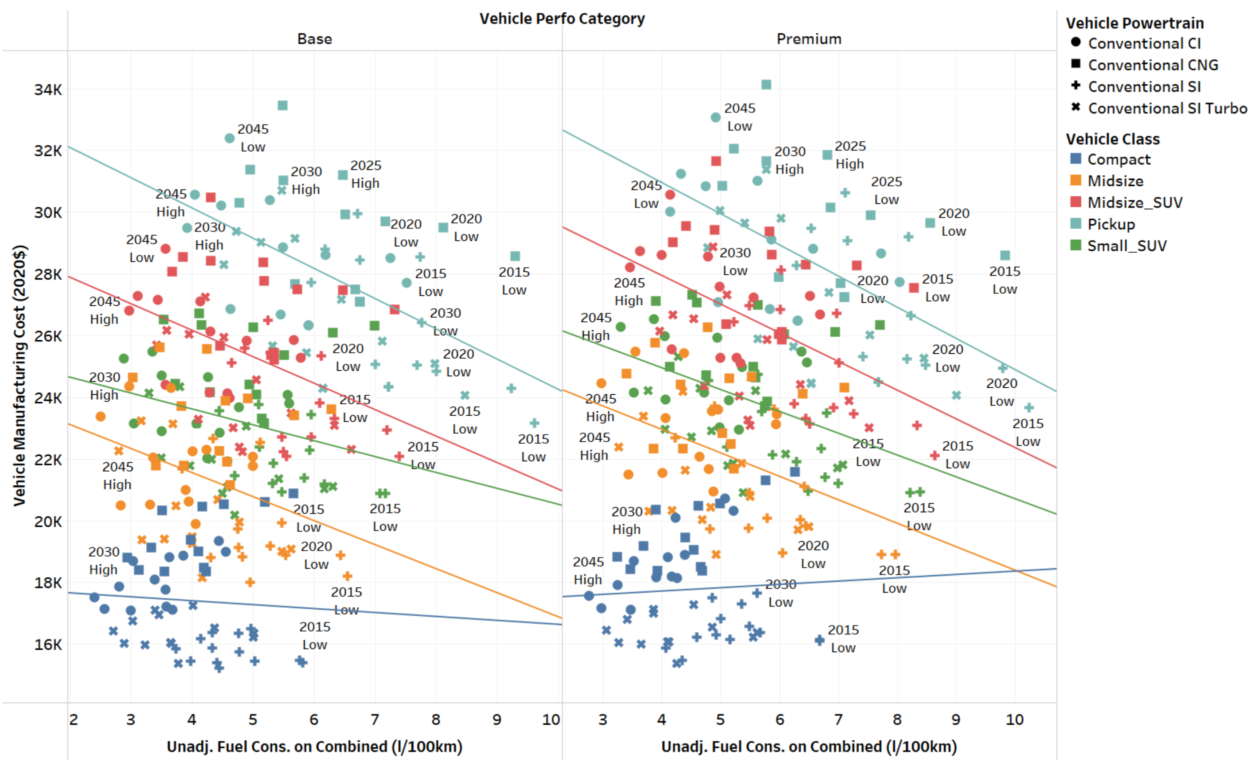

FIGURE 1-19 Vehicle-manufacturing cost versus fuel consumption for conventional vehicles

It can be observed from the figure above that over time the fuel consumption decreases due to various VTO improvements (engine efficiency, lightweighting, etc.). However due to increasing lightweighting, the lightweighting cost increases the vehicle manufacturing costs in the future.

7.2 POWER SPLIT HEVs

Figure 1-20 shows the comparison of vehicle-manufacturing cost versus fuel consumption for split HEVs across multiple vehicle classes. The different-colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different vehicle classes. The effect of the different vehicle classes on fuel consumption and manufacturing cost is similar to that observed for conventional vehicles. The figure further shows how fuel consumption and manufacturing costs progress across different laboratory years. As shown by the trend lines, over time, both fuel consumption and manufacturing costs decrease. As discussed earlier, these decreases are a result of the drop in battery and electric machine costs, which play a dominant role in manufacturing cost. The trend line also confirms the clustering.

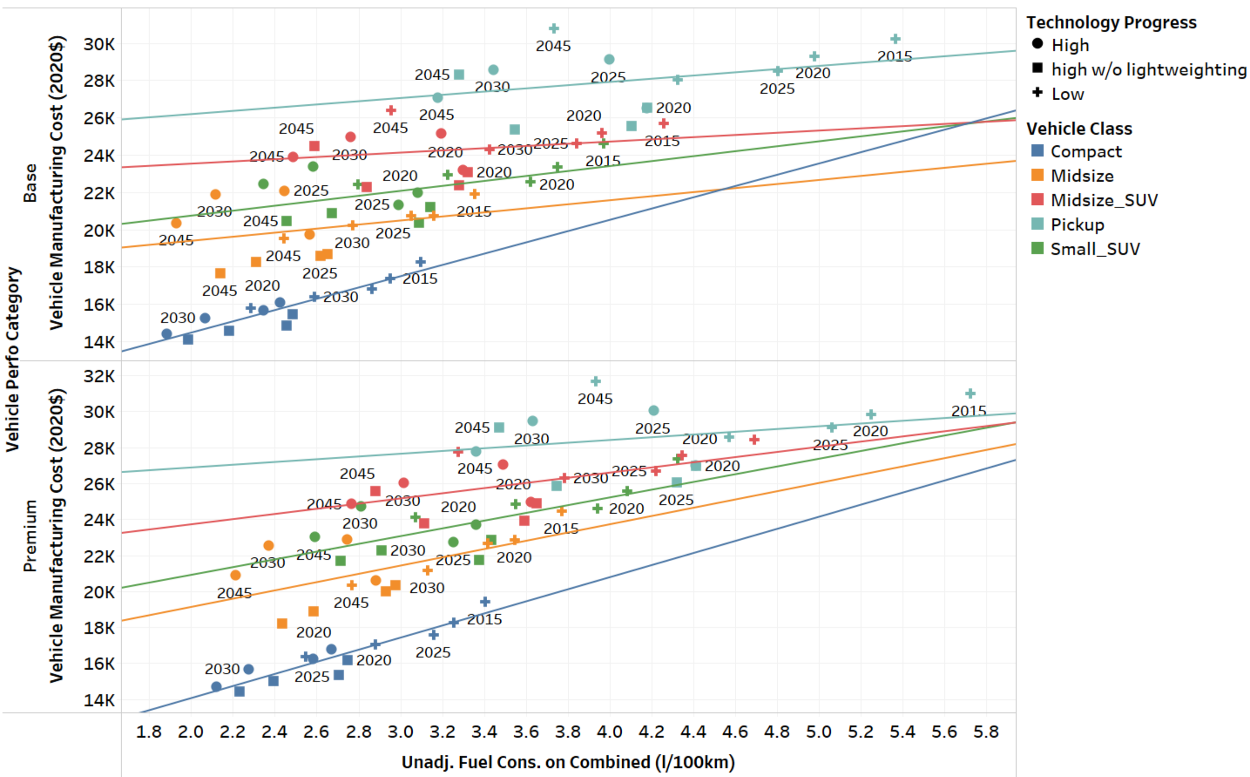

FIGURE 1-20 Vehicle-manufacturing cost versus fuel consumption for split HEVs

7.3 FUEL CELL ELECTRIC VEHICLES

Figure 1-21 compares vehicle-manufacturing cost and fuel consumption for fuel cell electric vehicles across multiple vehicle classes. The different-colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different vehicle classes. As shown by the trend lines, over time, both fuel consumption and manufacturing costs decrease. These decreases are a result of the drop in fuel cell and electric machine costs, both substantial components of manufacturing costs. As with other powertrain types, the trend lines also confirm the clustering of the different vehicle classes. For purposes of simplicity, only the Fuel Cell 300 illustration is shown below. The other fuel cell electric vehicle powertrains follow a similar pattern.

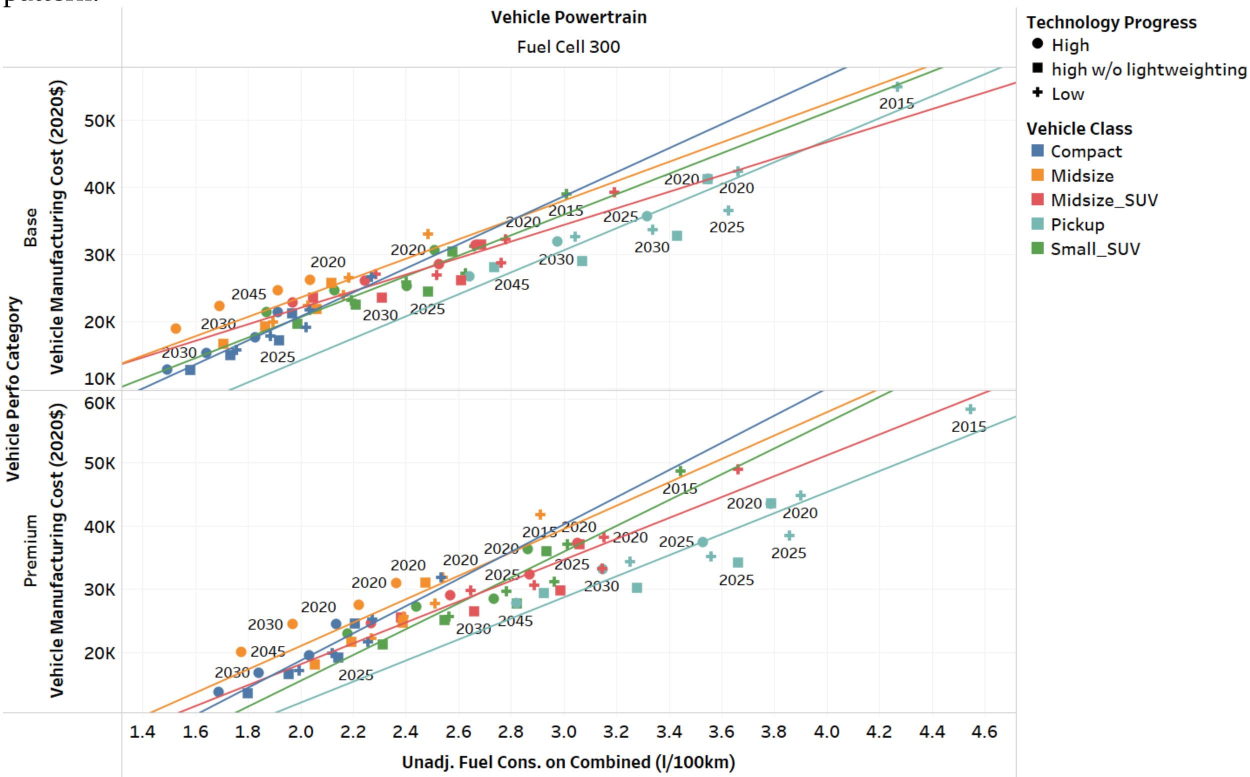

FIGURE 1-21 Vehicle-manufacturing cost versus fuel consumption for fuel cell vehicles

7.4 BATTERY ELECTRIC VEHICLES

Figure 1-22 compares vehicle-manufacturing cost and electrical energy consumption for BEVs across multiple vehicle classes. The different-colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different vehicle classes. The different vehicle classes follow trends similar to those previously discussed. As all-electric range (AER) increases (powertrain range is BEV200 through BEV500), manufacturing cost increases (owing to bigger battery sizes) and fuel consumption decreases. The effect of technological improvements over the years can be seen in the reduction in fuel consumption and manufacturing cost from laboratory years 2015 to 2045. Furthermore, the trend lines show an aggressive decline in manufacturing costs with respect to improved fuel consumption for BEVs with higher AERs. This cost decrease can be explained by the improvement in vehicle component specifications (e.g., battery energy density, lightweighting, etc.) followed by the decrease in battery costs over time.

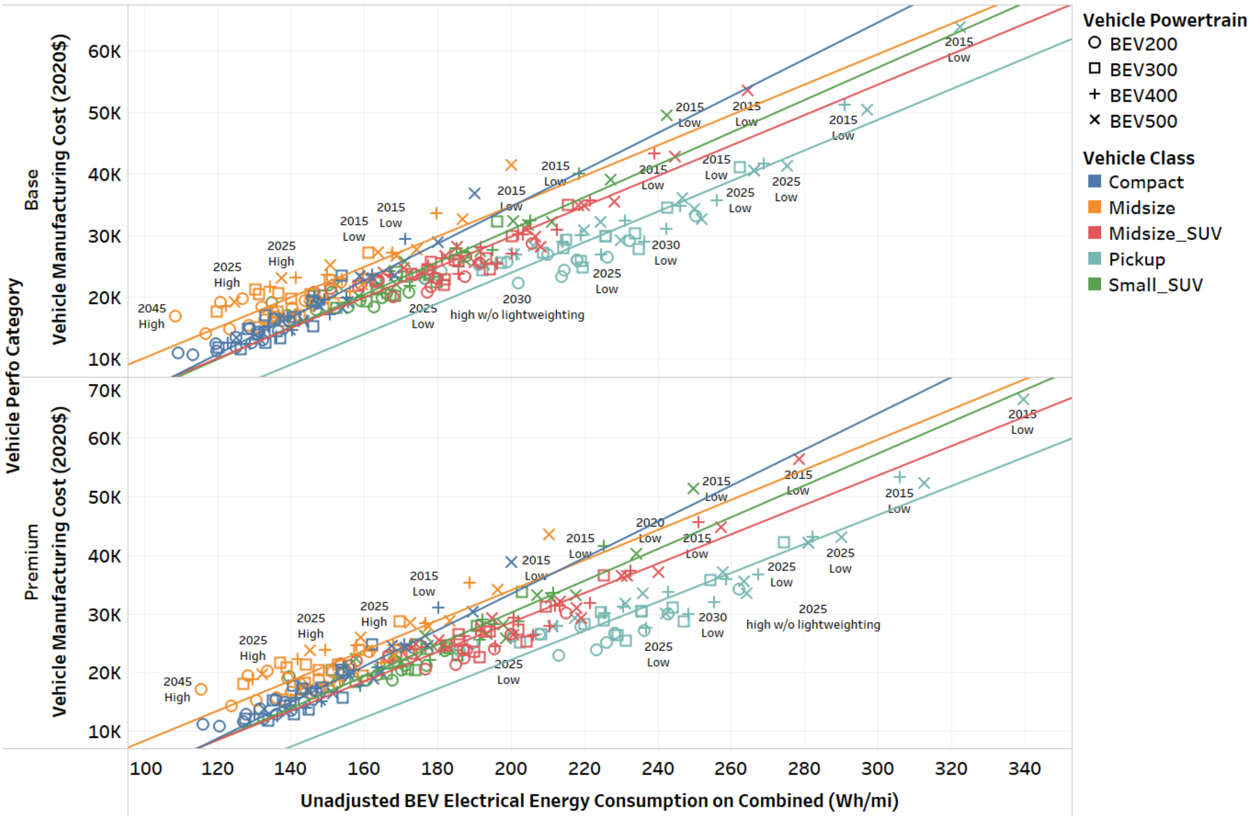

FIGURE 1-22 Vehicle-manufacturing cost versus electrical energy consumption for BEVs

8 LEVELIZED COST OF DRIVING (LCOD)

The levelized cost of driving (LCOD) provides an indicator of the average driving cost (in $/mile) for a specific vehicle lifetime and miles traveled (VMT). It is comprised of two components: vehicle purchase price and the net present value of the total fuel cost.

The main assumptions are mentioned in Table 1-12 and Table 1-13 below. The fuel and electricity price assumptions are consistent with Annual Energy Outlook 2021 (U.S. EIA, 2021) as well as Burnham et. al. (2021).

TABLE 1-12 Main parameter assumptions for cost of driving calculation

Parameter	Value
Retail price equivalent factor	1.5
Discount rate (%)	5
Vehicle lifetime (years)	3
Annual VMT	14,000
Finance rate (%)	4
Finance term	3

TABLE 1-13 Fuel and electricity price assumptions

		2015	2020	2025	2030	2045
Electricity ($/kWh)		0.122	0.122	0.152	0.171	0.233
Fuel price ($/gge)	SI	2.256	2.256	2.796	2.946	2.946
	CI	2.205	2.620	2.880	2.990	3.220
	CNG	1.595	1.478	1.453	1.376	1.354
	H2	13.820	13.820	5.340	4.650	4.650

8.1 CONVENTIONAL VEHICLES

Figure 1-23 shows the levelized cost of driving for midsize conventional vehicles across different lab years. Over time, the fuel consumption of conventional vehicles improves due to technological advances, as indicated by the technologies accelerated through future VTO targets; however, manufacturing costs increase due to increasing lightweighting costs, as observed earlier. The latter costs cause the levelized cost of driving to increase in future periods, with the highest costs occurring in the near-to-mid-term. Overall, the optimal technology progress case is observed to be the high-technology progress case without lightweighting effects.

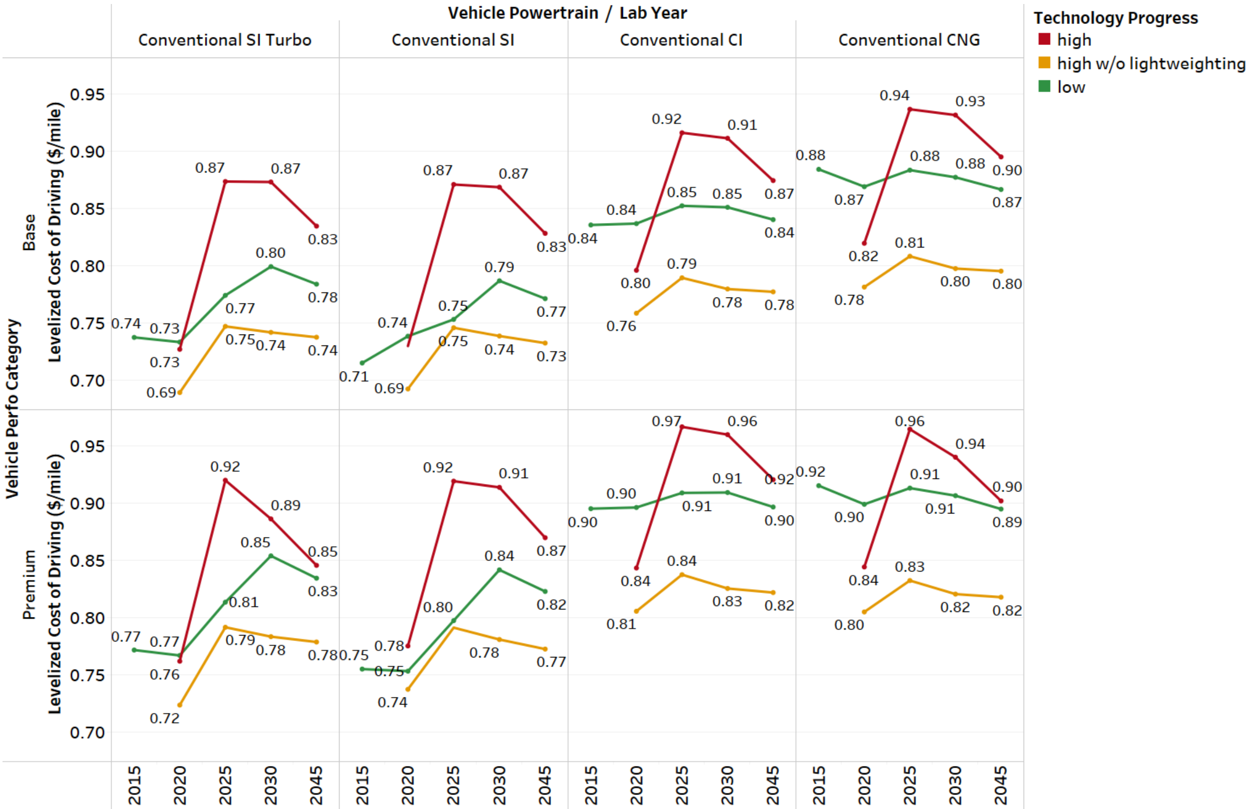

FIGURE 1-23 Levelized cost of driving, midsize conventional vehicles

8.2 POWER SPLIT HEVs

Figure 1-24 shows the levelized cost of driving for midsize power split HEVs across different lab years. With decreasing vehicle manufacturing costs and reduced fuel consumption over time, the levelized cost of driving is reduced by 8% to 25% by 2045. In future periods, the aggressive lightweighting costs and targets counter the cost benefits achieved via accelerating improvements in other VTO target areas (e.g. battery costs, motor costs, etc.), particularly in the near-to-mid-term. Therefore, as in the case of conventional vehicles, the optimal technology progress case is observed to be the high-technology progress case without lightweighting effects.

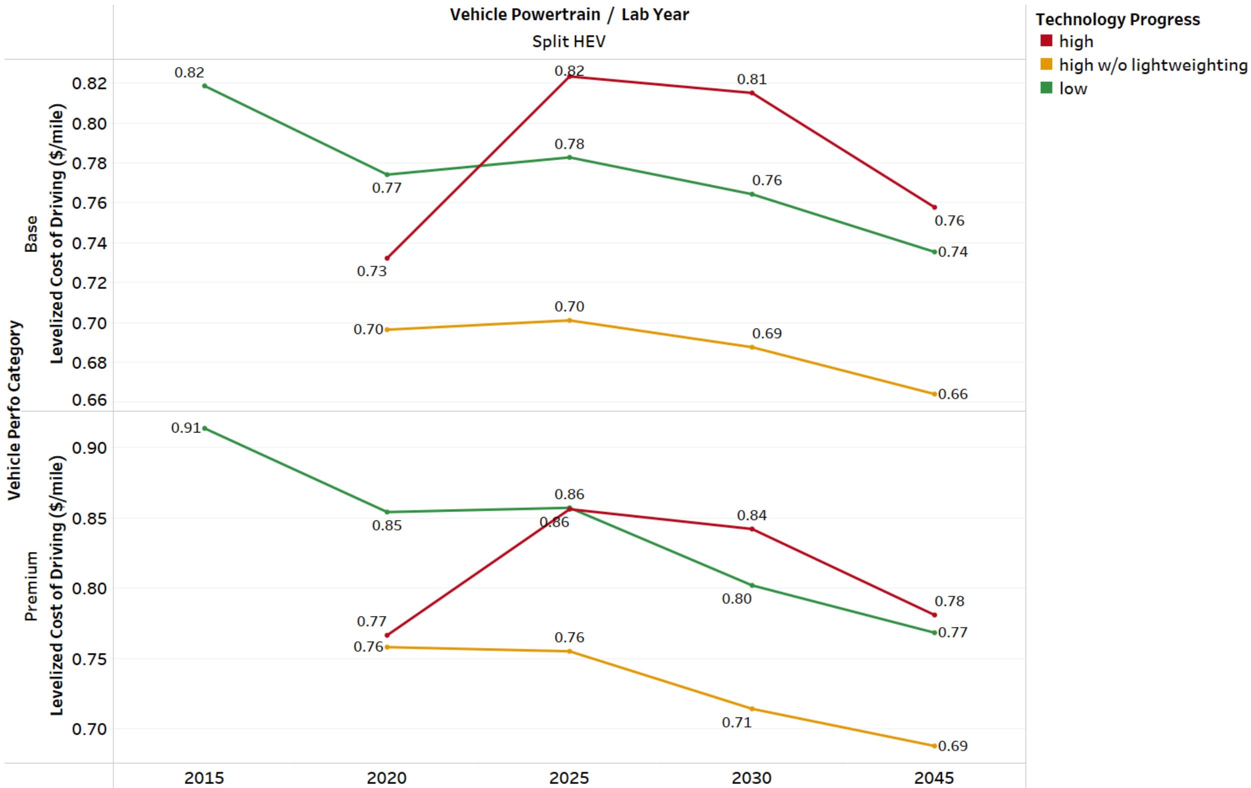

FIGURE 1-24 Levelized cost of driving of midsize split HEVs

8.3 FUEL CELL ELECTRIC VEHICLES

Figure 1-25 illustrates the levelized cost of driving midsize FCEVs across different lab years and performance categories. With decreasing vehicle manufacturing costs and reduced fuel consumption (due to vehicle lightweighting, fuel cell efficiency and power density improvements, etc.) over time, the levelized cost of driving is reduced by 45% to 60% by 2045. In future periods, the aggressive lightweighting costs and targets counter the cost benefits achieved via accelerating improvements in other HFTO and VTO target areas (e.g. fuel cell costs, hydrogen storage costs, motor costs, etc.). While this effect is not as pronounced as with the conventional powertrains and power split HEVs, lowest cost technology progress case is, again, observed to be the high-technology progress case without lightweighting.

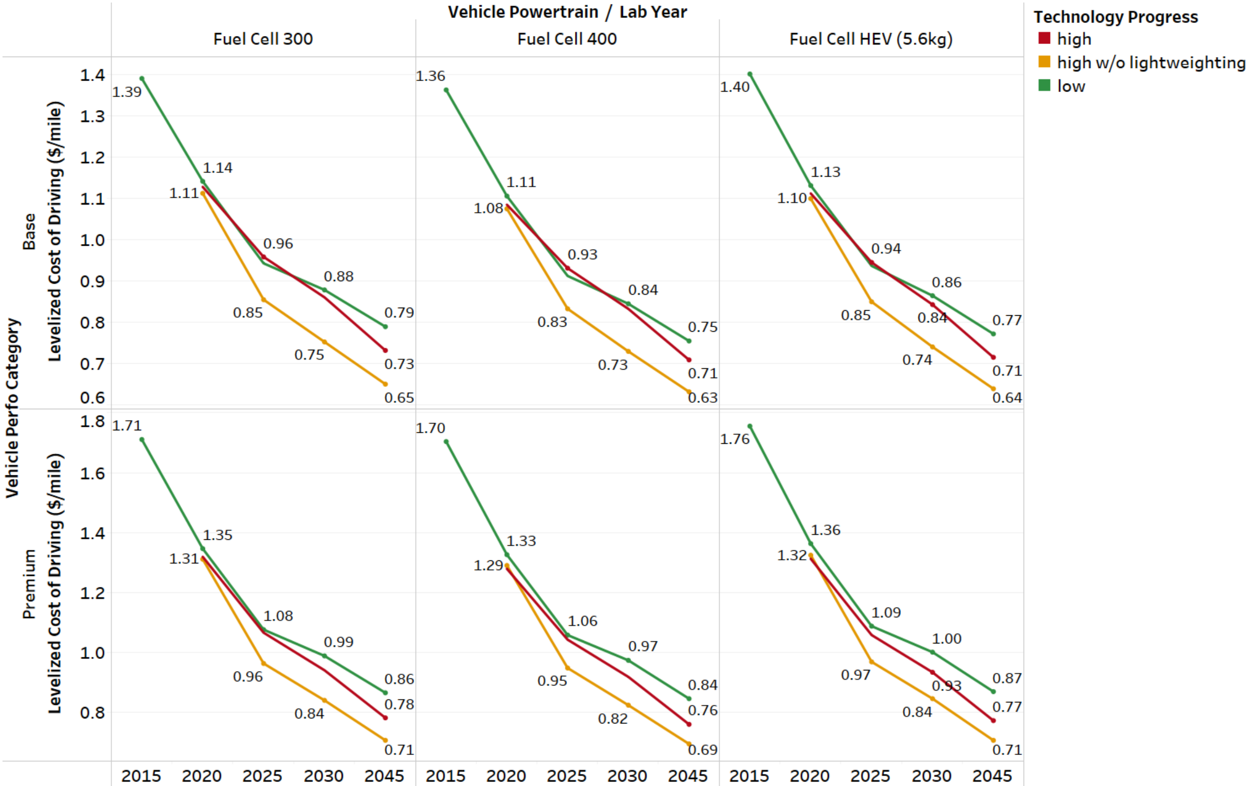

FIGURE 1-25 Levelized cost of driving of midsize fuel cell electric vehicles

8.4 BATTERY ELECTRIC VEHICLES

Figure 1-26 illustrates the levelized cost of driving of midsize BEVs across different lab years and performance categories. With decreasing vehicle manufacturing costs and reduced energy consumption over time (due to vehicle lightweighting and improvements in battery energy density and cost), the levelized cost of driving is reduced by 25% to 60% by 2045 across the different BEVs. In future periods, the aggressive lightweighting costs and targets counter the cost benefits achieved via accelerating improvements in other VTO target areas (e.g. battery costs, motor costs, etc.), particularly in the near-to-mid-term. As a result, the most optimal technology progress case is—as was observed in the case of the other powertrain types, discussed above---observed to be the high-technology progress case without lightweighting.

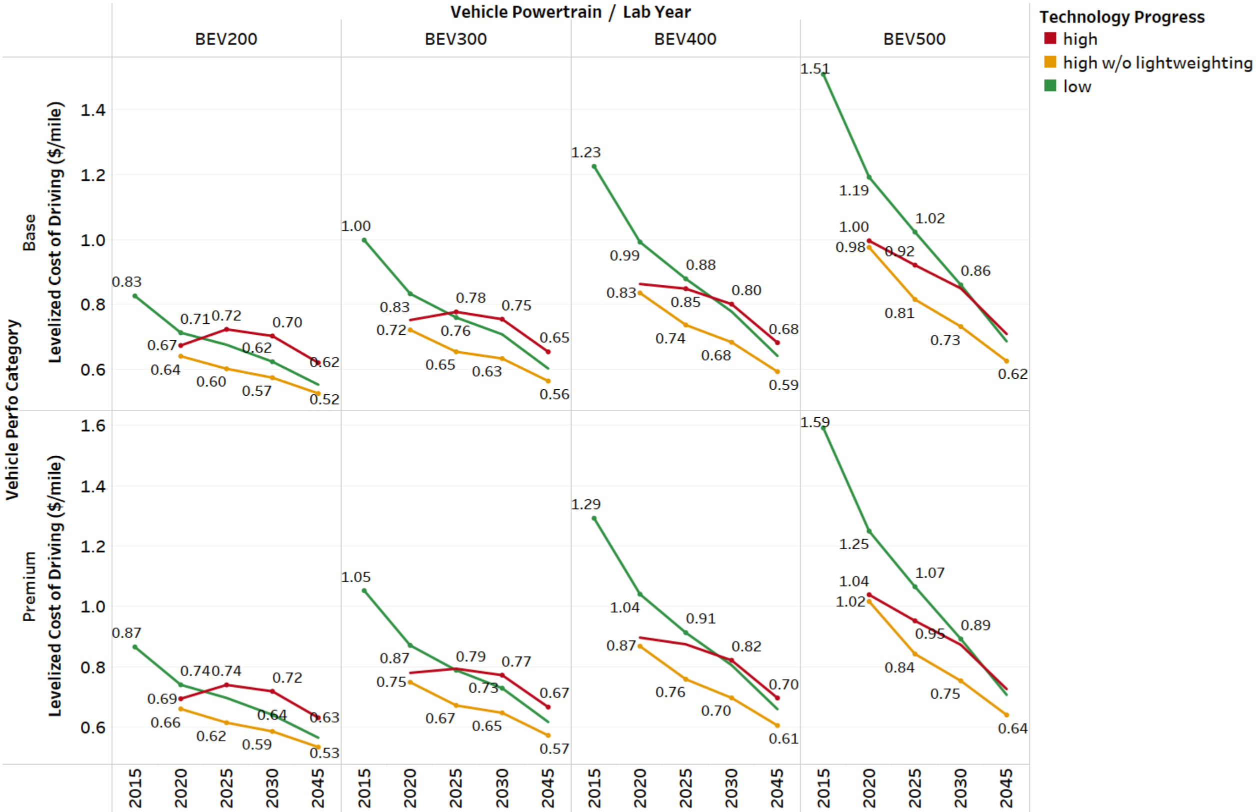

FIGURE 1-26 Levelized cost of driving of midsize BEVs

9 TOTAL COST OF OWNERSHIP (TCO)

The total cost of ownership (TCO) is an indicator that brings depreciation (residual value), maintenance, repair, insurance, and financing costs. Unlike the LCOD, it also includes the tax and fees in addition. TCO includes the scenario of the vehicle being sold at the end of its lifetime based on the depreciation. TCO can be calculated on a yearly basis ($/year) or averaged over the total miles traveled ($/mile).

The detailed assumptions and calculations for the TCO are available under Burnham et al. (2021).

9.1 CONVENTIONAL VEHICLES

Figure 1-27 shows the total cost of ownership of midsize conventional vehicles across laboratory years and performance categories. Over time, the TCO has different impacts across different engine technologies. This is due to the combined effect of increases in manufacturing costs (from engine, lightweighting, etc.) and fuel consumption reductions that accompany the acceleration of VTO targets. For example, the TCO of gasoline and gasoline-turbo midsize conventional vehicle increases by 4% to 7% by 2045 across the different technology scenario; however, the TCO of a midsize conventional CNG vehicle is reduced by almost 11% in the high without lightweighting technology scenario. It is further observed that lightweighting plays a significant role, as seen for LCOD costs as well.

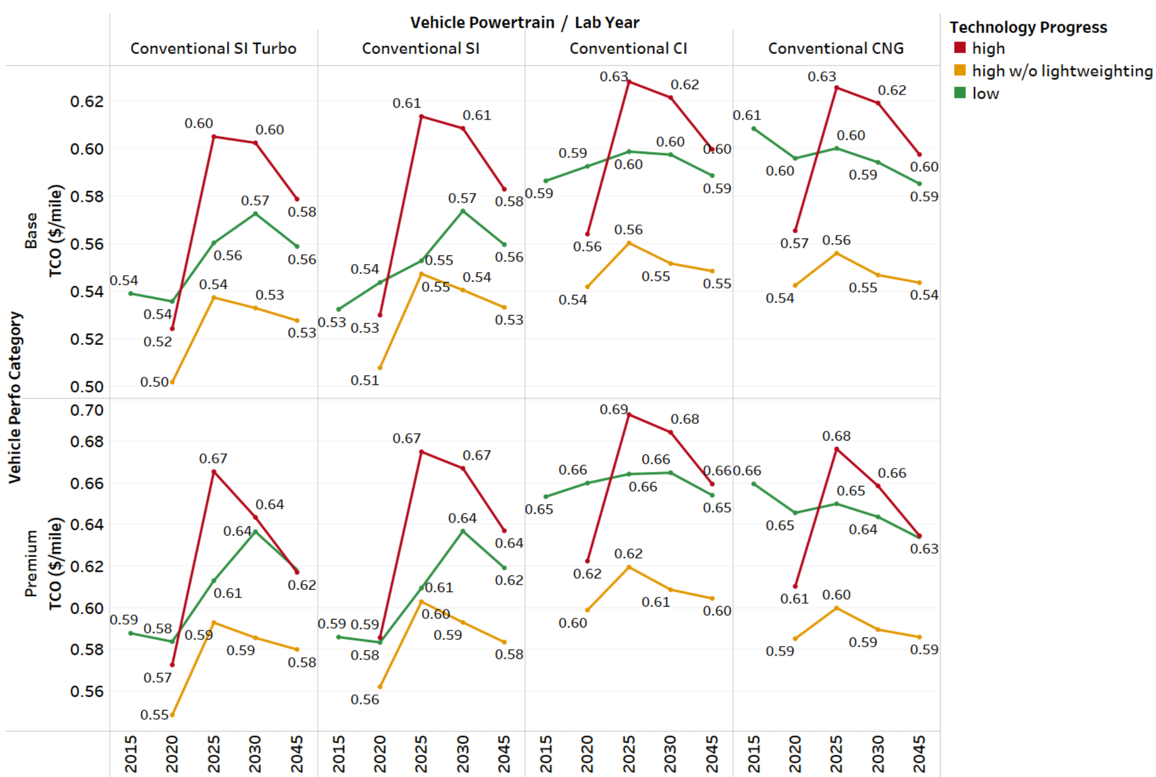

FIGURE 1-27 Total cost of ownership of midsize conventional vehicles

9.2 POWER SPLIT HEVs

Figure 1-28 shows the total cost of driving midsize power-split HEVs across different laboratory years and performance categories. Over time, the TCO of power-split HEVs is reduced by 10% to 16% by 2045 due to accelerating improvements in several VTO target areas (e.g. battery costs, motor costs, etc.).

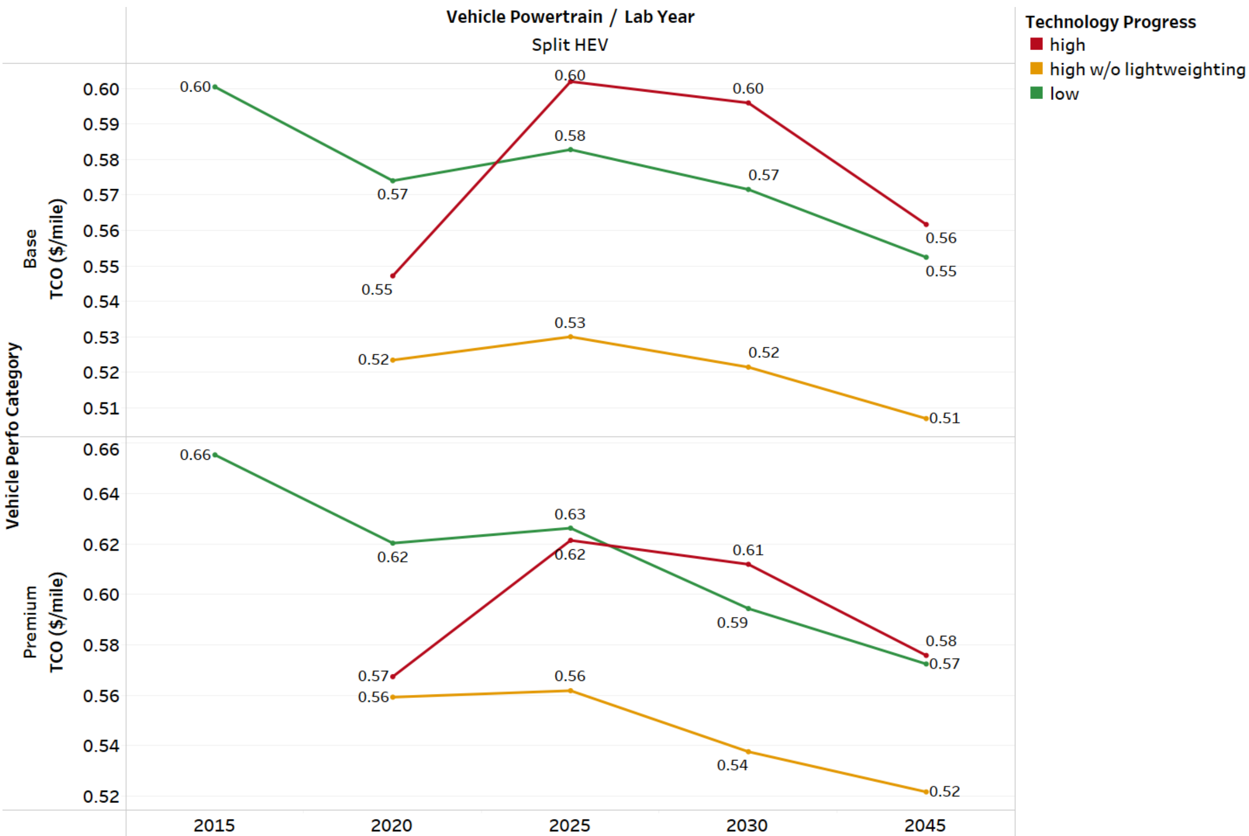

FIGURE 1-28 Total cost of ownership of midsize power-split HEVs

9.3 FUEL CELL ELECTRIC VEHICLEs

Figure 1-29 shows the total cost of driving midsize fuel cell electric vehicles across different laboratory years and performance categories. Over time, the TCO of fuel cell electric vehicles is reduced by 49% to 53% by 2045 due to accelerating improvements in different HFTO and VTO target areas (e.g. fuel cell costs, hydrogen storage costs, battery costs, motor costs, etc.).

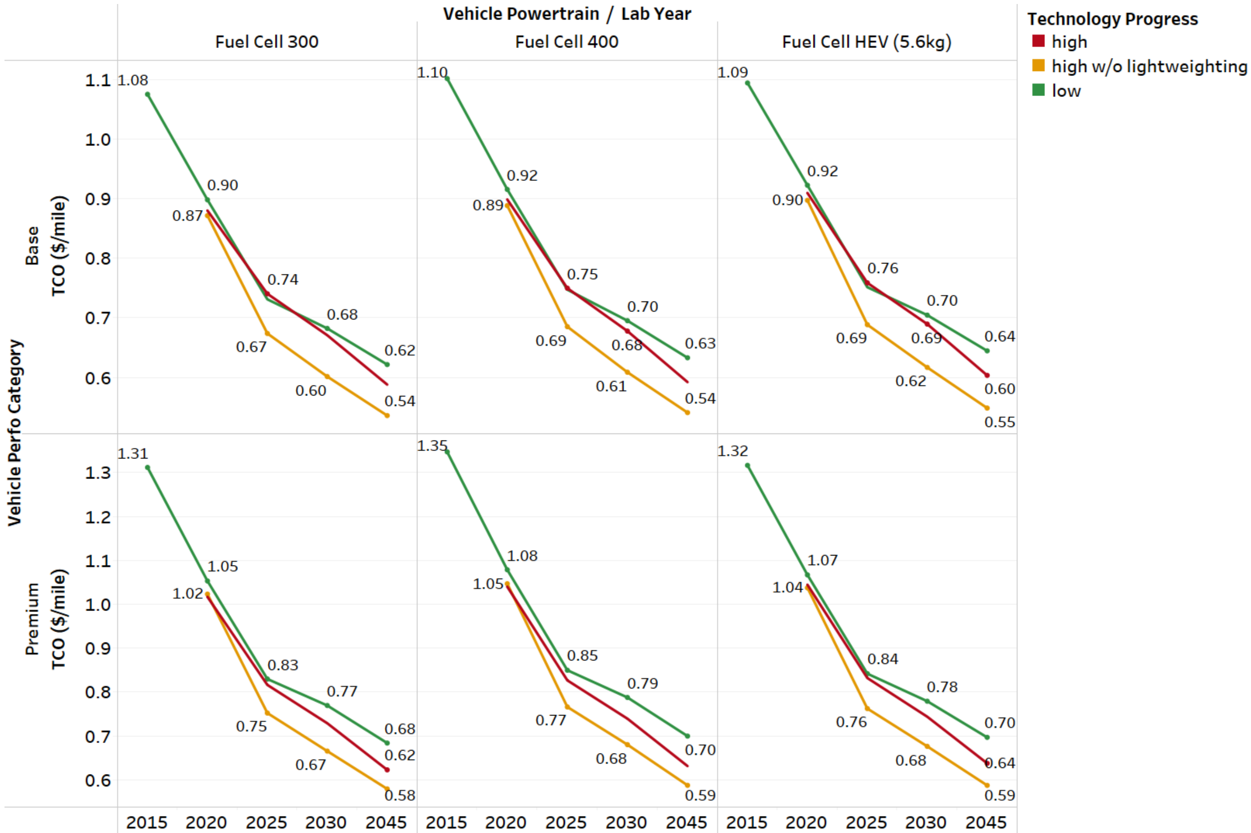

FIGURE 1-29 Total cost of ownership of midsize fuel cell electric vehicles

9.4 BATTERY ELECTRIC VEHICLES

Figure 1-30 shows the total cost of driving midsize BEVs across different laboratory years and performance categories. Over the years, the TCO of BEVs is reduced by 31% to 53% by 2045 due to accelerating improvements in several VTO target areas (e.g. battery costs, motor costs, etc.).

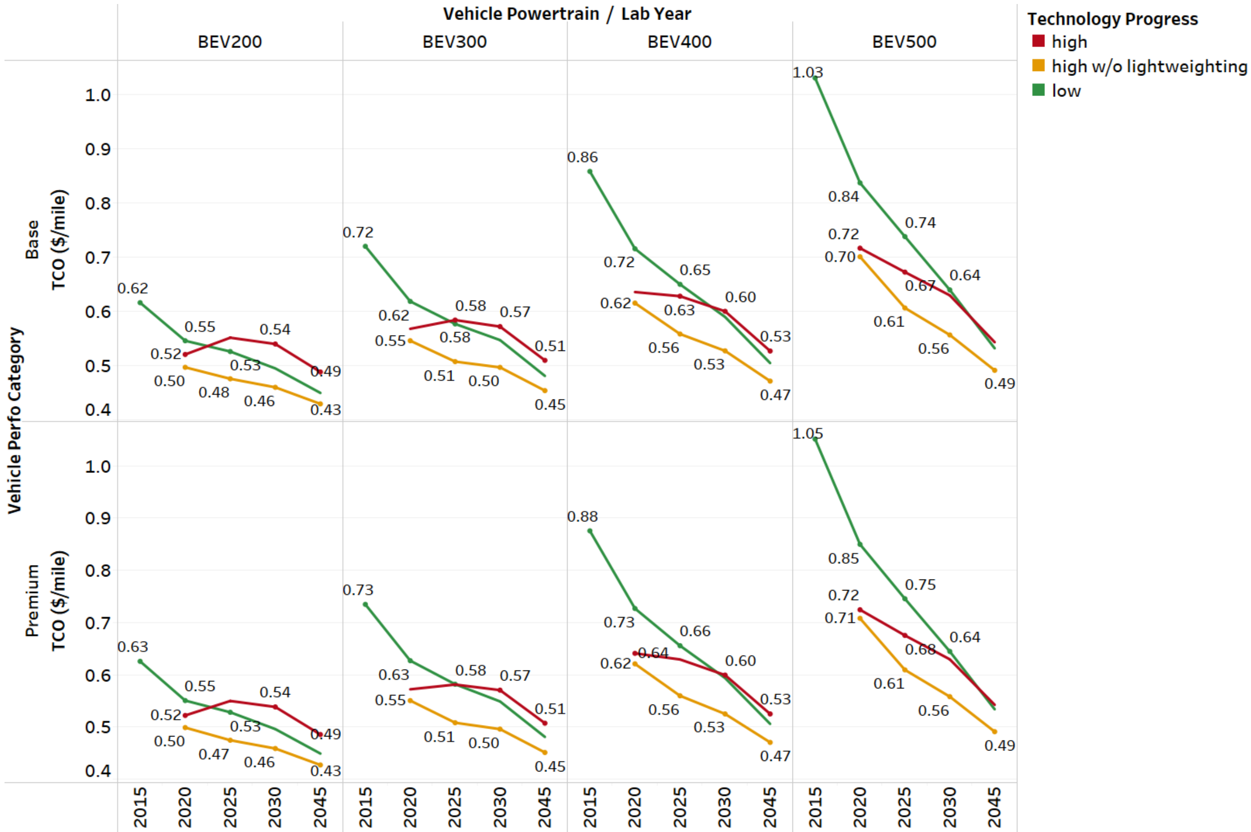

FIGURE 1-30 Total cost of ownership of midsize BEVs

10 LIGHT-DUTY REPORT SUMMARY

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 light duty vehicles. Vehicle purchase price, energy consumption, levelized cost of driving and total cost of ownership were estimated for ten vehicle classes, five powertrains, and six timeframes with upper and lower limits for three different technology progress scenarios. Detailed results are reported in the complementary Excel worksheets.

New technologies being developed under VTO and HFTO R&D programs are shown to improve the cost-effectiveness and fuel economy of light duty vehicles.

PART TWO. Analysis of Medium & Heavy Duty Vehicles

1 INTRODUCTION

The U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO) and Hydrogen and Fuel Cell Technologies Office (HFTO) aim to develop sustainable, affordable, and efficient technologies for passenger and freight movement. These offices seek to advance DOE investments in advanced transportation technologies that translate to potential vehicle-level fuel savings. In the current analysis, we quantify the costs and potential benefits of these technologies in medium and heavy duty vehicles given potential advancements over the next several decades.

In this work, we focus on technologies funded by VTO and HFTO that we expect to see implemented in vehicles 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–Class 6) to Class 8 (the largest heavy duty trucks, which span Classes 7 and 8). The output of this study provides the fuel consumption, estimated purchase price, and levelized cost of ownership (LCOD) for trucks that employ advanced technologies. This work offers 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 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, described in some detail in Section 2.2, is the primary tool for evaluating vehicle energy consumption levels. Originating from the collaborative efforts of 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 used for the simulation. 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 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 2021 to 2050. This 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. Section 3 discusses the results of vehicle-level modeling and analysis.

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 0-1 illustrates the boundaries of the work described in this report.

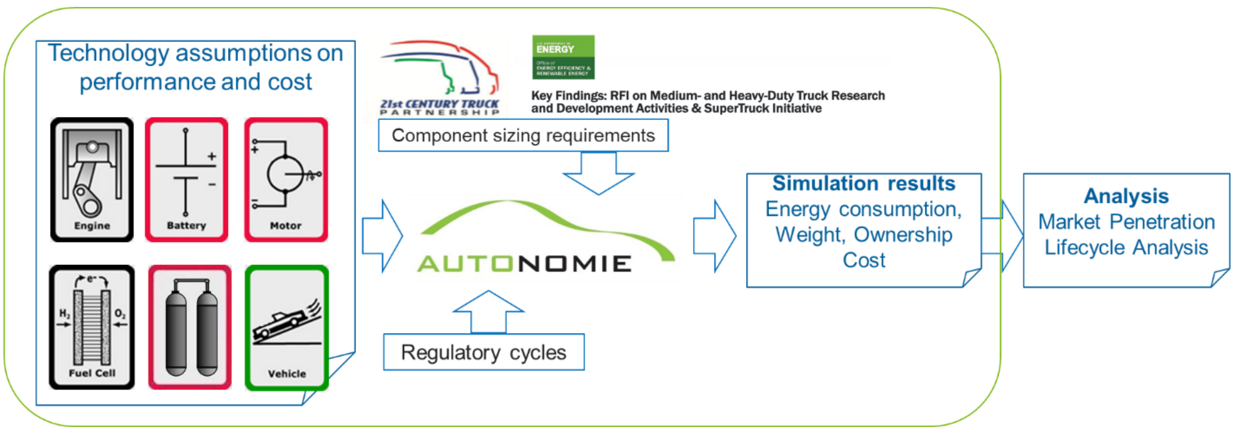

FIGURE 0-1 Scope of the work described in this report

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 guidance on the types of vehicles 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 many different types of these vehicles operate on America's roads today.

The analysis work done in 2019 (Vijayagopal et al. 2019) was well received by stakeholders. There was significant, helpful feedback, including one of suggestion to move from generic vehicle models to more specific choices based on vocation and body type. We have made this change in the selection of vehicles for the 2021 effort. For example, the Class 6 pickup and delivery vehicle was replaced with a box truck and a step van. Class 8 trucks, too, have several vocation-specific vehicle examples in this report. This analysis examines 23 truck types, as listed in TABLE 0-1. Each of these trucks was modeled with multiple powertrain choices (conventional, mild hybrid, parallel hybrid, series plug in hybrid, and battery electric) using Autonomie. To keep this analysis tractable, only a subset of representative vehicles modeled herein are analyzed in detail in subsequent sections.

TABLE 0-1 Summary of all types of trucks modeled in Autonomie

Class	Purpose
2	Van
3	Delivery
3	Van
3	School
3	Pickup
4	WalkIn
4	Service
5	Utility
6	StepVan
6	Box
6	Construction
7	Tractor
7	Vocational
7	Van
7	School
8	Long haul
8	Tractor
8	Beverage
8	Drayage
8	Vocational
8	Transit
8	Refuse
8	Regional

Classes 2-6 are categorized as medium duty vehicles and classes 7 and 8 are categorized as heavy duty vehicles. 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 information gathered in survey data by the National Renewable Energy Laboratory (NREL) and from the Vehicle Inventory and Use Survey (VIUS), these trucks cover approximately 62% of the truck population, 82% of the total distance driven, and 90% of the fuel consumed by trucks throughout the United States.

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 many other 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 have guided various departments of the U.S. government in setting targets for future research. Technology target setting activities carried out by consortiums such as US DRIVE and 21st Century Truck Partnership (21CTP) also use Autonomie as the platform for vehicle simulations. Several Supertruck teams use Autonomie as the simulation tool for quantifying the energy consumption of their vehicles. In addition, 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 used in the 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, 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. 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.
6. Maximum cruising speed.
7. Start/launch capability on grade.
8. Maximum sustainable grade at highway cruising speed.

By simulating conventional vehicle models over various test cycles, the performance requirements for various types of vehicles are determined (Table 2-2). This performance is measured for the maximum gross vehicle weight allowed for each class of truck. Although targets vary depending on size class, all powertrain variants of a given type of truck should meet or exceed these minimum requirements. See the EPA rulemaking documents (EPA and NHTSA, 2016a) for the cargo mass used for sizing and fuel economy evaluations.

TABLE 0-2 Summary of vehicle classes and vocations and their performance requirements considered in this work

Class	Purpose	0-30 mph (s)	0- 60 mph (s)	6% Grade Speed (mph)	Cruise Speed (mph)	Cruise Grade (%)	Max. Speed (mph)	Max grade at launch (%)
2	Van	7	18	50	70	1.5	75	15
3	Delivery	7	30	50	65	1.5	70	15
3	Van	7	24	50	65	1.5	70	15
3	School	7	20	60	55	1.5	60	15
3	Pickup	7	15	65	70	1.5	75	15
4	PnD	9	30	50	55	1.5	60	15
4	WalkIn	7	35	40	55	1.5	60	15
4	Service	7	18	60	70	1.5	75	20
5	Utility	9	24	50	55	1.5	60	20
6	StepVan	14	40	40	55	1.5	70	15
6	Box	14	40	45	65	1.5	70	20
6	Construction	12	50	40	60	1.5	65	20
7	Tractor	18	60	30	65	1.25	70	15
7	Vocational	18	60	30	60	1.25	65	15
7	Van	18	60	30	55	1.25	60	15
7	School	19	60	30	55	1.25	60	15
8	Long haul	20	80	30	65	1.25	70	15
8	Tractor	20	66	30	65	1.25	70	15
8	Beverage	20	66	30	65	1.25	70	15
8	Drayage	20	80	30	60	1.25	65	15
8	Vocational	20	120	25	50	1	55	15
8	Transit	17	120	25	50	1	55	15
8	Refuse	20	120	25	50	1	55	15
8	Regional	20	80	30	65	1.25	70	15

PnD = pickup and delivery

Performance capabilities for vehicles were chosen to include both transient and continuous power requirements, as shown in FIGURE 0-2. 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 (depending on the motor characteristics). This factor is important enough to be considered specifically while sizing the components for commercial trucks with electric drivetrains.

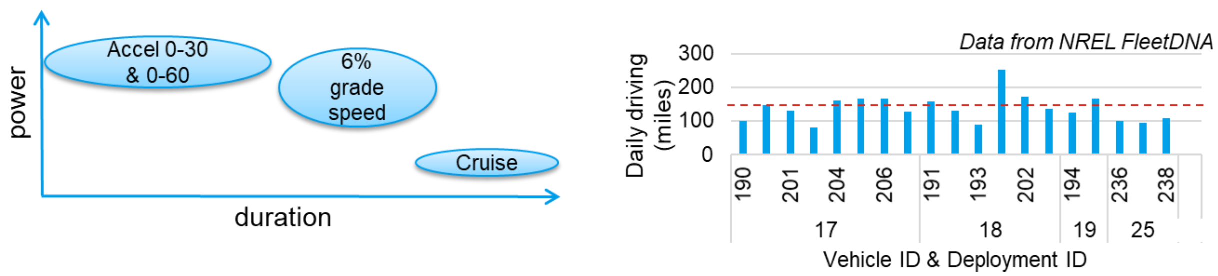

FIGURE 0-2 Overview of the performance parameters considered in this work

The new sizing requirements added in this year's work—namely, launch capability and the highway gradeability—necessitate the use of 2 or 3-speed transmission in heavier vehicles that use an electric drive. The determination of the gear ratios and shift algorithms are also now part of the powertrain sizing algorithm developed in Autonomie.

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 used to evaluate different operational conditions (Figure 2-3).

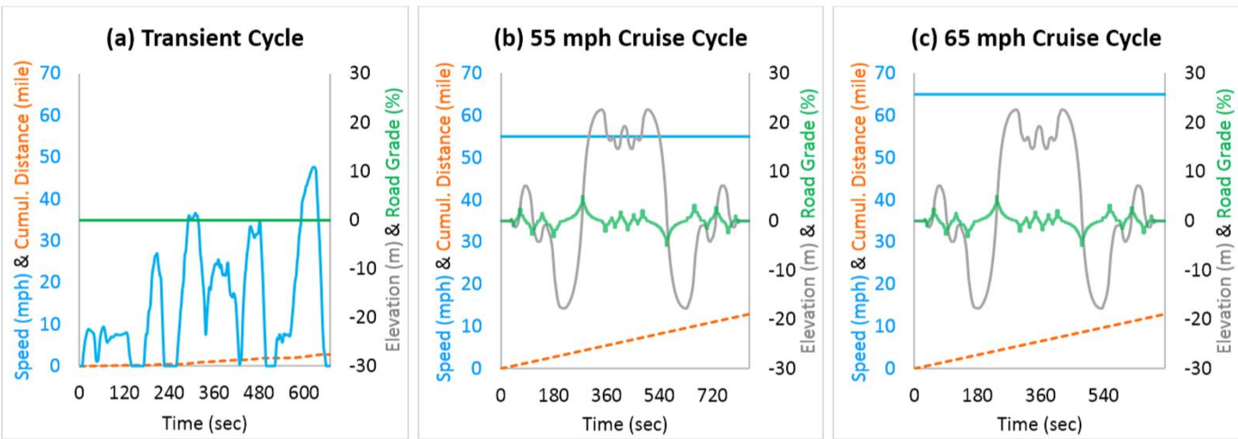

FIGURE 0-3 Drive cycles used for evaluating fuel consumption of medium and heavy duty cycles

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 seven powertrain configurations for trucks, with varying degrees of hybridization. This year, we were able to include a fuel cell truck variant with a higher degree of hybridization. The component layouts of those powertrains are shown in FIGURE 0-4. 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 pretransmission 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.

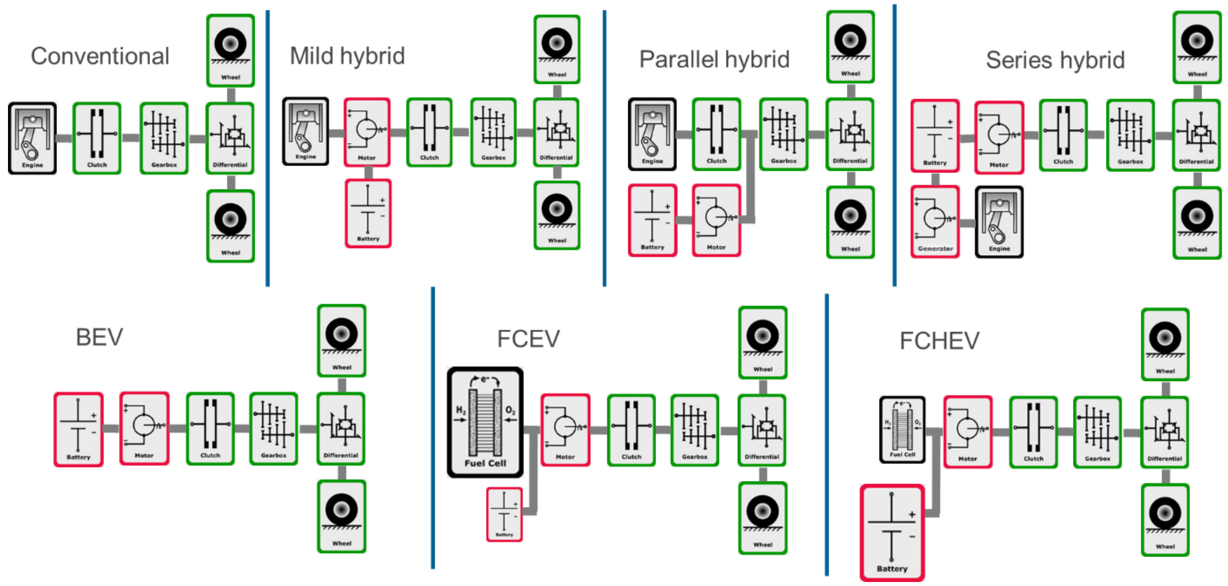

FIGURE 0-4 Component layout in powertrain architectures considered in this work

The PHEV, BEV, and fuel cell architectures may use a gearbox in cases where it is necessary to meet the performance requirements. Fuel cell powertrains can be modeled in three ways:

1. Fuel cell electric vehicle (FCEV)
   - Fuel cell provides power for all types of driving performance requirements (e.g., grade climbing, launch, cruise, etc.).
   - Battery is used for regenerative braking and transient power demand (e.g., acceleration).

2. Fuel cell hybrid with a battery to assist during prolonged high power operations (FCHEV)
   - Fuel cell is sized to meet the maximum *steady* load needed to drive (e.g., highway driving).
   - Battery helps during grade climbing, but overall operation is charge sustaining.

3. Battery electric vehicle with a fuel cell range extender (FCREX)
   - Fuel cell system sized to extend the battery desired vehicle range. Once the battery is depleted, the vehicle will have diminished performance, i.e., fuel cell can only provide enough power for a limp home capability while the battery is sized to meet all vehicle performance.

- Due to the charging infrastructure requirement and the need for two energy sources, this option is not considered in this analysis.

2.2.4 Component Technologies

Key performance parameters were identified for each component based on their impact on the overall energy consumption of the vehicle. These are summarized in FIGURE 0-5, with some of these discussed in more detail in subsequent sections.

Technology managers at DOE who are responsible for specific research areas provided their best estimates on how their respective technology areas could evolve over the next few decades. A “business as usual” (low) scenario, in which technology will progress at a slow pace given limited future R&D success, has been provided, while a “program success” (high) case has also been provided to demonstrate the level of improvement targeted by DOE through various research initiatives.

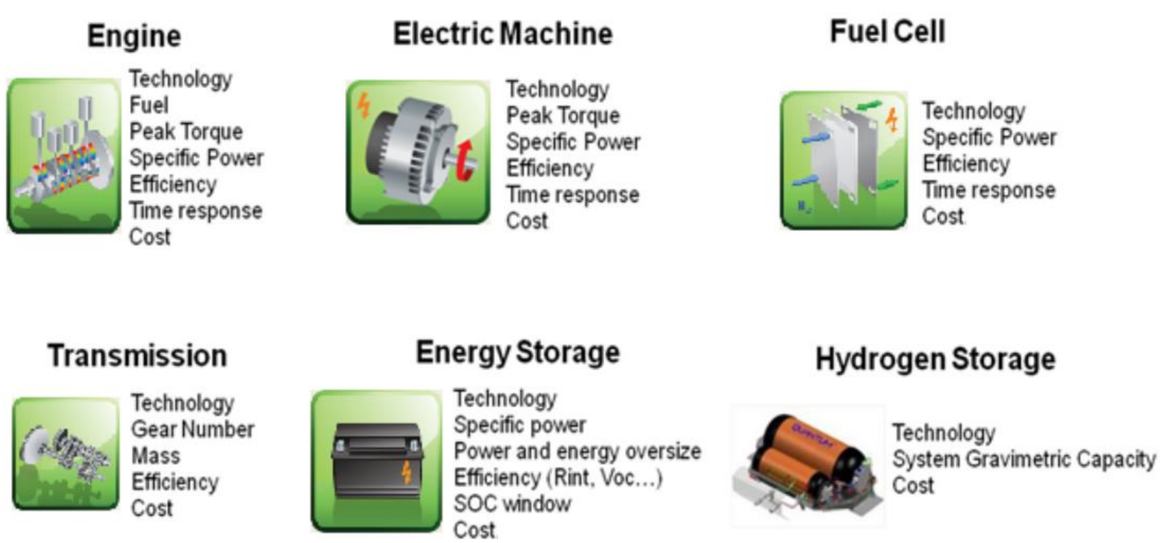

FIGURE 0-5 Component-specific parameters that affect energy consumption and operating cost estimation

2.2.4.1 Engine

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

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

We expect that the technologies developed to achieve these targets will be put into production in the near future and will help improve efficiency of smaller engines as well. Based on these targets and on 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 0-6 for vehicles in each size class and application. Cases are shown for the two scenarios described above, with the DOE target case shown as "High" and the business-as-usual case 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 rulemaking served as a guide to estimate the engine cost impact of achieving the efficiency targets. Even the business-as-usual case will incur an increase in engine cost due to the higher cost of meeting consumer demands for better fuel economy. The program success scenario assumes higher efficiency gains for the same cost increase.

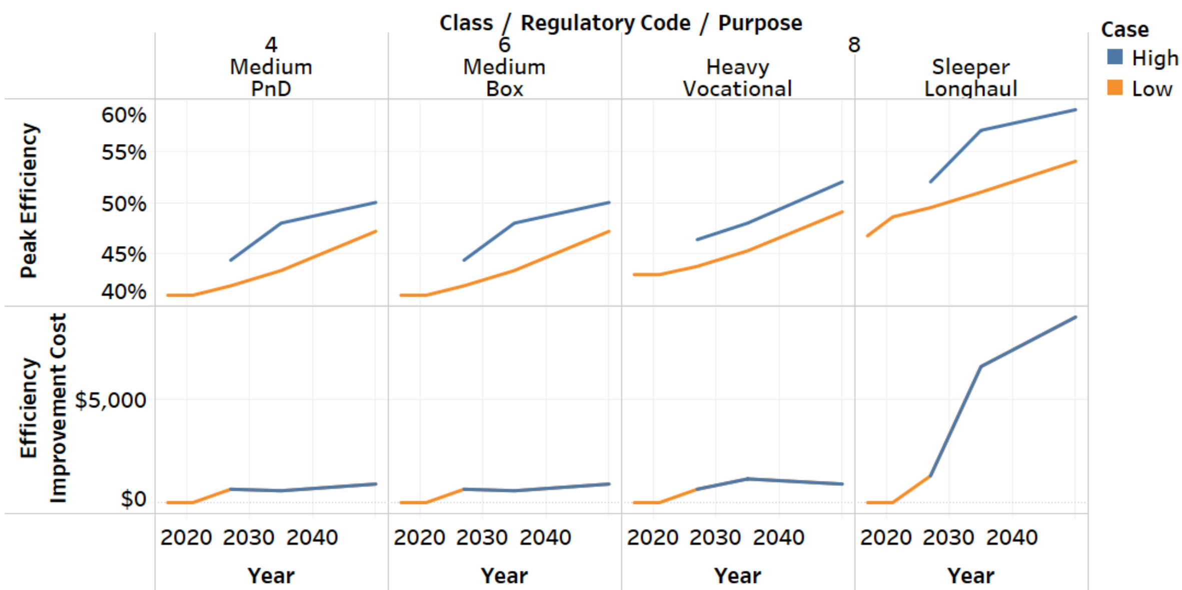

FIGURE 0-6 Efficiency and cost estimates for medium and heavy duty engines

In addition to the cost increase due to increased efficiency, the cost of the engine itself would change with engine size. 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 reduction 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 experts from national labs, the Argonne Autonomie team chose the cost assumptions shown in FIGURE 0-7.

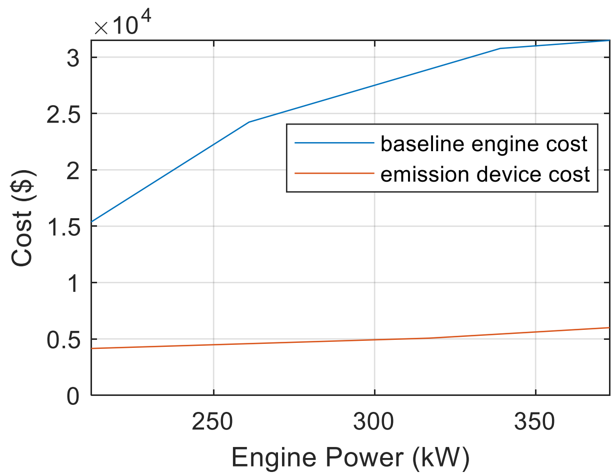

FIGURE 0-7 Estimated cost of diesel engine system as a function of engine power

These estimates provide the base cost to manufacture an engine. As technology improves, we expect to see higher costs associated with the devices and materials used to achieve higher efficiency, as assumed in FIGURE 0-6.

2.2.4.2 Electric Machine

VTO has set goals for electric traction drive system cost ($/kW). Data from the A2Mac1 database (A2Mac1 2019) and feedback from other national labs that work on this topic was used to estimate the efficiency and power density (kW/kg) values. The assumptions regarding the efficiency and cost of future electric traction drive systems are shown in FIGURE 0-8. The system efficiency and cost assumptions are the cumulative values for electric machine and power electronics components needed to operate the machine.

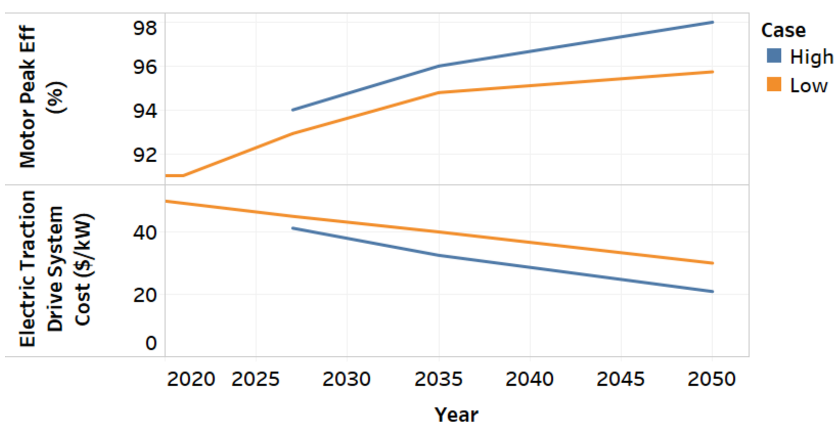

FIGURE 0-8 Cost and efficiency assumptions for electric traction drive system

2.2.4.3 Transmission

VTO does not have any specific goals regarding the number of gears needed for vehicles. This value is chosen based on the transmission choices available in present-day production vehicles. FIGURE 0-9 summarizes the number of gears used in each type of conventional vehicle. We assume that hybrid variants of these vehicle will use the same gearbox. Medium duty vehicles with electric drive trains (BEV, PHEV) can achieve their performance requirements even with a direct drive system. Heavy duty (class 7-8) electric vehicles, on the other hand, require both a transmission and at least 2-speed ratios to ensure that all performance requirements are met.

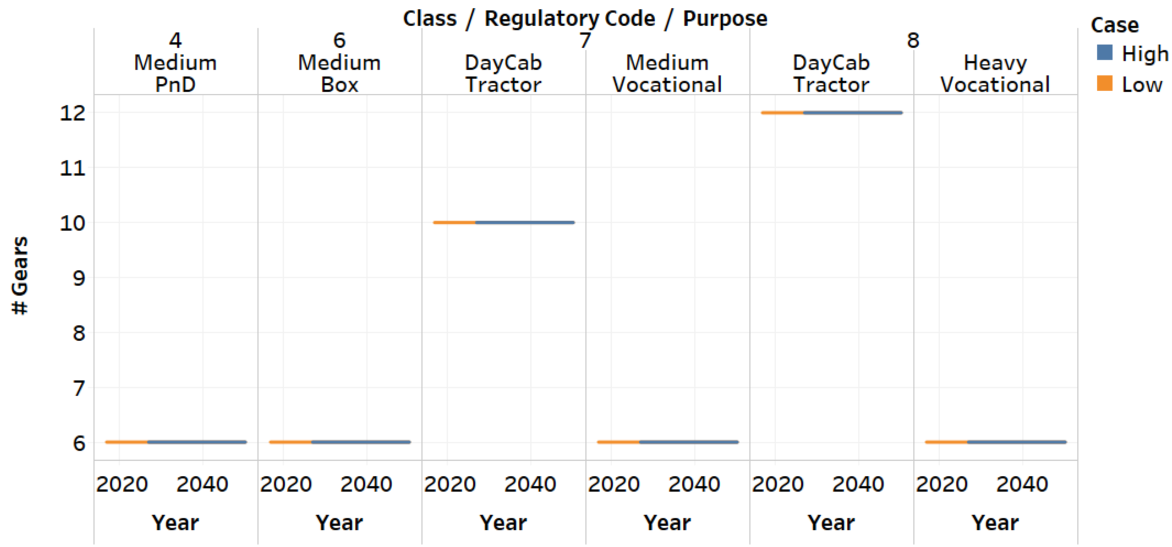

FIGURE 0-9 Assumed number of gears in conventional truck transmissions

2.2.4.4 Energy Storage

Research on batteries for light duty vehicles is supported by VTO. No goals were established exclusively for medium and heavy duty vehicles at the time of this study. Similar battery technologies can be used for passenger cars and heavy duty trucks, but higher levels of power and energy will be needed for the latter application. 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 0-10 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.

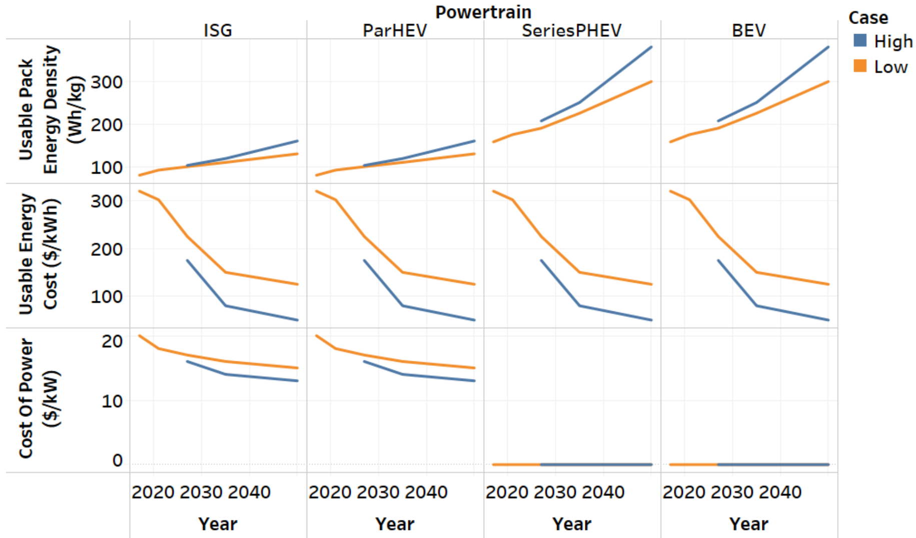

FIGURE 0-10 Battery assumptions for trucks

Power and energy capacity of the cell will determine the cost of the energy storage system. The higher of the two values is assumed. In the case of hybrid vehicles, where a high power battery is employed, the cost of battery is determined by the $/kW assumption. The cost of energy batteries, used in PHEVs and BEVs, is determined by the amount of energy stored in the pack. The power output from the energy batteries used in this study is restricted to 2C rate to enforce safe operating conditions for the battery.

2.2.4.5 Fuel Cells

In 2019, HFTO establishedHD-specific fuel cell targets (Marcincoski et al. 2019). As is the case with battery packs, many factors that affect the fuel cell design would be different in heavy-duty vehicles relative to light-duty, 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. The shape of the fuel cell efficiency curve assumed for HD applications in shown in FIGURE 0-11.

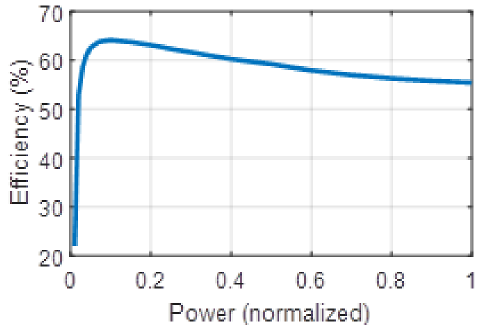

FIGURE 0-11 Operating efficiency of the fuel cell plotted against the normalized net power output

Assumptions for fuel cells in medium and heavy duty applications are shown in FIGURE 0-12. For present day, we scale down the efficiency curve to have a peak of 61%. By 2050, this peak efficiency is assumed to reach 72% (i.e. in the "High" scenario). The ultimate cost targets for the heavy duty fuel cell systems are set to ensure that they will be comparable to the cost of diesel engines in the future (Marcinkoski, J., et al. 2019). Most of this cost reduction is targeted in the interim period, by 2035.

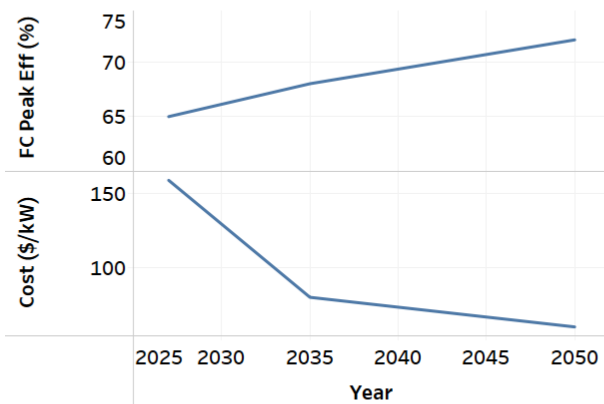

FIGURE 0-12 Fuel cell system efficiency and cost coefficients for trucks

Fuel cell components are sized using the beginning of life performance characteristics, to be consistent with the assumptions used for BEVs.

2.2.4.6 Hydrogen Storage

The amount of hydrogen that can be stored in a given mass of tank is expected to increase with R&D efforts encouraged by HFTO. Tank cost is also projected to decrease, as shown in

Figure 2-12. For simplicity, FIGURE 0-13 displays the cost per kWh for a hydrogen tank, and the energy storage density of the tank. It also shows the combined production and delivery cost of hydrogen assumed for this work.

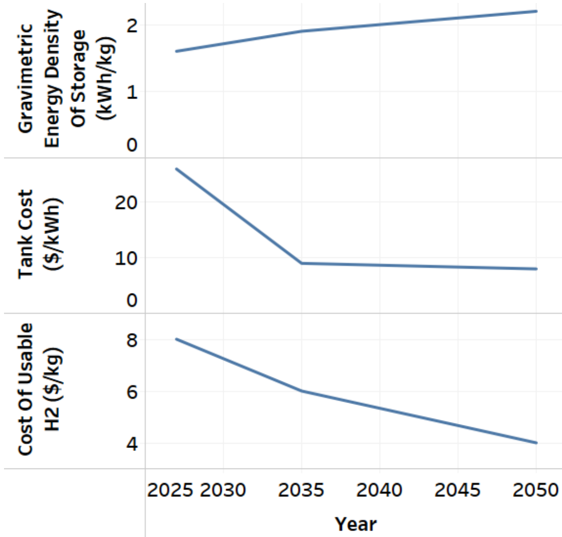

FIGURE 0-13 Hydrogen storage assumptions.

2.2.4.7 Lightweighting

Use of advanced materials and optimized design can lower the weight of trucks. A DOE workshop in 2013 provided estimates on weight savings that could be achieved by 2050 and the expected cost 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 0-14.

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.

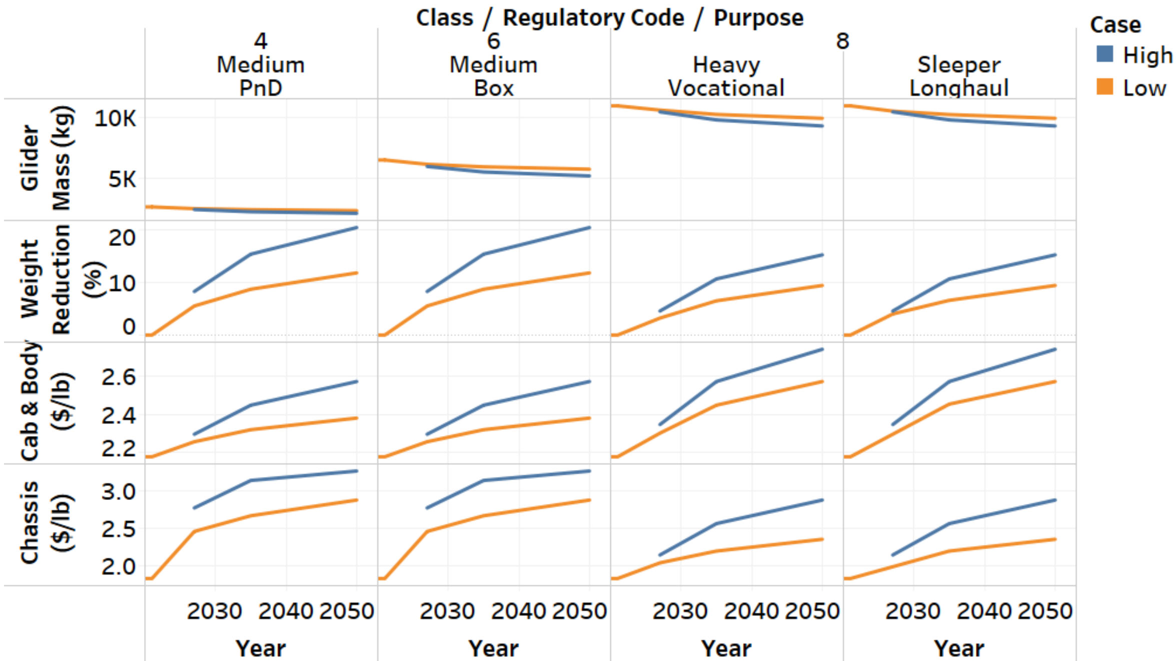

FIGURE 0-14 Assumptions regarding glider weight reduction in trucks and cost of lightweighting

In a prior year's work, the second option was chosen, thereby providing a way to reduce the load-specific fuel consumption (gallon/mile/ton). Based on feedback from various stakeholders, this year's work used a constant payload for an application and the full impact of lightweighting is measured in terms of fuel consumption and cost of ownership.

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 20–30% with better body design. The powertrain-specific characteristics may also influence this design. 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 larger air intake openings than electric trucks for effective cooling, necessitating 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 0-15 were developed for conventional trucks, and these were applied to all other powertrains.

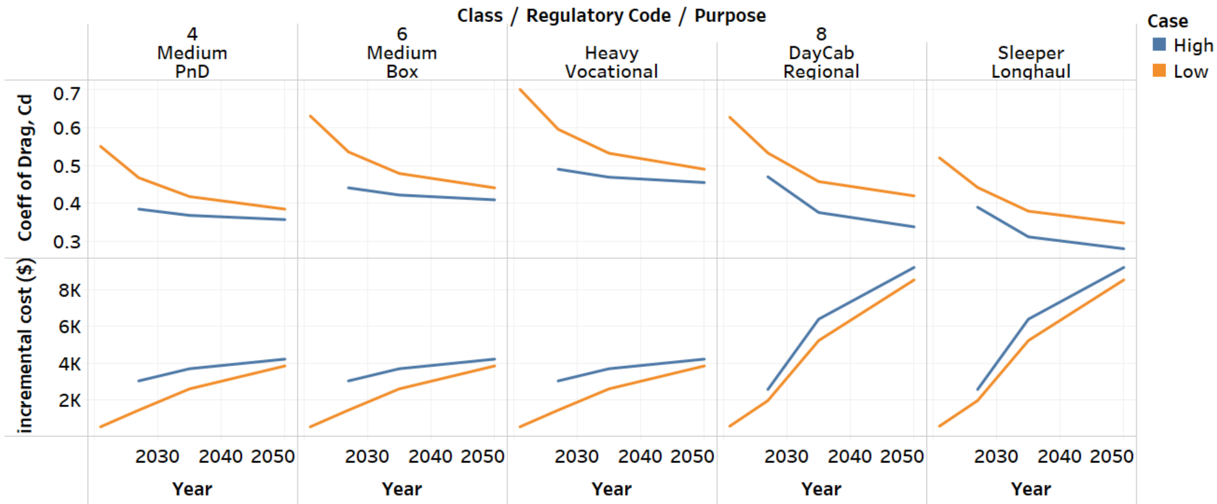

FIGURE *0-15* Aerodynamic improvement and the associated incremental cost assumed for different type of trucks

2.2.4.9 Other Cost Assumptions

Technology-specific assumptions show the direct manufacturing costs of components and the cost of technology improvements over the years. DOE cost targets assume manufacturing of components at a high enough volume to achieve economies of scale. In addition to direct manufacturing costs, a retail price equivalent factor of 1.2 was assumed based on discussions with industry experts. Vehicle prices were estimated by summing the component manufacturing costs and applying the retail price equivalent factor.

3 IMPACT OF VEHICLE TECHNOLOGY IMPROVEMENTS ON ENERGY CONSUMPTION

The simulation results for all vehicles are shared through the Excel spreadsheets associated with this document (https://www.autonomie.net/publications/fuel_economy_report.html). The detailed plots shown in this document focus on some of the vehicle classes and vocations that are of interest to stakeholders.

Combination unit trucks (represented in this study by long haul sleeper trucks and regional haul trucks) constitute about 63% of the overall fuel usage by trucks in the United States (BTS 2021). These trucks are designed to maximize their fuel economy on steady highway driving conditions. Regional trucks are very similar to long haul trucks, but they have shorter driving range requirements. In this study, long haul trucks are designed for a 500-mile range and regional trucks are designed for a 250-mile range. Comparing these two cases shows how BEVs and FC-powered trucks can compete for different segments of the heavy duty truck market. In addition to the heavy duty case, we will also look at class 4 and 6 delivery trucks to examine the medium duty market segment.

3.1 FUEL CONSUMPTION BENEFITS

In this heavy duty trucking analysis, fuel consumption was estimated from simulations over three drive cycles identified in Section 2.2.2:

1. The (California) Air Resource Board (ARB) Transient.
2. EPA 55 mph.
3. EPA 65 mph.

The combined fuel economy value is computed by applying different weighting to each of the EPA prescribed cycles. For example, for sleeper trucks, 86% weightage is assigned to fuel consumption observed in EPA 65 cycle, 9% to EPA 55 cycle and the remaining to the fuel consumption observed in the ARB transient cycle. For vocational trucks, the multi-purpose weightage used in this study assigns 50% of the weightage to ARB transient cycle, with the remainder shared between the other two cycles.

A summary of the fuel consumption of present-day trucks on the regulatory test procedure is shown in FIGURE

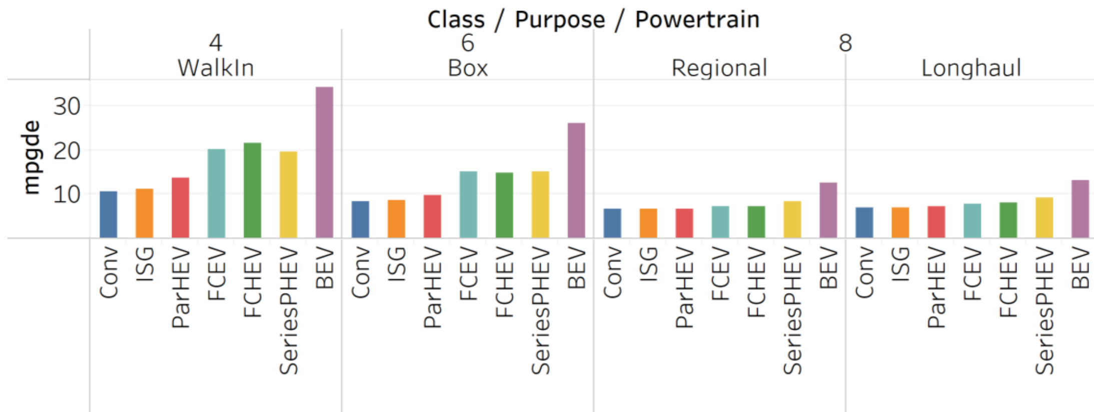

FIGURE 2-16 Overview of energy consumption of present-day trucks for highway driving expressed as miles per diesel gallon equivalent

FIGURE 6 shows that start-stop (ISG) and HEV systems do not provide large fuel savings for regional and long haul applications, where there is mostly highway driving, little idling, and only a limited opportunity for regenerative braking. For heavy trucks, hybrid powertrains might even result in increased fuel consumption during highway driving as a result of the additional weight of hybrid components. But these mild and full hybrid architectures provide appreciable gains for smaller trucks whose fuel economy is measured in a mix of transient and highway driving. The electrical energy consumption during the charge-depleting operation of a PHEV and fuel consumption in charge sustaining mode is combined evenly to form the diesel equivalent fuel economy values. Energy consumption for fuel cell trucks and electric trucks is based on diesel equivalent fuel economy as well.

The potential to downsize the engine, as a part of hybridizing, varies with the class and vocation of the truck. If a truck engine is sized to climb grades under fully loaded conditions, it will still require the same engine power even if it uses a hybrid powertrain. On the other hand, if the engine was sized for acceleration performance or to provide higher launch capability, we can expect the motor to assist the engine under those conditions, and it will allow the use of a smaller engine without sacrificing performance.

Each vehicle is sized for a specific application. As noted earlier, Class 8 sleeper trucks are sized to drive 500 miles without refueling or recharging. On the other hand, 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 equal weightage to charge depleting and charge sustaining modes for PHEVs. Fuel economy of ISGs, HEVs, and fuel cell trucks are measured under charge-sustaining conditions.

The percentage of fuel savings potentially realized by each powertrain for various types of trucks is shown in
FIGURE *1*-17. It displays estimated savings for different powertrains, between now and 2050, under regulatory test conditions (as previously described). The fuel consumed by a conventional

truck in each time frame is taken as the reference and the energy consumed by all other advanced powertrain variants is converted to diesel equivalent gallon per mile for this calculation.

About 70% savings in energy consumption is observed for small electric trucks. Although BEVs displace 100% of the petroleum consumption, they still consume energy from the electric grid. The savings are lower for larger trucks on highway driving. This is due to a combination of drive cycle properties and vehicle design attributes. Long haul trucks are designed for steady operation at highway speeds; hence, they operate very close to their peak efficiency at these conditions. In regulatory tests, highway driving provides 95% of the weightage for such trucks. Electrified trucks display the greatest advantage under transient driving conditions considered for evaluating the energy consumption of delivery trucks.

Future improvements in powertrain components will slightly alter the relative advantages of each powertrain, but the overall trend shows that energy savings from the advanced powertrains will gradually improve as batteries and motors become lighter and more efficient.

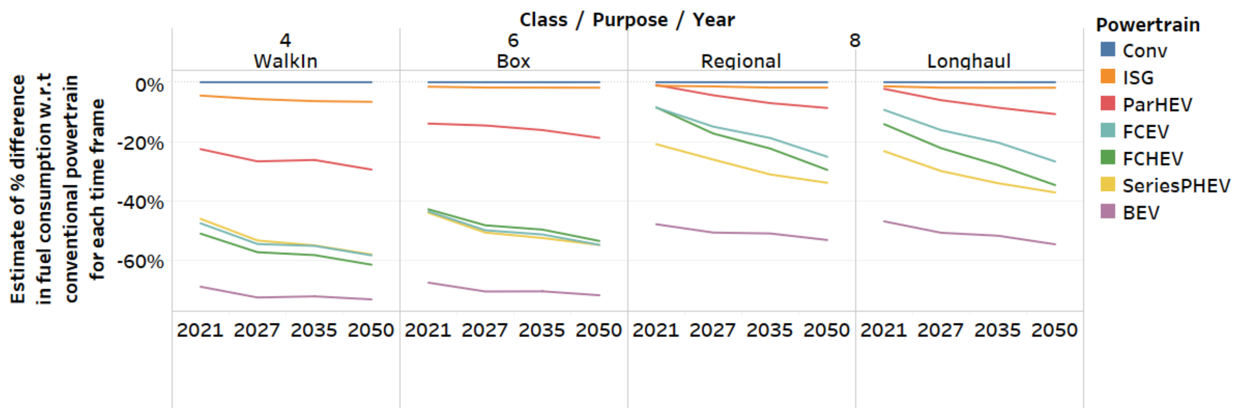

FIGURE *1*-17 Comparison of diesel equivalent fuel consumption for various powertrains

In addition to the fuel economy estimates, this analysis looks at the cost and mass estimates for the vehicles. Figure 2-18 shows that, in the near term, advanced powertrains have cost and weight penalties when compared to conventional options. But, as technology improves by 2035 and 2050, several advanced powertrains will be cheaper than conventional vehicles in terms of both initial cost as well as ownership costs.

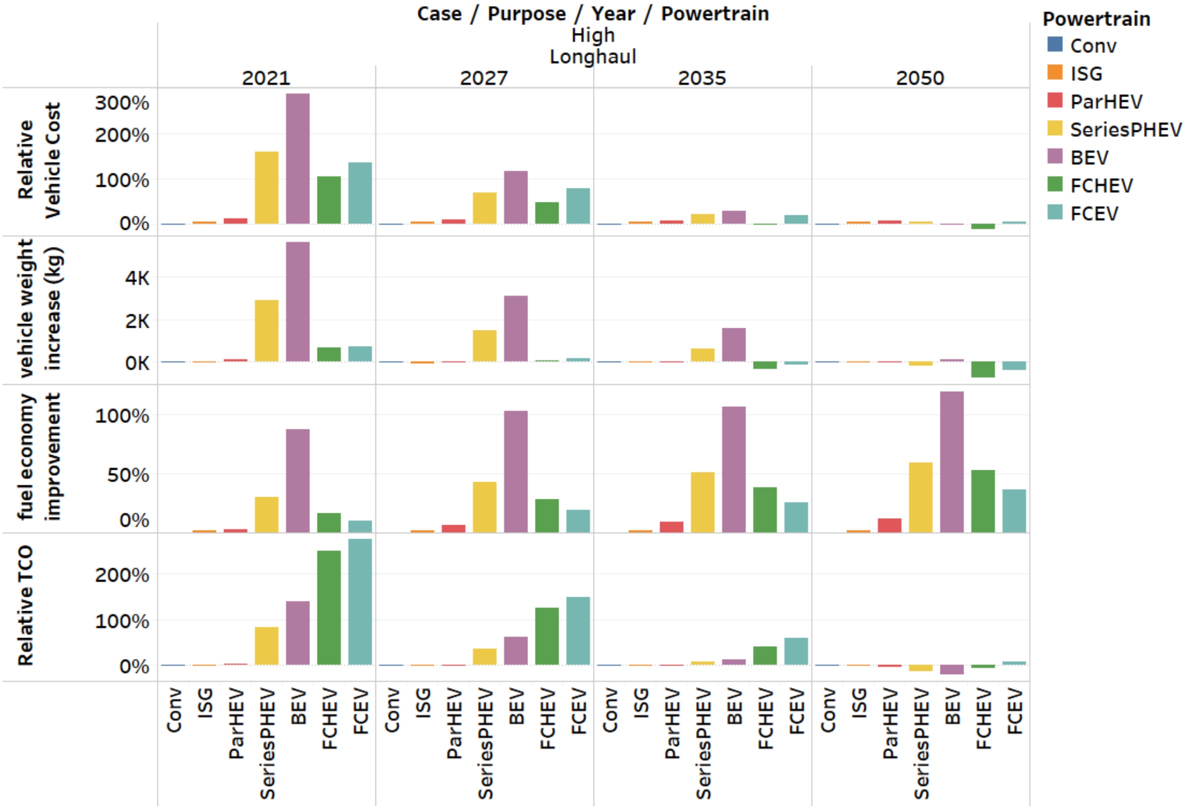

FIGURE 2-18 Evolution of vehicle cost, weight and energy consumption for long haul trucks that use advanced powertrains. All percentages are computed based on the conventional truck parameters for that year.

Similar plots for three more trucks are provided in the Appendix. The data needed to plot this is available for all trucks and is shared as excel sheet accompanying this report.

Fuel economy values for advanced trucks are used as inputs for other VTO-funded projects that estimate lifecycle cost as well as WTW CO_2 emission of trucks.

3.2 MASS & COST ESTIMATES

Mass estimates for each component in Autonomie vary with the power rating or component design characteristics. Figure 2-19 shows the mass of various components on a long haul truck. We see that the PHEV and BEV variants are significantly heavier than the conventional baseline vehicles in 2021 and 2027. This increase in component weight can reduce the cargo carrying capacity; however, battery technology improvements are expected to reduce the vehicle weight penalty as we get closer to 2050. A more detailed view of the mass associated with energy storage in electric and fuel cell trucks in shown in the appendix.

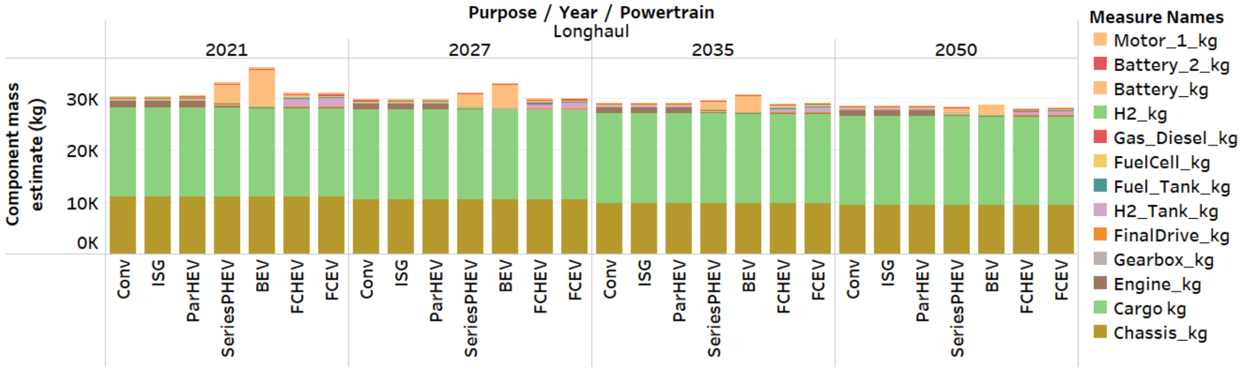

FIGURE 2-19 Mass of each component in long haul trucks that employ advanced powertrains

A recent focus by DOE on cradle-to-grave (C2G) impacts of technologies has made the Autonomie outputs even more valuable to fellow researchers. The overall estimates of component mass are useful in understanding the need for various raw materials used for manufacturing these specific components. The primary focus of these Autonomie simulations was the powertrain, so several non-powertrain components (e.g., body, frame, fluids) were grouped together as chassis mass in this project. Researchers using the mass estimates from Autonomie have provided suggestions and requests for additional component mass estimates from this work. We will improve the mass estimation methods in future work.

Similar to the mass share of the various components, the Autonomie results provide the cost share of components. Figure 2-20 shows that, in the near term (2021-2027), electric and plug-in hybrid long haul trucks are much more expensive than the conventional diesel variant. The main reason for this is battery cost. As the technology improves, we can see the battery cost becoming a relatively smaller part of the overall vehicle cost.

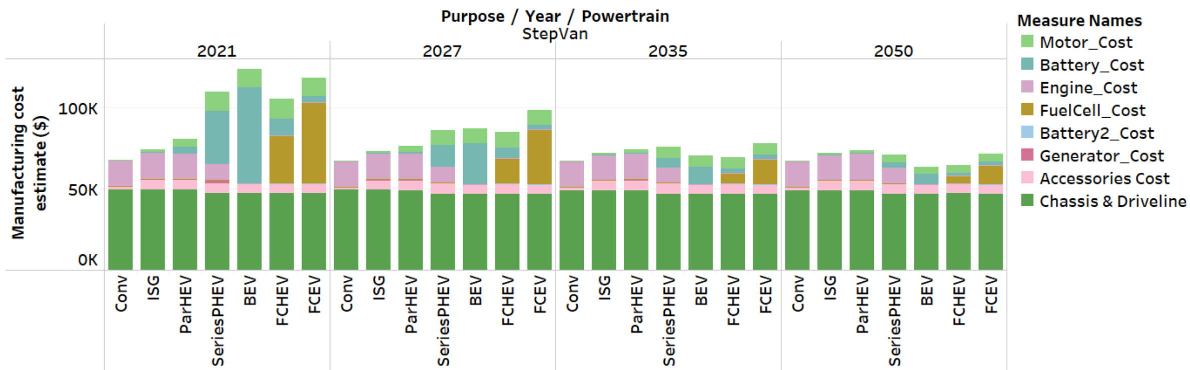

FIGURE 2-20 Cost of each component in long haul trucks that employ advanced powertrains

Technology progress estimates have low and high values for all future years. Figure 2-21 shows both sets of values out to 2050 for a long haul truck.

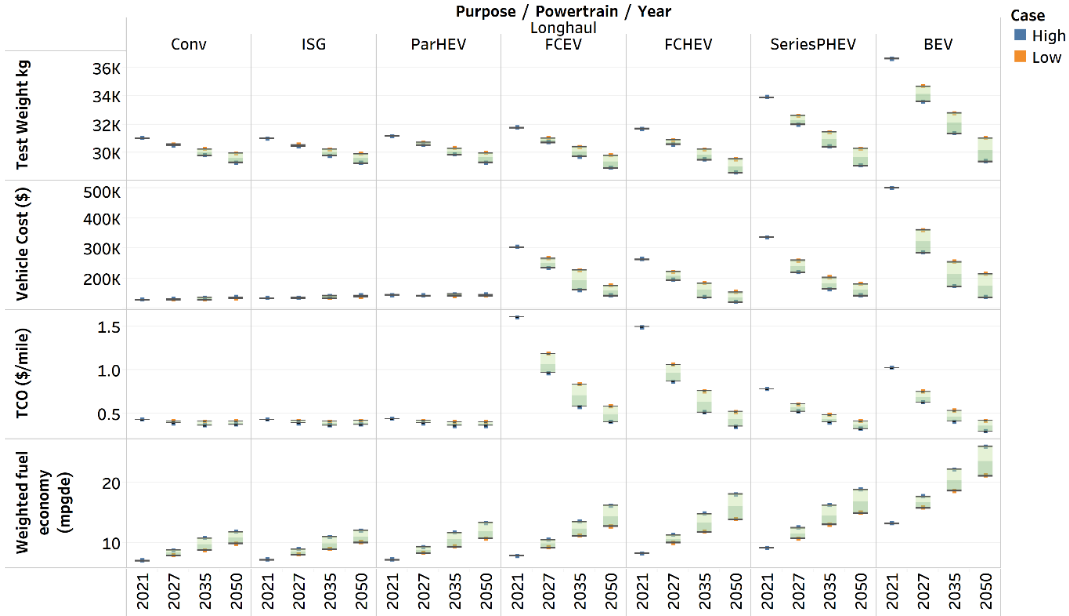

FIGURE 2-21 Varying levels of technology progress (seen here for a long haul truck) has direct impact on fuel economy, vehicle cost and overall ownership cost of trucks

The figure demonstrates that lower levels of technology progress have an impact on vehicle cost, energy consumption, and ownership cost for the vehicles, with the uncertainty particularly pronounced for advanced powertrains. These results demonstrate that achieving a high level of technology progress, as targeted by DOE, will be crucial for the successful introduction of clean affordable vehicles in the medium and heavy duty segment.

Similar plots for three more trucks are provided in the Appendix. The data needed to plot this is available for all 20 types of trucks and is shared as excel sheet accompanying this report. More truck types are being added to this analysis and further improvements will be made based on feedback received from DOE, industry, universities, and national laboratories.

Technology adoption decisions for commercial vehicles are made on the basis of cost of ownership. For the scenario-based analysis, the levelized cost of driving (LCOD) estimate is based on the vehicle purchase price estimate along with the estimated cost of operating the vehicle over the service time assumed for each type of vehicle. A market penetration analysis is beyond the scope of this report, but the data provided by this analysis is used by other agencies and national laboratories for predicting the market adoption of advanced powertrains.

3.3 LEVELIZED COST OF DRIVING (LCOD) ANALYSIS

Autonomie has a built-in method for estimating the levelized cost of driving. This section specifies how Autonomie carries out its LCOD analysis. 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.

A retail price equivalent (RPE) factor of 1.2 is used to estimate the vehicle purchase price from the estimated manufacturing cost.

Other factors are also important when determining the total cost of ownership (TCO), but when we compare the merits and demerits of powertrains, the focus should be on the above two factors. This follows the guidance provided by 21CTP on the economic analysis followed in their target setting process. A separate tool named BEAN has been developed for detailed TCO analysis that involve the other operating costs, such as driver wages, insurance costs, registrations costs, tolls, penalties associated with loss of cargo, down time, etc.

Fuel price is an important factor in determining the competitiveness of various powertrains. The cost of delivering and dispensing diesel, hydrogen, and cost of electricity assumed for this work is shown in Figure 2-22.

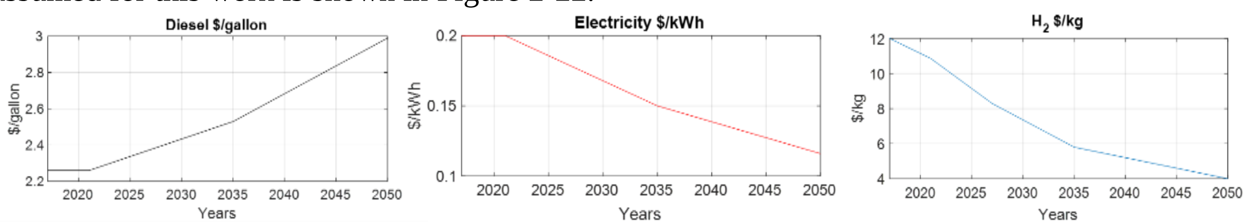

FIGURE 2-22 Cost of diesel, electricity and hydrogen assumed for this analysis

LCOD analysis provides a quick glimpse into how advanced powertrains might emerge in the medium and heavy duty segment. This calculation follows the LCOD calculation methodology adopted for the 21CTP program, and considers the impact of vehicle manufacturing cost and energy cost. Other factors such as downtime associated with charging or loss of cargo capacity attributable to the weight of energy storage systems are not considered in this case. This is something we hope to improve on in future analysis.

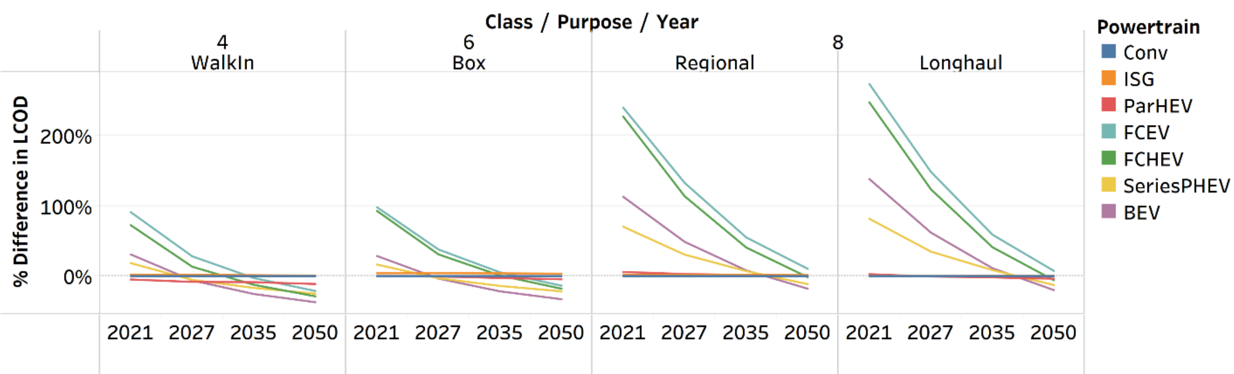

FIGURE 2-23 Comparison of LCOD for 4 types of trucks and 7 powertrain choices

Figure 2-23 shows that the smaller electric trucks and fuel cell trucks are expected to achieve LCOD parity with conventional trucks between 2027 and 2035. Bigger trucks with advanced powertrains will, more likely, achieve LCOD parity in the long term, between 2035 and 2050.

4 CONCLUSIONS

This report outlines the input assumptions (including performance requirements and sizing process assumptions) and modeling processes used to estimate future vehicle-level fuel economy, vehicle weight, and manufacturing cost for medium and heavy trucks. A few sample plots have been shown to demonstrate the analysis process. The full results are shared in the Excel files that accompany this report. Fuel economy, vehicle purchase price, and energy consumption estimates were made for more than 20 class-vocation combinations, seven powertrains, and four time frames, with upper and lower limits for technology progress levels. These results are used as inputs for the scenario-based analysis, the DOE's target setting process, lifecycle cost analysis, cradle to grave 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 DOE targets will be necessary to make BEVs and FCETs economically attractive as compared to conventional diesel powertrains.

This work considers the impact of combined improvement of several vehicle technologies. A separate effort is underway to quantify the energy-saving potential of each component technology target (e.g., lightweighting, aerodynamic improvement, better motors, lighter batteries, etc.). This will quantify the monetary value for the consumer, due to improvements various vehicle characteristics such as motor efficiency, energy density of battery, coefficient of drag, rolling resistance etc.

The vehicles developed as a part of this work are already being used to support half a dozen DOE-funded projects. Representative vehicles for several popular types of trucks will be included in the upcoming release of Autonomie in order to widely distribute the new capabilities developed as part of this project. Future iterations of this work will include new features and analysis, as requested by various stakeholders.

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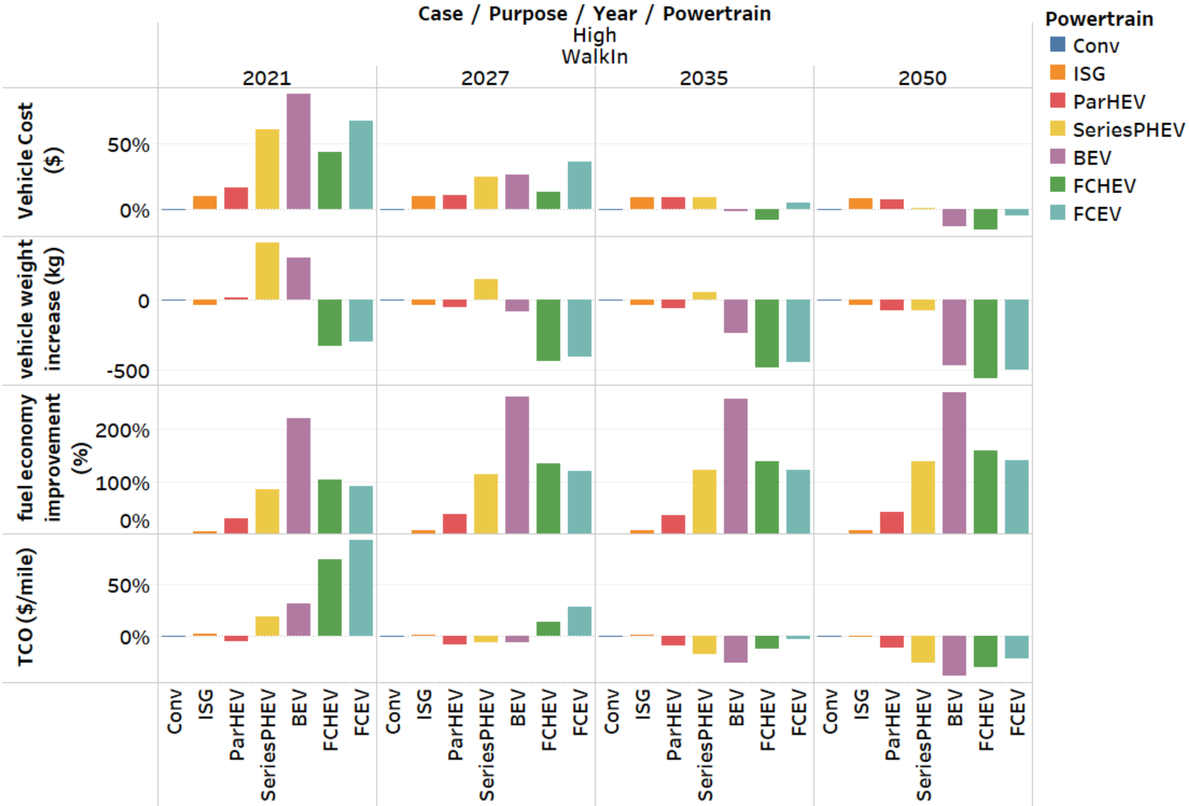
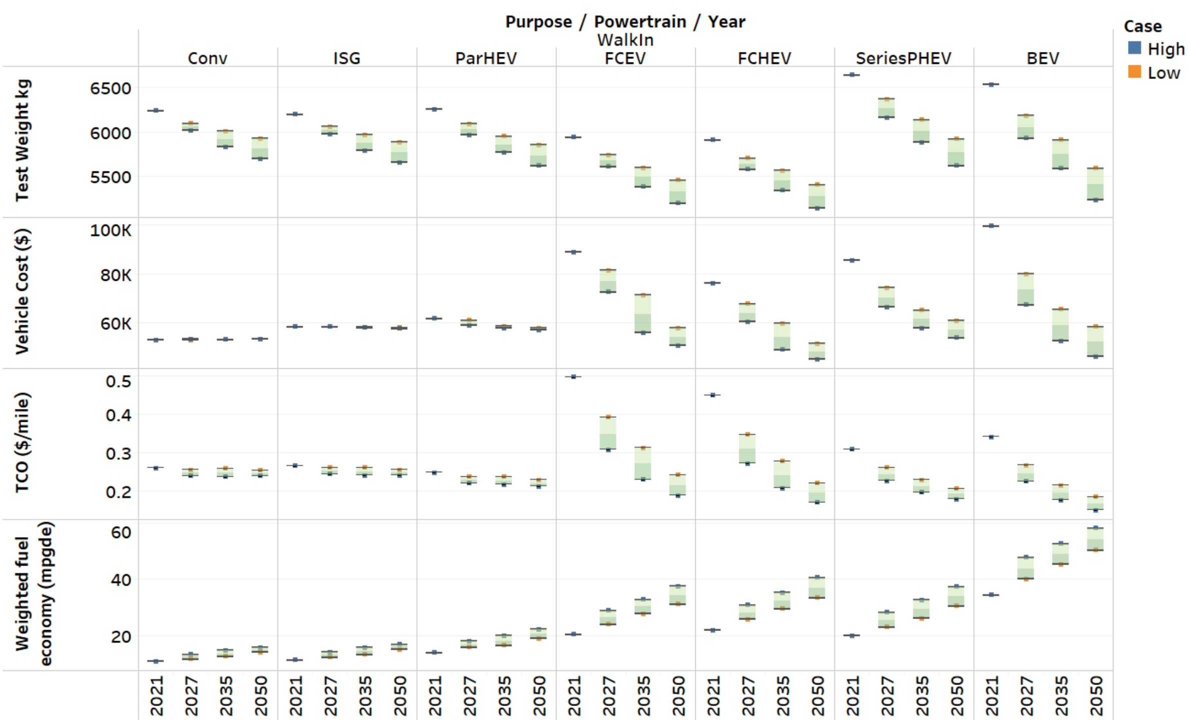
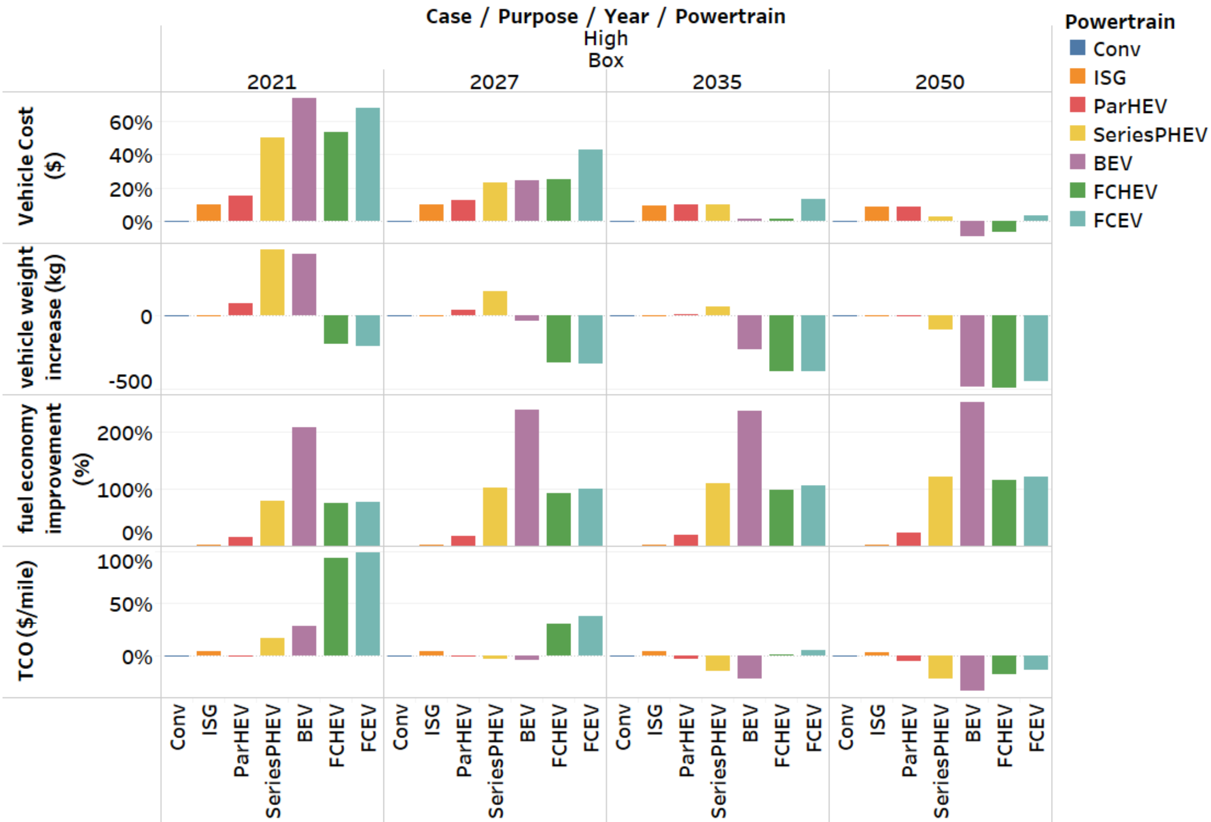
Appendix

Class4 WalkIn





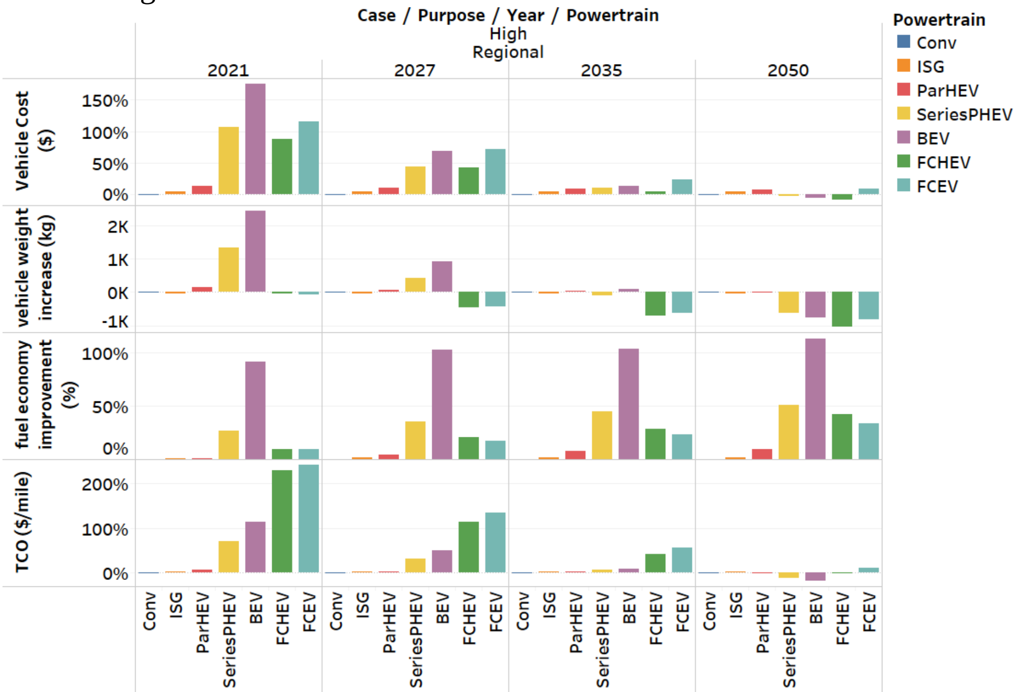
Class 6 Box

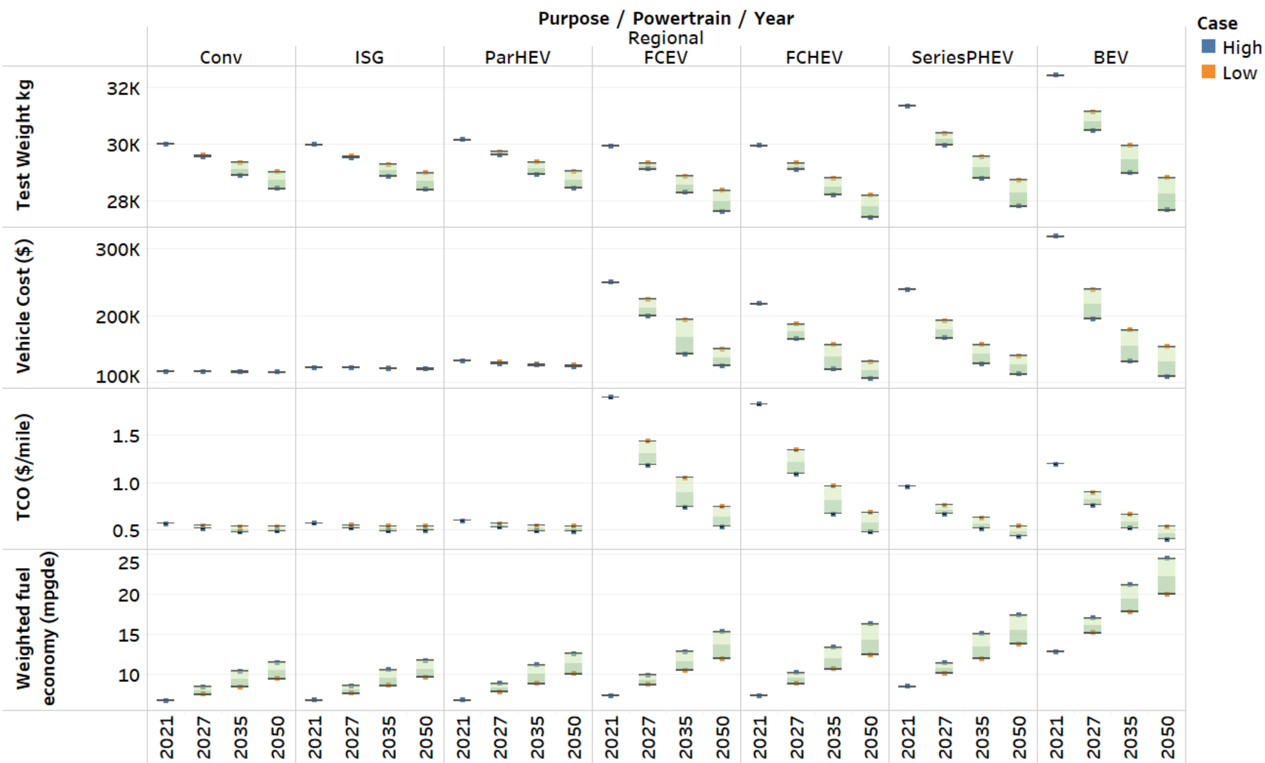


Case / Purpose / Year / Powertrain
High
Box
2021
2027
2035
2050
Powertrain
Conv
ISG
ParHEV
SeriesPHEV
BEV
FCHEV
FCEV
Vehicle Cost ($)
60%
40%
20%
0%
vehicle weight increase (kg)
0
-500
fuel economy improvement (%)
200%
100%
0%
TCO ($/mile)
100%
50%
0%

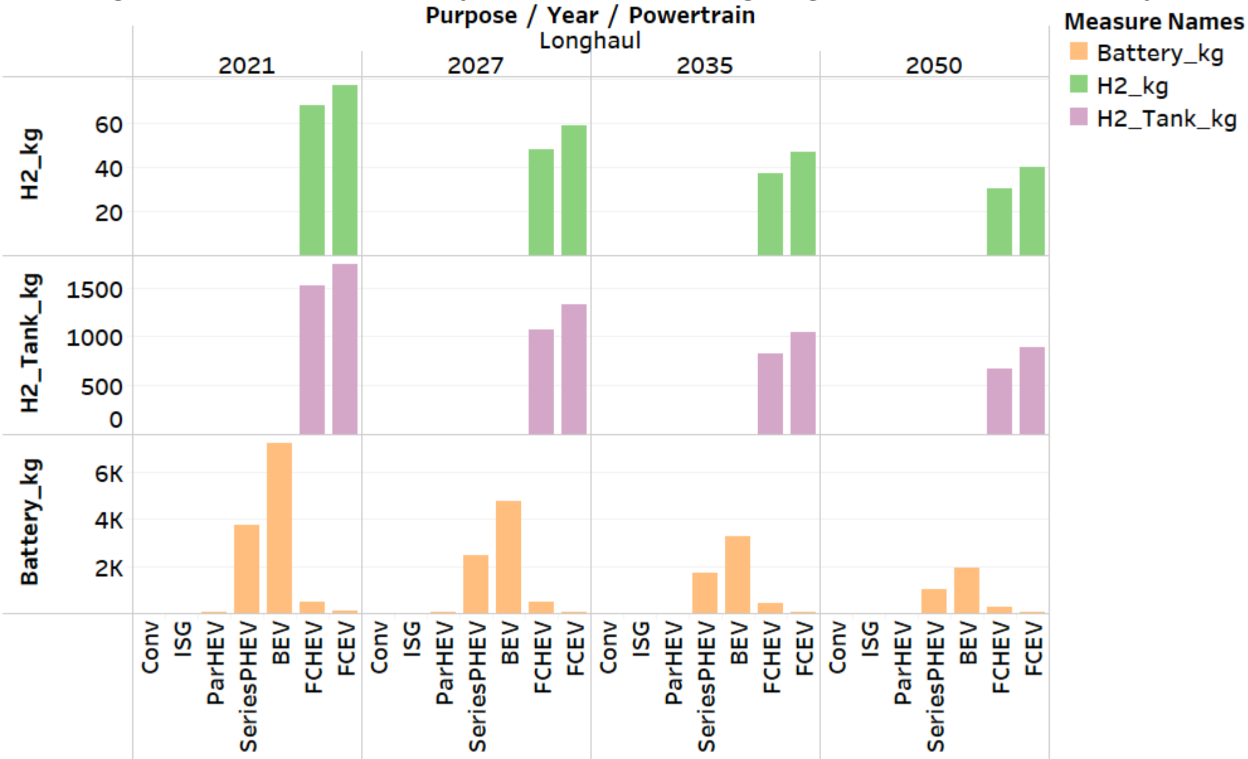
Purpose / Powertrain / Year
Box
Conv
ISG
ParHEV
FCEV
FCHEV
SeriesPHEV
BEV
Case
High
Low
Test Weight kg
11K
10K
Vehicle Cost ($)
120K
100K
80K
TCO ($/mile)
0.6
0.4
0.2
Weighted fuel economy (mpgde)
40
30
20
10
2021
2027
2035
2050

Class 8 Regional





Among the vehicles considered in this work, onboard energy storage requirement is highest for class 8 long haul trucks. This figure shows how the evolution of battery, hydrogen and tank mass for a longhaul truck over the future years. 500 mile driving range is assumed for this analysis.



Argonne NATIONAL LABORATORY

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4832

www.anl.gov

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