ANL/ESD-22/6

A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential

Transportation and Power Systems Division

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Transportation and Power 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
COTS	commercial-off-the-shelf
CVT	continuously variable transmission
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EDV	electric drive vehicle
EERE	Office of Energy Efficiency and Renewable Energy
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
FCEV	fuel cell electric vehicle
FCREX	battery electric vehicle with a fuel cell range extender
Genset	engine plus generator
GHG	greenhouse gas

GREET™	Greenhouse gases, Regulated Emissions, and Energy use in Technologies model
H_2	hydrogen
HEV	hybrid electric vehicle
HFTO	Hydrogen & Fuel Cell Technologies Office
HIL	hardware-in-the-loop
HWFET	Highway Federal Emissions Test
ICE	internal combustion engine
ICCT	International Council on Clean Transportation
ISG	integrated starter/generator
LCA	life-cycle analysis
Li-ion	lithium ion
LCOD	levelized cost of driving
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
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)
PTW	pump-to-wheel
R&D	research and development
RCP	rapid-control prototyping
RPE	retail price equivalent
SAE	Society of Automotive Engineers
SI	spark ignition
SIL	software-in-the-loop
SOC	state of charge
SUV	sport utility vehicle
TEMPO™	Transportation Energy and Mobility Pathway Options model
TCO	total cost of ownership
UDDS	Urban Dynamometer Driving Schedule
U.S. DRIVE	U.S. 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
VVL	variable valve lift
VVT	variable valve timing
WTP	well-to-pump
WTW	well-to-wheel

UNITS OF MEASURE

Cd	coefficient of drag
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
mpgde	miles per gallon diesel equivalent
sec	second(s)
V	volt(s)
W	watt(s)
Wh	watt hour(s)

PREFACE

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

1. Islam, E., R. Vijayagopal, A. Moawad, N. Kim, B. Dupont, D. Nieto Prada, and A. Rousseau, 2021.*"A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050,"* ANL/ESD-21/10, Argonne National Laboratory, Lemont, Ill., Oct.
2. Islam, E., A. Moawad, N. Kim, and A. Rousseau, 2019. *Energy Consumption and Cost Reduction of Future Light-Duty Vehicles through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050*, ANL/ESD-19/10, Argonne National Laboratory, Lemont, Ill., June.
3. Vijayagopal R., D. Nieto Prada, and A. Rousseau, 2019. *Fuel Economy and Cost Estimates for Medium- and Heavy-Duty Trucks*, ANL/ESD-19/8, Dec.
4. Islam, E., A. Moawad, N. Kim, and A. Rousseau, 2018. *An Extensive Study on Vehicle Sizing, Energy Consumption and Cost of Advance Vehicle Technologies*, ANL/ESD-17/17, Argonne National Laboratory, Lemont, Ill.
5. 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*, ANL/ESD 15/28, Argonne National Laboratory, Argonne, Ill., March.
6. Moawad, A., and A. Rousseau, 2016. *Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045*, ANL/ESD-14/4 Revision 1, Argonne National Laboratory, Argonne, Ill., April.
7. Moawad, A., P. Sharer, and A. Rousseau, 2011. *Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045*, ANL/ESD-11/4, Argonne National Laboratory, Argonne, Ill., July.

Links to these reports and the accompanying datasets are on the Argonne Autonomie webpage under "U.S. DOE VTO/HFTO R&D Benefits." The webpage also contains a link to the main assumptions and results for each component and results for each vehicle (by revision).

With each revision of the study, Argonne made improvements 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. From 2020 onwards, summaries for both light- and heavy-duty vehicles are consolidated into one report. The first part of the report covers the impact of technology progress on light-duty vehicles and the second 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

Under the umbrella of EERE’s Office of Sustainable Transportation, the U.S. Department of Energy’s (DOE) Vehicle Technologies Office (VTO) and Hydrogen and Fuel Cell Technologies Office (HFTO) seek to develop sustainable, affordable, and efficient technologies for transportation of goods and people. Translating investments in advanced transportation component technologies and powertrains to estimate the potential for vehicle-level fuel savings is critical to understanding DOE’s impact and success in this mission

For this study, Argonne National Laboratory (Argonne) simulated technologies funded by VTO and HFTO for light-duty vehicles across the following:

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

We assessed each technology for five different timeframes: laboratory years 2015 (reference), 2020, 2025, 2030, and 2045. We assumed a delay of 5 years between laboratory year and model year (i.e., the year the technology is introduced into production). Finally, we included uncertainties for both technology performance and cost by considering two cases (note that these cases are not intended as predictions of future performance):

- *Low case*, aligned with DOE technology manager estimates of expected original equipment manufacturer (OEM) improvements based on business as usual regulatory and market environments.
- *High case*, aligned with aggressive technology advancements based on research and development (R&D) targets developed through support by VTO and HFTO.

We estimated the energy and cost impact of different technologies using Autonomie (Argonne undated), a state-of-the-art vehicle system simulation tool developed by Argonne and used to assess the energy consumption, performance, and cost of multiple advanced vehicle technologies. The tool comprises a complete set of vehicle models to assess impacts across a wide range of classes (from light- to heavy-duty), powertrain configurations (from conventional to hybrid electric vehicles [HEVs], fuel cell electric vehicles [FCEVs], plug-in hybrid electric vehicles [PHEVs], and battery electric vehicles [BEVs]), components, and control strategies, including vehicle-level and component-level controls developed and calibrated using dynamometer test data. Autonomie has been used to support a wide range of studies: analyzing various component technologies, sizing powertrain components to meet 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 made and the vehicle-level energy consumption benefits and associated technology costs estimated for various types of light-duty vehicles. Details regarding 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, Argonne considered the following:

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

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

- *Five timeframes*: 2015 (reference), 2020, 2025, 2030, and 2045 (all "laboratory years" with a 5-year delay to production year).

- *Seven powertrain configurations*: conventional, micro-hybrid, mild-hybrid belt-integrated starter generator (BISG), HEV (including split and parallel HEVs), PHEV (including split, extended-range electric vehicle (EREV), and parallel PHEVs), FCEVs, and BEVs of different all-electric ranges (AERs).

- *Five fuel combinations:* gasoline, diesel, compressed natural gas (CNG), hydrogen and electricity

- *Two technology progress uncertainty levels: low and high*. These correspond to low uncertainty (aligned with OEM improvements based on "business as usual" regulatory and market environments), and high uncertainty (aligned with aggressive technology advancement based on DOE VTO and HFTO programs). Low-technology progress corresponds to low uncertainty in achieving the target; that is, the manufacturers would be very likely to achieve this target without technology advances by DOE VTO and HFTO programs. High-technology progress corresponds to high uncertainty in manufacturers achieving the target as they respond to DOE VTO and HFTO targets for the corresponding technology and laboratory year. These uncertainties do not necessarily lead to predicting future performance.

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

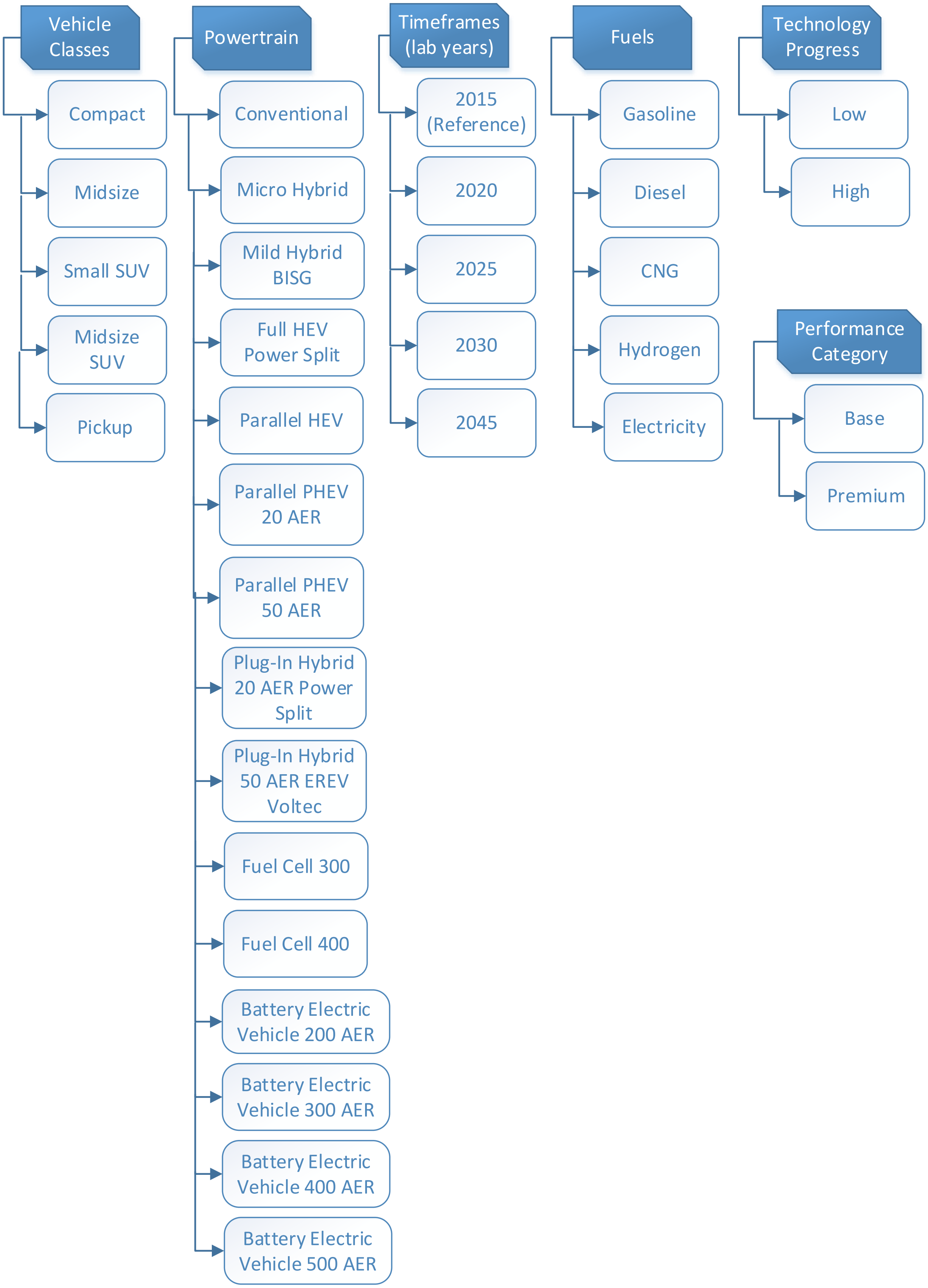

Vehicle Classes
Compact
Midsize
Small SUV
Midsize SUV
Pickup
Powertrain
Conventional
Micro Hybrid
Mild Hybrid BISG
Full HEV Power Split
Parallel HEV
Parallel PHEV 20 AER
Parallel PHEV 50 AER
Plug-In Hybrid 20 AER Power Split
Plug-In Hybrid 50 AER EREV Voltec
Fuel Cell 300
Fuel Cell 400
Battery Electric Vehicle 200 AER
Battery Electric Vehicle 300 AER
Battery Electric Vehicle 400 AER
Battery Electric Vehicle 500 AER
Timeframes (lab years)
2015 (Reference)
2020
2025
2030
2045
Fuels
Gasoline
Diesel
CNG
Hydrogen
Electricity
Technology Progress
Low
High
Performance Category
Base
Premium

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

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 DOE VTO, is designed for rapid and easy integration of models with varying levels of detail (i.e., low to high fidelity), abstraction (i.e., 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 reuse 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 (COTS) software applications, including GT-POWER, AMESim™, and CarSim®, for detailed, physically based models.
- Protect proprietary models and processes.

Autonomie allows the rapid simulation of a very large number of component technologies and powertrain configurations. Its capabilities include 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

We simulated energy consumption using the Urban Dynamometer Driving Schedule (UDDS) and the Highway Federal Emissions Test (HWFET) (U.S. EPA 2021), a combination we will refer to in this report as “the combined driving cycle.” The vehicle costs are calculated from individual component characteristics (e.g., power, energy, weight).

3 ASSUMPTIONS

Argonne determined individual vehicle component target assumptions in collaboration with experts from DOE; various vehicle assumptions are based on consultation with other national laboratories, industry, and academia. Each vehicle simulation relies on a number of component assumptions.

3.1 ENGINE

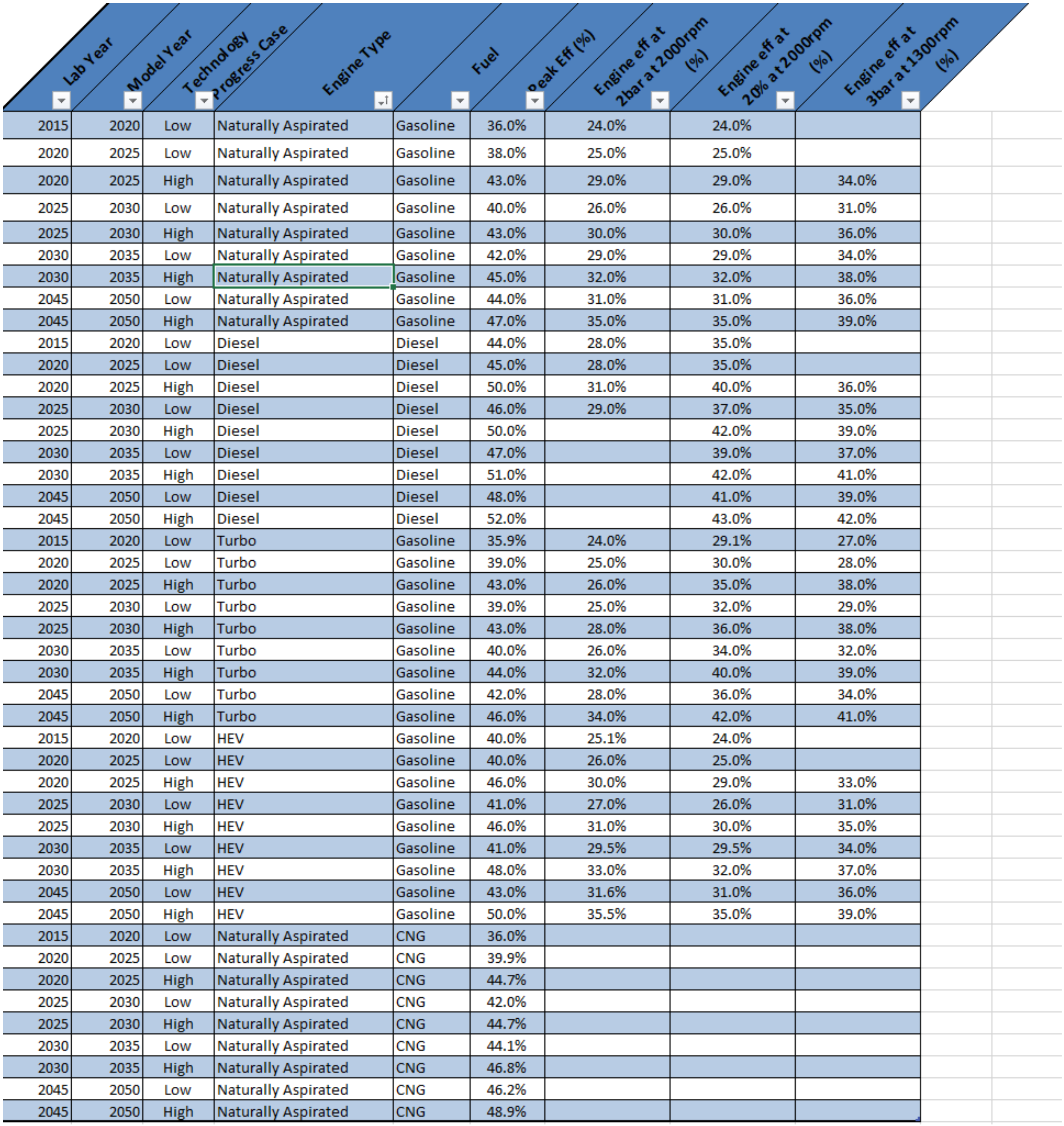
We selected the latest designs of internal combustion engines (ICEs) with current state-of-the-art technologies as the baseline for the types of fuel considered: gasoline (spark ignition [SI]) and diesel (compression ignition [CI]). The engines used for HEVs and PHEVs are based on Atkinson cycles generated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

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

- 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), and
- Stoichiometric and lean-burn gasoline direct injection

Rather than analyzing individual engine technologies, we considered “baskets” of advanced technologies consistent with expectations of engine performance over time. We selected peak and part-load efficiencies for each fuel type and timeframe on the basis of discussions with experts and review of the available literature. The different part-load operations ensure that different operating regions of the engines correspond to coupling with advanced transmissions. These regions determine the vehicle operations in standard U.S. regulatory cycles, which then dictate the fuel economy of the vehicles. Table 1-1 lists 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

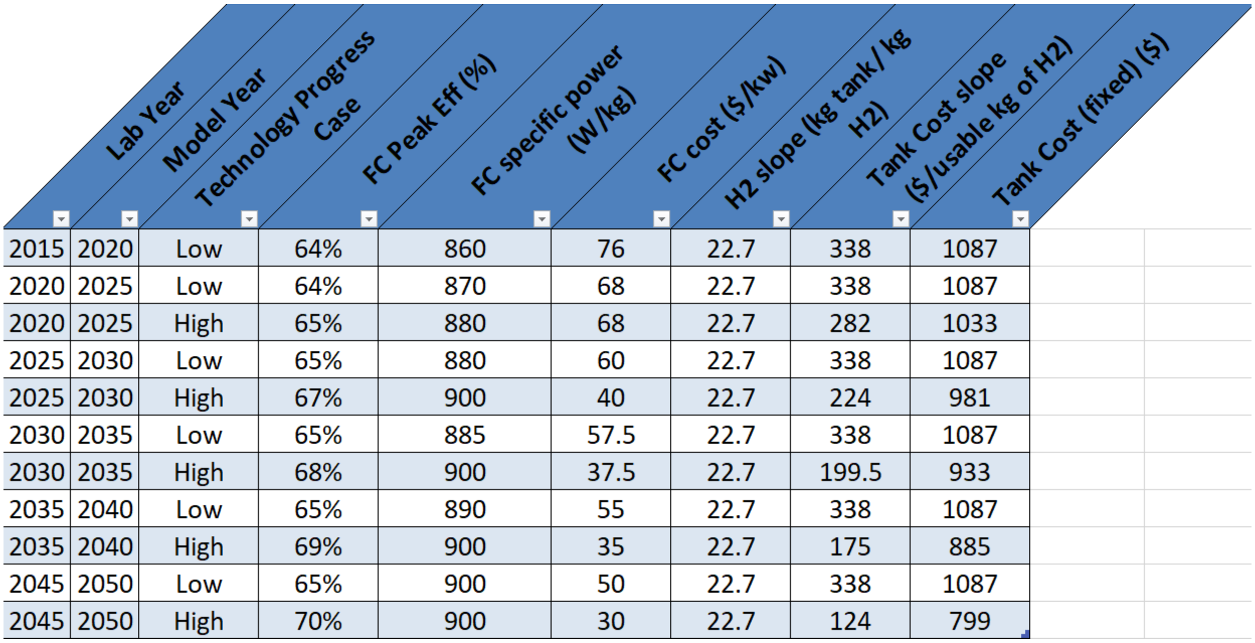


Lab Year	Model Year	Technology Progress Case	Engine Type	Fuel	Peak Eff (%)	Engine eff at 2bar at 2000rpm (%)	Engine eff at 20% at 2000rpm (%)	Engine eff at 3bar at 1300rpm (%)
2015	2020	Low	Naturally Aspirated	Gasoline	36.0%	24.0%	24.0%	
2020	2025	Low	Naturally Aspirated	Gasoline	38.0%	25.0%	25.0%	
2020	2025	High	Naturally Aspirated	Gasoline	43.0%	29.0%	29.0%	34.0%
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%	36.0%
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%	38.0%
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%		42.0%	41.0%
2045	2050	Low	Diesel	Diesel	48.0%		41.0%	39.0%
2045	2050	High	Diesel	Diesel	52.0%		43.0%	42.0%
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%	35.0%	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%	40.0%	39.0%
2045	2050	Low	Turbo	Gasoline	42.0%	28.0%	36.0%	34.0%
2045	2050	High	Turbo	Gasoline	46.0%	34.0%	42.0%	41.0%
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 AND HYDROGEN STORAGE TANK SYSTEM

Table 1-2, which lists the power density of fuel cell systems, reveals that, between the reference case of laboratory years 2015 and 2045, the power density increases from 860 watts per kilogram (W/kg) for the low scenario to up to 900 W/kg for the high scenario. The low and high labels correspond to the two technology performance cases considered in the study. Along with the various assumed characteristics of the fuel cell systems, the table also lists the parameters of the corresponding hydrogen storage tank systems.

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	64%	860	76	22.7	338	1087
2020	2025	Low	64%	870	68	22.7	338	1087
2020	2025	High	65%	880	68	22.7	282	1033
2025	2030	Low	65%	880	60	22.7	338	1087
2025	2030	High	67%	900	40	22.7	224	981
2030	2035	Low	65%	885	57.5	22.7	338	1087
2030	2035	High	68%	900	37.5	22.7	199.5	933
2035	2040	Low	65%	890	55	22.7	338	1087
2035	2040	High	69%	900	35	22.7	175	885
2045	2050	Low	65%	900	50	22.7	338	1087
2045	2050	High	70%	900	30	22.7	124	799

The hydrogen tank weight is measured using the following 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 following equation:

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

We sized the fuel cell systems to correspond to various ranges on the adjusted combined cycles. In addition, we assumed that 100% of the hydrogen present in the tank is usable. The fuel cell peak efficiency is assumed to be 64% for reference laboratory year 2015, increasing to 70% for laboratory year 2045.

3.3 ELECTRIC MACHINE

Argonne used the following two electric machines as references in this study:

- Power-split vehicles use a permanent magnet electric machine (similar to that in 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 inverter losses. The electric machine power, like the engine power, 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 and PHEV	Hyundai Sonata HEV data from ORNL (Olszewski 2011)	
Power -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 FCEV	Chevrolet Bolt EM data (Momen 2018)	

We scaled the peak efficiency of electric machines to varying peak efficiencies for the different powertrains, as shown in Table 1-4. The values listed are the peak efficiency values 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 / Parallel PHEV	96
Blended PHEV20 AER/E-REV PHEV50 AER	96
BEV and FCV	98

Table 1-5 details the electric traction drive system and other cost assumptions across the different lab years and technology progresses modeled in Autonomie. The electric traction drive system cost includes the electric machine and associated high-voltage power electronics (inverter) as a system in whole.

TABLE 1-5 Electric traction drive system assumptions

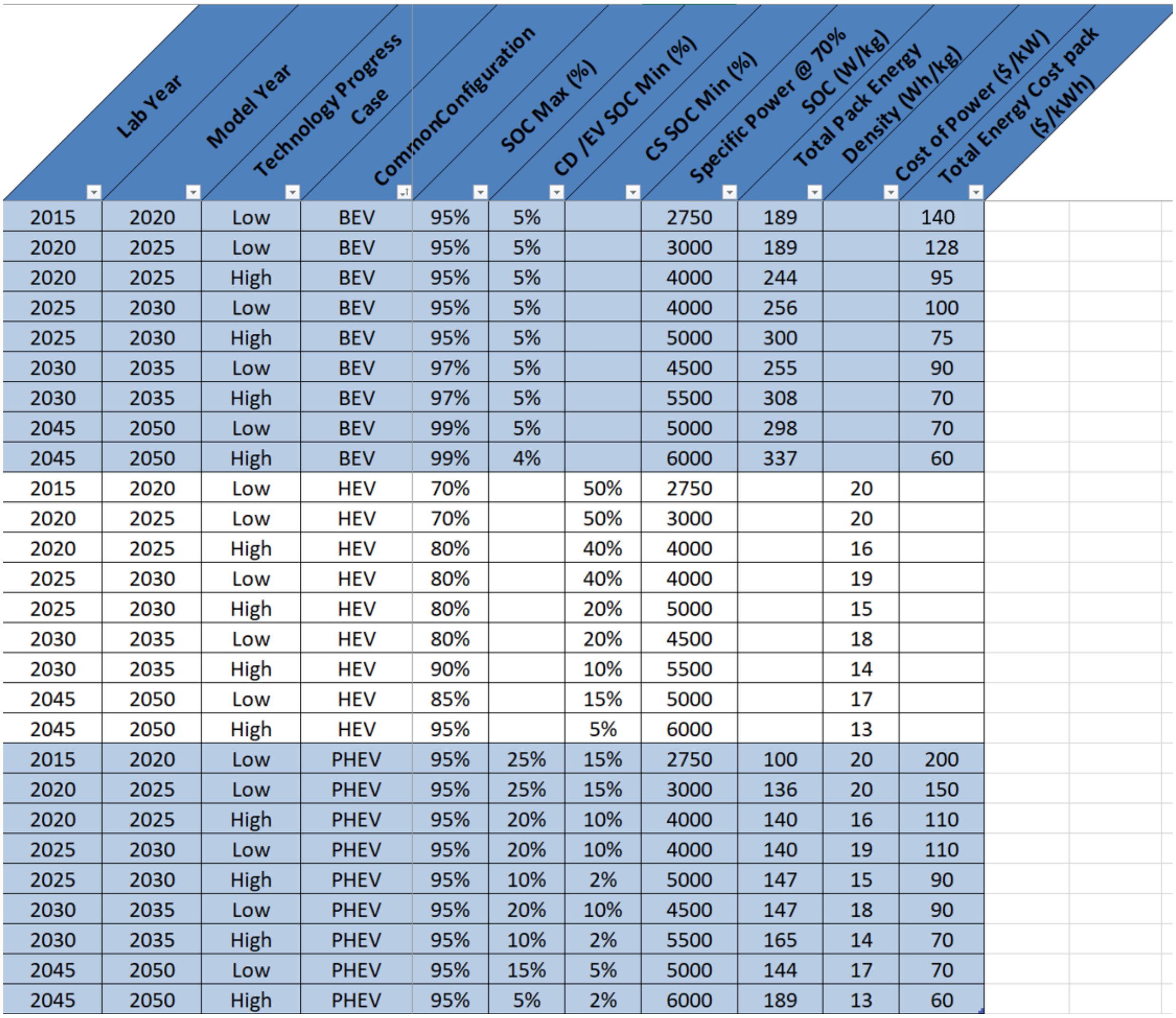
Lab Year	Model Year	Technology Progress Case	Electric Drive System Cost (based on peak power) ($/kW)	DC/DC Buck Converter Cost ($/kw)	Boost Converter Cost ($/kW)	On-board Charger cost ($)	On-Board Charger Efficiency (%)
2015	2020	Low	12	75	8	75	97%
2020	2025	Low	9	45	5	45	97%
2020	2025	High	6	30	3	30	98%
2025	2030	Low	6	30	4.8	30	97%
2025	2030	High	4	20	2.7	20	99%
2030	2035	Low	4.8	25	4.8	25	98%
2030	2035	High	3.2	16.7	2.6	16.7	99%
2045	2050	Low	2.25	13.33	4.5	13.33	98%
2045	2050	High	1.5	8.89	2	8.89	99%

3.4 ENERGY STORAGE SYSTEM

Battery performance data used in this study are provided by Argonne, Idaho National Laboratory, and major battery suppliers (Francfort 2014). The scaling algorithm used for high-energy cases, developed by Argonne (Nelson et al. 2007), is used to scale the battery cell capacity as well as the 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 1-6 summarizes the battery characteristics including the state-of-charge (SOC) assumptions.

TABLE 1-6 Battery assumptions

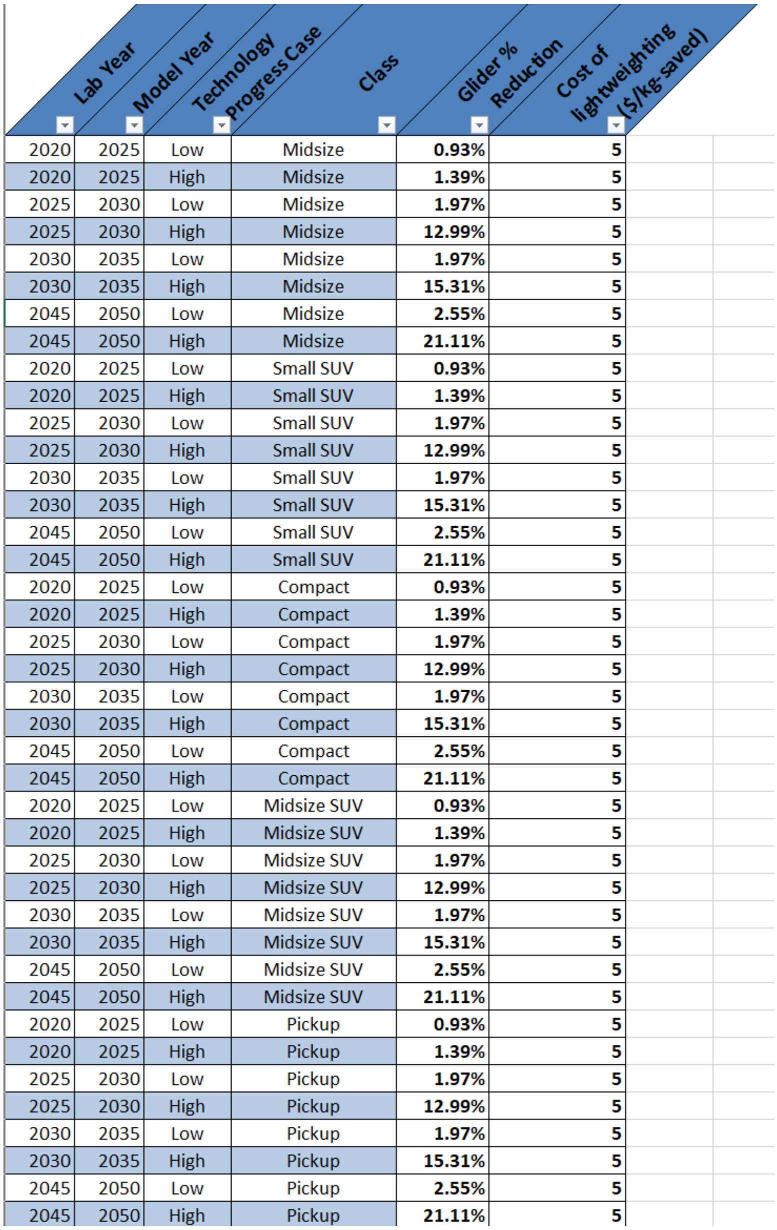


Lab Year	Model Year	Technology Progress Case	CommonConfiguration	SOC Max (%)	CD /EV SOC Min (%)	CS SOC Min (%)	Specific Power @ 70% SOC (W/kg)	Total Pack Energy Density (Wh/kg)	Cost of Power ($/kW)	Total Energy Cost pack ($/kWh)
2015	2020	Low	BEV	95%	5%		2750	189		140
2020	2025	Low	BEV	95%	5%		3000	189		128
2020	2025	High	BEV	95%	5%		4000	244		95
2025	2030	Low	BEV	95%	5%		4000	256		100
2025	2030	High	BEV	95%	5%		5000	300		75
2030	2035	Low	BEV	97%	5%		4500	255		90
2030	2035	High	BEV	97%	5%		5500	308		70
2045	2050	Low	BEV	99%	5%		5000	298		70
2045	2050	High	BEV	99%	4%		6000	337		60
2015	2020	Low	HEV	70%		50%	2750		20	
2020	2025	Low	HEV	70%		50%	3000		20	
2020	2025	High	HEV	80%		40%	4000		16	
2025	2030	Low	HEV	80%		40%	4000		19	
2025	2030	High	HEV	80%		20%	5000		15	
2030	2035	Low	HEV	80%		20%	4500		18	
2030	2035	High	HEV	90%		10%	5500		14	
2045	2050	Low	HEV	85%		15%	5000		17	
2045	2050	High	HEV	95%		5%	6000		13	
2015	2020	Low	PHEV	95%	25%	15%	2750	100	20	200
2020	2025	Low	PHEV	95%	25%	15%	3000	136	20	150
2020	2025	High	PHEV	95%	20%	10%	4000	140	16	110
2025	2030	Low	PHEV	95%	20%	10%	4000	140	19	110
2025	2030	High	PHEV	95%	10%	2%	5000	147	15	90
2030	2035	Low	PHEV	95%	20%	10%	4500	147	18	90
2030	2035	High	PHEV	95%	10%	2%	5500	165	14	70
2045	2050	Low	PHEV	95%	15%	5%	5000	144	17	70
2045	2050	High	PHEV	95%	5%	2%	6000	189	13	60

3.5 LIGHTWEIGHTING

Table 1-7 lists the lightweighting assumptions for the glider mass across vehicle classes and laboratory years. Low and high cases illustrate the different technology performance scenarios. Glider mass reduction and lightweighting cost ($/kg-saved) assumptions over time are similar among similarly sized vehicles. The weight-reduction assumption is attributable to the use of better materials and technologies in the future, such as aluminum unibody structures.

TABLE 1-7 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	**0.93%**	**5**
2020	2025	High	Midsize	**1.39%**	**5**
2025	2030	Low	Midsize	**1.97%**	**5**
2025	2030	High	Midsize	**12.99%**	**5**
2030	2035	Low	Midsize	**1.97%**	**5**
2030	2035	High	Midsize	**15.31%**	**5**
2045	2050	Low	Midsize	**2.55%**	**5**
2045	2050	High	Midsize	**21.11%**	**5**
2020	2025	Low	Small SUV	**0.93%**	**5**
2020	2025	High	Small SUV	**1.39%**	**5**
2025	2030	Low	Small SUV	**1.97%**	**5**
2025	2030	High	Small SUV	**12.99%**	**5**
2030	2035	Low	Small SUV	**1.97%**	**5**
2030	2035	High	Small SUV	**15.31%**	**5**
2045	2050	Low	Small SUV	**2.55%**	**5**
2045	2050	High	Small SUV	**21.11%**	**5**
2020	2025	Low	Compact	**0.93%**	**5**
2020	2025	High	Compact	**1.39%**	**5**
2025	2030	Low	Compact	**1.97%**	**5**
2025	2030	High	Compact	**12.99%**	**5**
2030	2035	Low	Compact	**1.97%**	**5**
2030	2035	High	Compact	**15.31%**	**5**
2045	2050	Low	Compact	**2.55%**	**5**
2045	2050	High	Compact	**21.11%**	**5**
2020	2025	Low	Midsize SUV	**0.93%**	**5**
2020	2025	High	Midsize SUV	**1.39%**	**5**
2025	2030	Low	Midsize SUV	**1.97%**	**5**
2025	2030	High	Midsize SUV	**12.99%**	**5**
2030	2035	Low	Midsize SUV	**1.97%**	**5**
2030	2035	High	Midsize SUV	**15.31%**	**5**
2045	2050	Low	Midsize SUV	**2.55%**	**5**
2045	2050	High	Midsize SUV	**21.11%**	**5**
2020	2025	Low	Pickup	**0.93%**	**5**
2020	2025	High	Pickup	**1.39%**	**5**
2025	2030	Low	Pickup	**1.97%**	**5**
2025	2030	High	Pickup	**12.99%**	**5**
2030	2035	Low	Pickup	**1.97%**	**5**
2030	2035	High	Pickup	**15.31%**	**5**
2045	2050	Low	Pickup	**2.55%**	**5**
2045	2050	High	Pickup	**21.11%**	**5**

3.6 VEHICLE ASSUMPTIONS

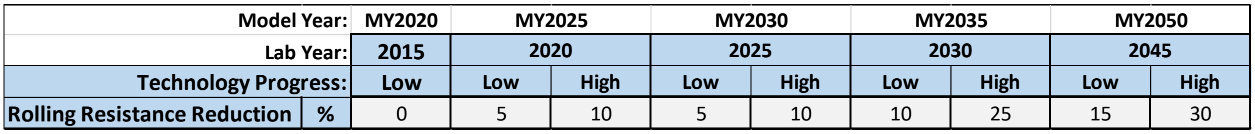
Table 1-8 summarizes values for the frontal area of the reference vehicles for the different vehicle classes and performance categories.

TABLE 1-8 Frontal area summary

Vehicle Class	Performance Category	Reference Value (m^2)
Compact	Base/Premium	2.30
Mid-size	Base/Premium	2.35
Small SUV	Base/Premium	2.65
Mid-size SUV	Base/Premium	2.85
Pickup	Base/Premium	3.25

The fixed rolling resistance coefficient is set at 0.006 (reference value) for all vehicle classes and performance categories. Table 1-9 details the rolling resistance coefficient reductions for all vehicle classes and performance categories across laboratory years and the two technology progress levels.

TABLE 1-9 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 1-10 summarizes the reference drag coefficient assumptions for different vehicle classes.

TABLE 1-10 Reference drag coefficient assumptions

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

Table 1-11 details the drag coefficient reductions for all vehicle classes and performance categories across laboratory years and technology progress.

TABLE 1-11 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 SPECIFICATIONS

The first step in sizing individual powertrain components is to define the vehicle technical specifications (e.g., maximum speed, 0-60 miles per hour [mph], gradeability). We developed minimum requirements based on an in-depth analysis of current vehicles in the market.

Table 1-12 provides the 0-60 mph minimum requirements across vehicle classes and categories.

TABLE 1-12 0-60 mph time(s) across vehicle classification and performance categories

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

Additional performance metrics include the following:

- Gradeability: 6% grade at 65 mph,
- Payload: 900 kg (pickup base/premium only), and
- 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 BEV as an example: increasing the required battery energy would increase the vehicle weight, which would 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 (e.g., specific power, efficiency) is taken into account to define the entire set of vehicle attributes (e.g., vehicle curb weight). The process is recursive in the sense that each assumption influences the main component characteristics (e.g., maximum power, vehicle weight) 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.

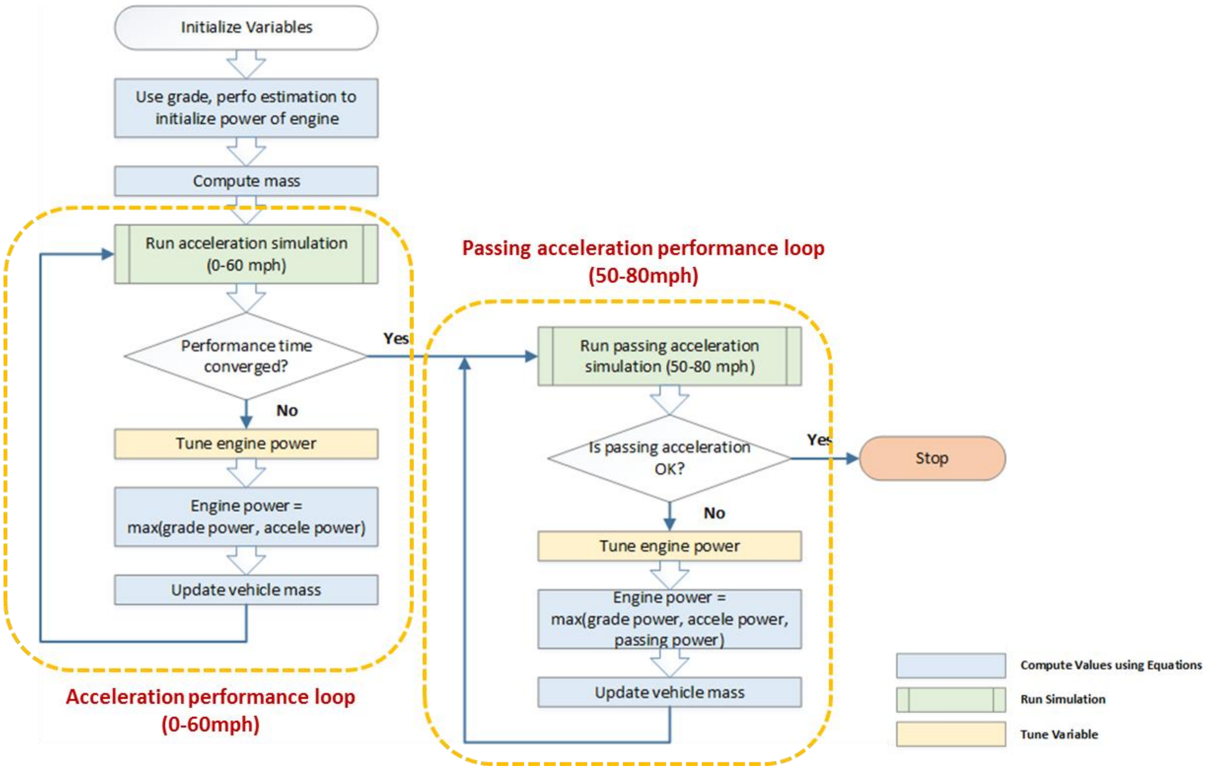


FIGURE 1-2 Conventional powertrain sizing algorithm

Similar to conventional powertrain sizing, we account for the following for other powertrains:

- For HEVs, we assumed that the electric machine and battery power levels 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 (PHEV with 20 mi of all-electric range [end-of-life] on combined driving cycle [adjusted]), we sized the electric machine and battery power levels 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.) We define battery-usable energy to follow the combined drive cycle for 20 mi (with U.S.

Environmental Protection Agency [EPA]-adjusted sticker values), then size the engine to meet both performance and gradeability requirements.

- For PHEV50s (PHEV with 50 mi of all-electric range [end-of-life] on combined driving cycle [adjusted]), we sized the main electric machine and battery power levels to follow the aggressive EPA US06 drive cycle (US06) (duty cycle with aggressive highway driving) in electric-only mode. We defined the battery-usable energy to follow the combined drive cycle for 50 mi (adjusted), depending on the requirements. The generator set (engine plus generator) are sized to meet gradeability requirements.

4.3 POWERTRAIN SIZING RESULTS

This section provides examples of maximum power, energy, and weight for the small SUVs across several powertrain configurations and performance categories.

4.3.1 Conventional Vehicles

Figure 1-3 illustrates the evolution in engine maximum power for small SUV conventional vehicles across laboratory years and technology progress cases for the various performance categories. Driven by lightweighting and aerodynamic improvements, the engine peak power decreases over time. The transmission selection for different laboratory years affects the performance sizing.

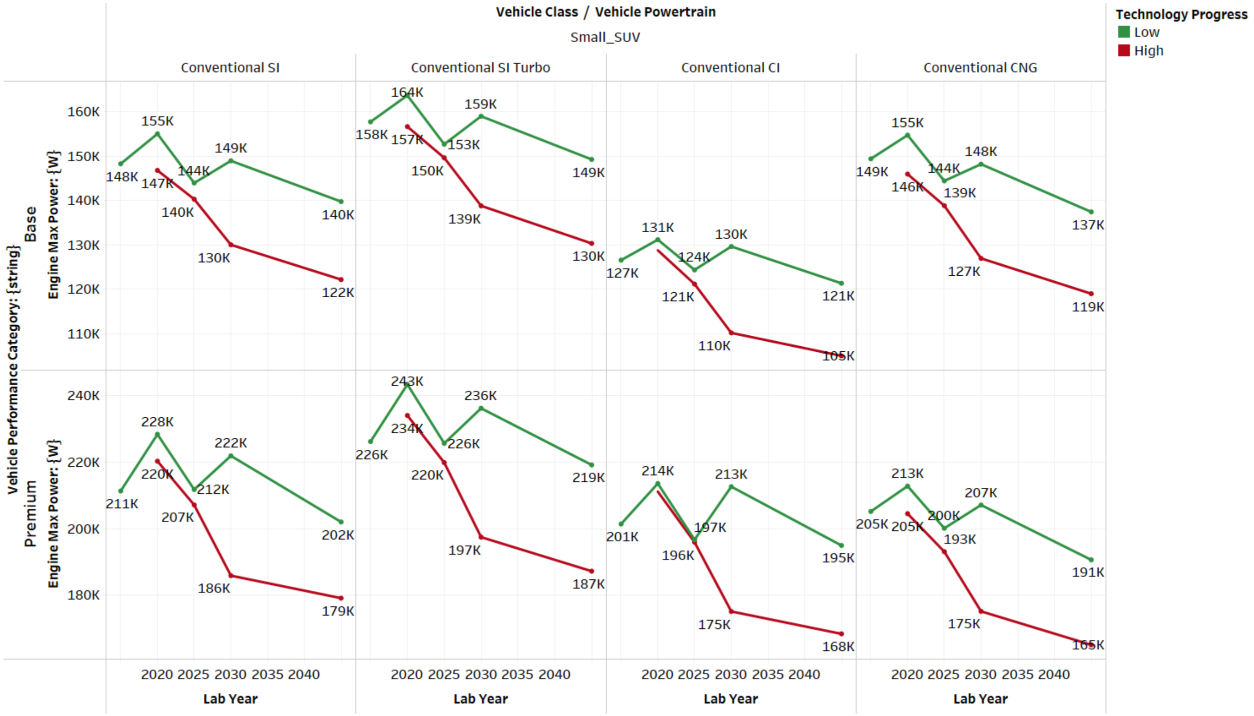


FIGURE 1-3 Engine maximum power for conventional small SUVs

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

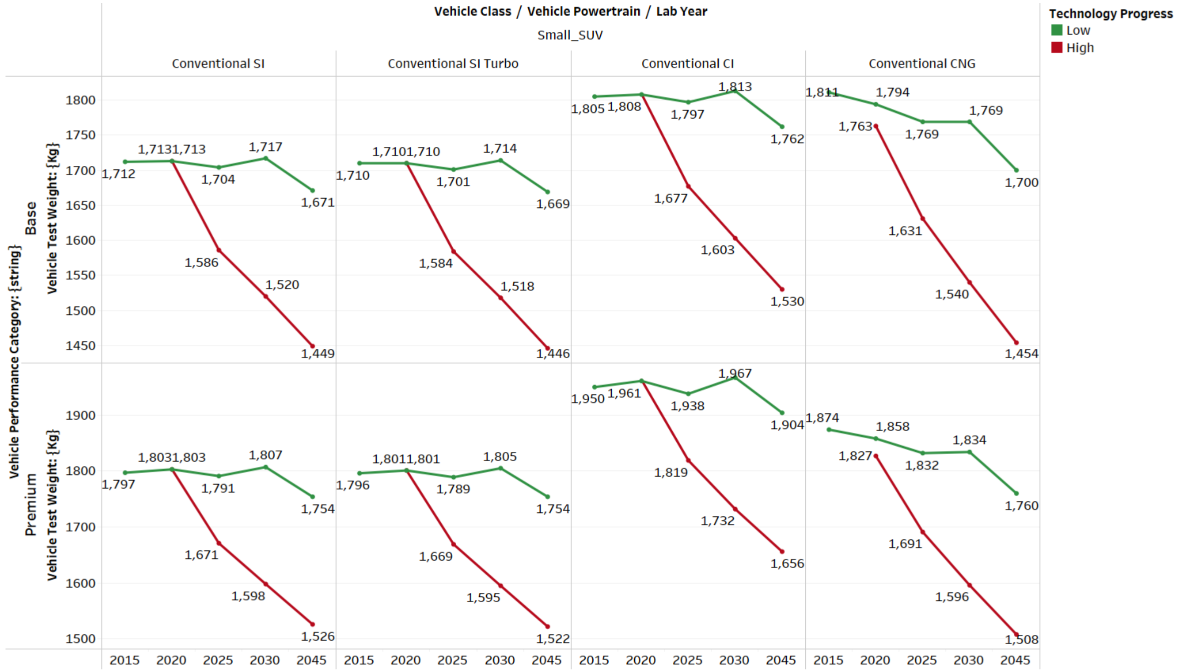


FIGURE 1-4 Vehicle test weight of conventional small SUVs

Over time, the vehicle test weight of conventional vehicles decreases by about 15–20% across the different fuel types, technology progress cases, and performance categories. The main reason for the decrease is future vehicle lightweighting.

4.3.2 Power-Split HEVs

Figure 1-5 illustrates the engine maximum power for small SUV 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 17–18% across the low and high technology progress cases over time.

FIGURE 1-5 Engine peak power for small SUV power-split HEVs

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

FIGURE 1-6 Electric machine peak power for small SUV power-split HEVs

The electric machine peak power requirement decreases by about 15% across the high technology progress cases for both performance categories from the reference case (2015 low technology progress case).

4.3.3 Fuel Cell Electric Vehicles

Figure 1-7 illustrates the fuel cell maximum power for small SUV FCEVs. 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 2015 low technology case to the 2045 high technology case ranges around 10-20% for FCEVs across the different performance categories.

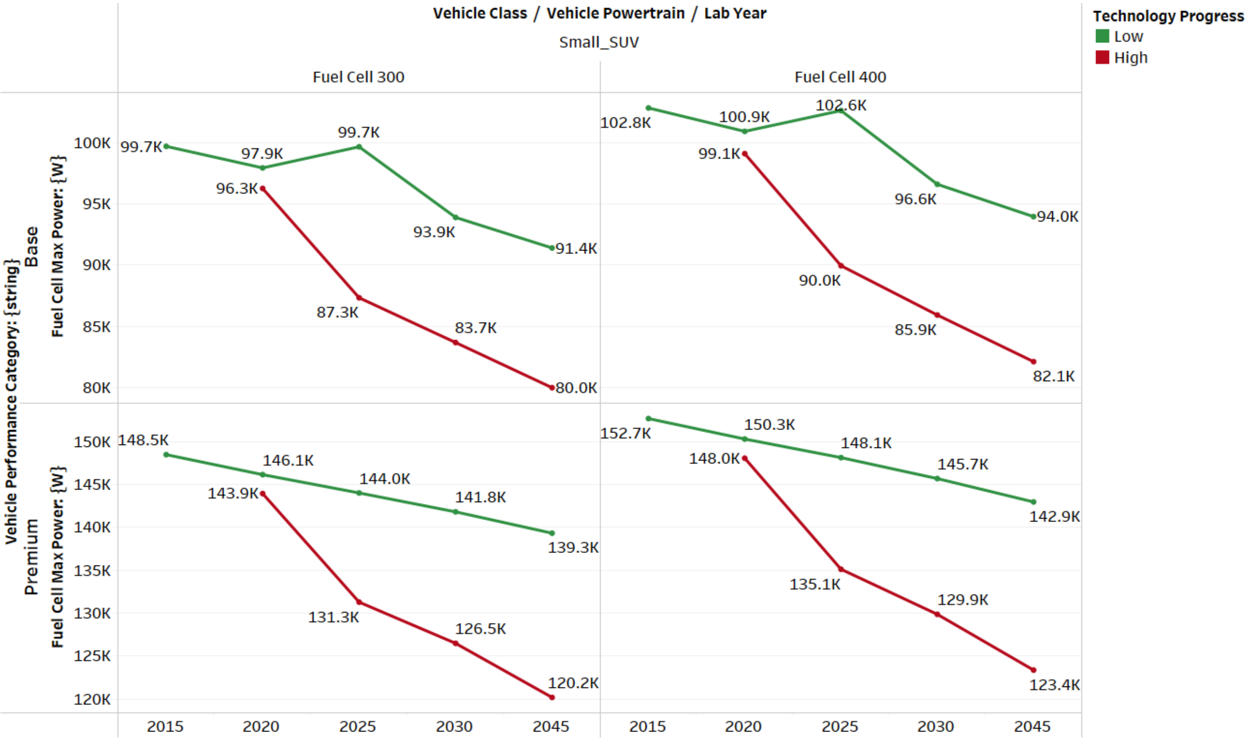


FIGURE 1-7 Fuel cell system power for small SUV FCEVs

4.3.4 Battery Electric Vehicles

Figure 1-8 shows the electric machine maximum power for the different BEVs in the small SUV vehicle class. Electric machine maximum power requirements are assumed to decrease over time as a result of lightweighting and electric machine efficiency improvements.

The decrease from 2015 low technology progress case to 2045 low - high technology progress case ranges are as follows:

- BEV200 (BEV with 200 mi of AER [beginning of life] on the combined driving cycle [adjusted]): 12-25%
- BEV300 (BEV with 300 mi of AER [beginning of life] on the combined driving cycle [adjusted]): 15-27%
- BEV400 (BEV with 400 mi of AER [beginning of life] on the combined driving cycle [adjusted]): 19-32%
- BEV500 (BEV with 500 mi of AER [beginning of life] on the combined driving cycle [adjusted]): 23-36%

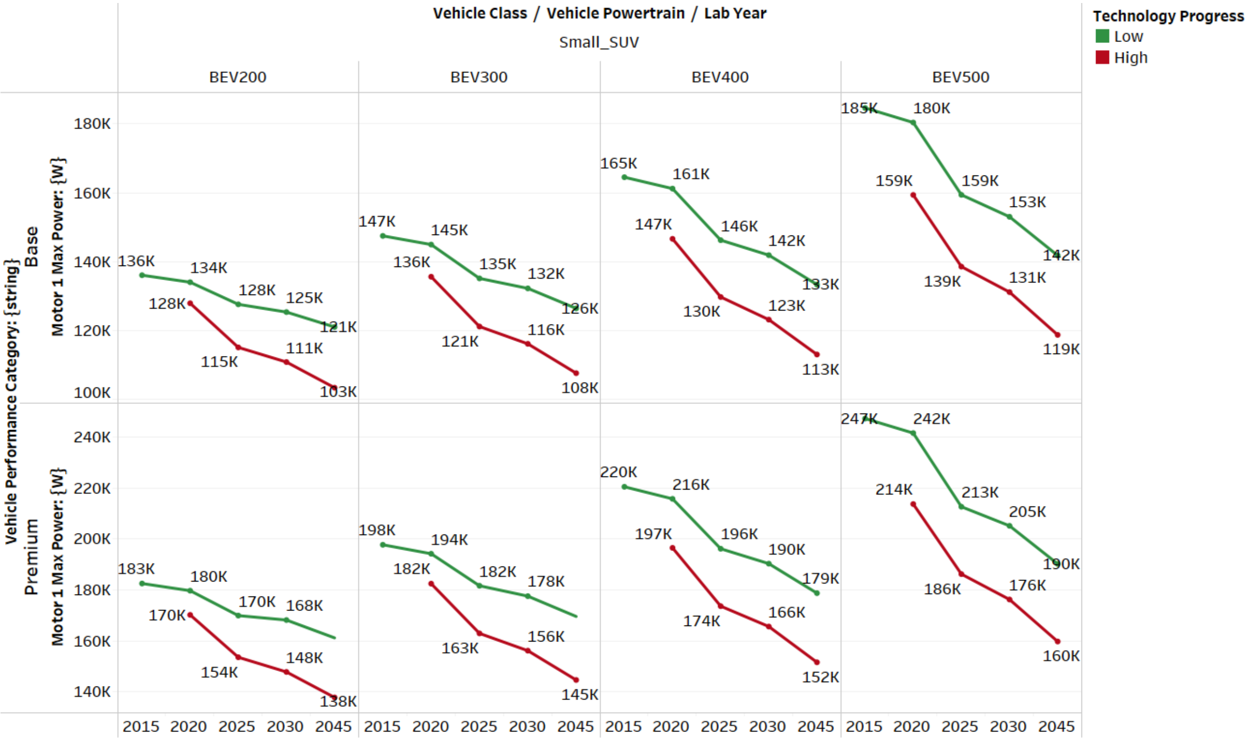


FIGURE 1-8 Electric machine power for small SUV BEVs across powertrains

Figure 1-9 shows the battery pack power for different small SUV BEV powertrains across the timeframes. Both the electric machine and the battery demonstrate a nearly 24% drop in required power by 2045 high technology progress case compared with the reference low technology progress case in 2015 for BEV200; the required power decrease reaches almost 32% for the BEV400. This decrease can be explained by the impact of lightweighting, as well as the combined effect of several assumptions about vehicle component improvements. With lightweighting and technology advances, the same performance could be achieved with a much smaller battery, so the sizing logic results in less powerful electric machines and batteries in the future compared with the reference case in 2015. BEVs with higher ranges, and therefore bigger battery and motor sizes, will undergo higher reductions due to advances in vehicle technologies.

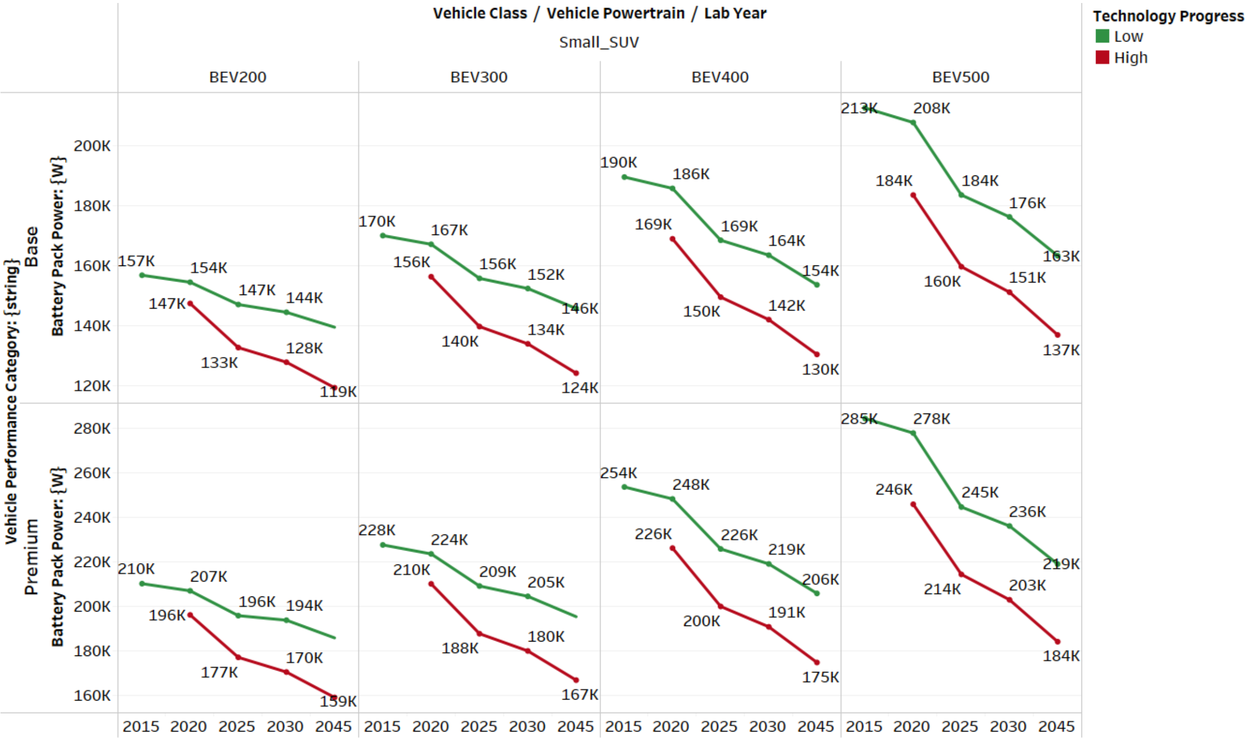


FIGURE 1-9 Battery pack power for small SUV BEVs across powertrains

Figure 1-10 shows the battery pack total energy for the different small SUV 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 35% for 2045 high technology progress case compared with 2015 low technology progress (reference) case. This reduction reaches almost 40% 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 small SUV BEVs across powertrains

5 ENERGY CONSUMPTION RESULTS

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 small SUV vehicle class only (full results available in the supplemental data).

5.1 CONVENTIONAL VEHICLES

Figure 1-11 shows the evolution of fuel consumption for the small SUV conventional powertrain for gasoline and diesel fuel types.

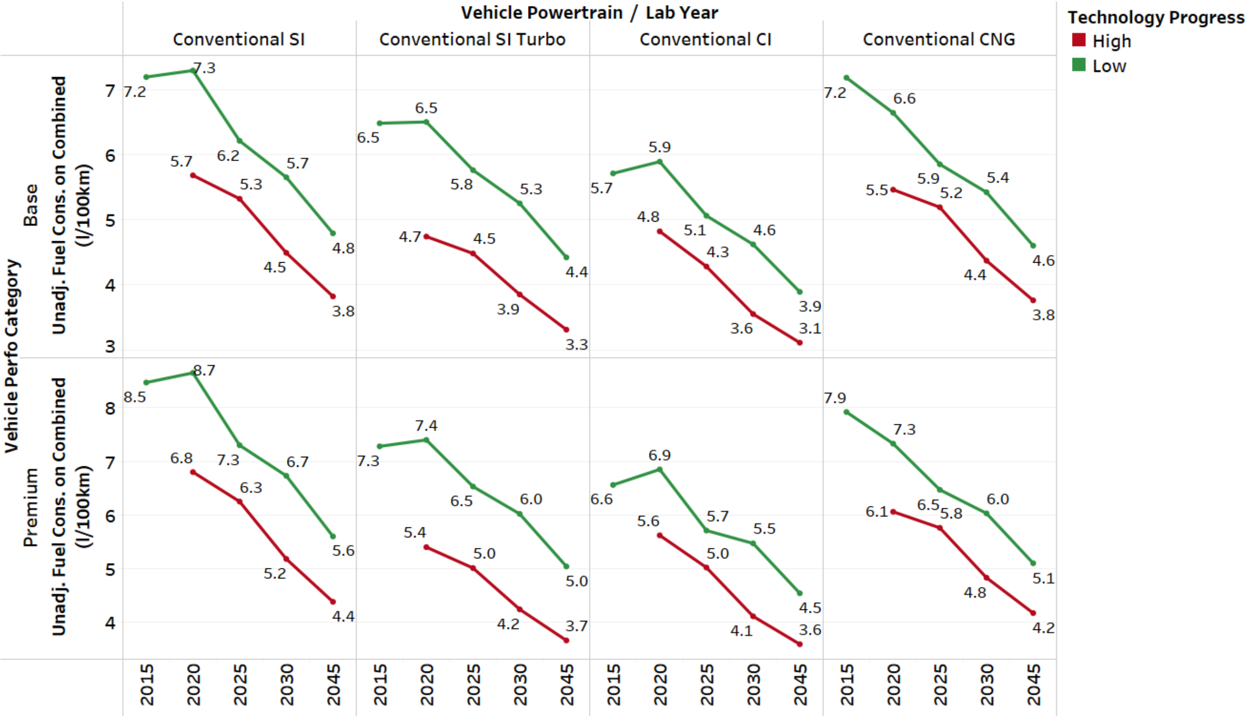


FIGURE 1-11 Unadjusted fuel consumption for conventional small SUVs

Fuel consumption decreases over time across fuels. Gasoline conventional vehicles consume from 33–47% less fuel by 2045 (spanning both technology progress cases) compared with the reference (2015) laboratory year low technology progress case. Diesel powertrains evolve somewhat differently, with decreases ranging from 32–46% for the base performance category. The improvement in fuel consumption varies slightly across the different performance categories. The initial slight increase in gasoline and diesel engine powers due to the transmission selection and low lightweighting effects influence the fuel consumption results.

5.2 POWER-SPLIT HEVs

Figure 1-12 shows the evolution in fuel consumption for small SUV power-split HEVs. 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 24%–39% in laboratory year 2045 low – high technology progress cases for the base performance category. The improvement in fuel consumption varies slightly across the different performance categories.

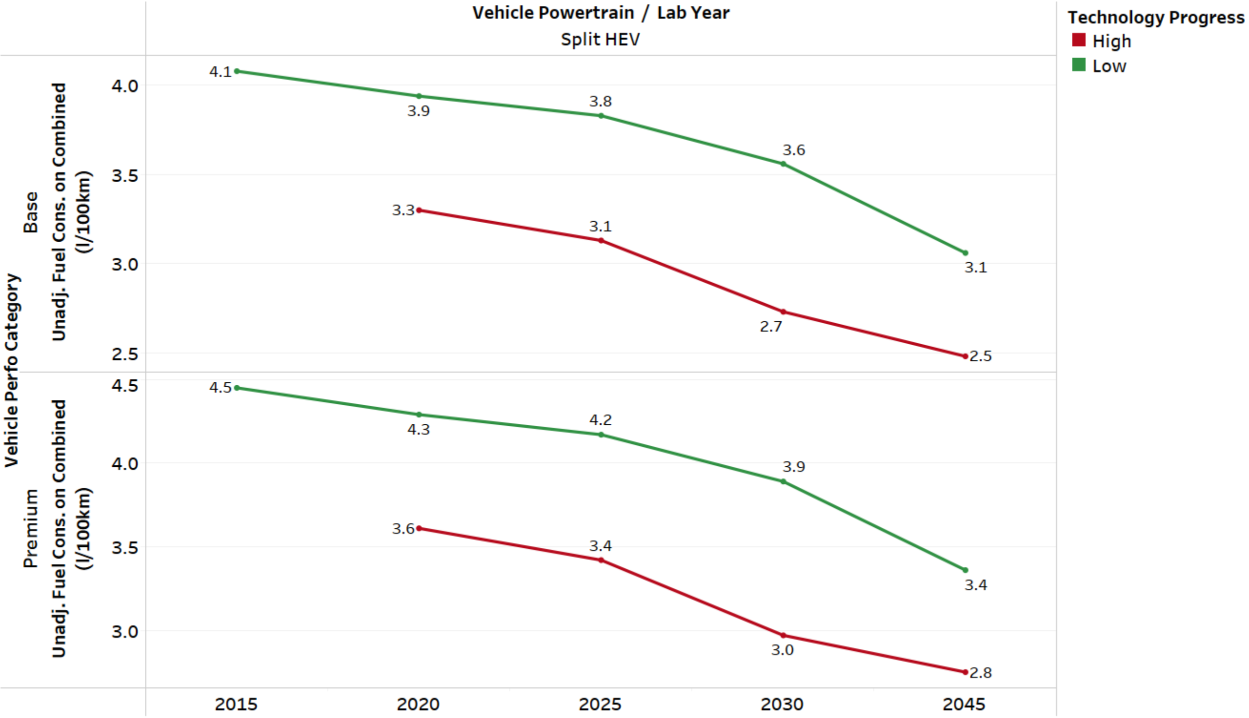


FIGURE 1-12 Unadjusted fuel consumption for small SUV power-split HEVs

5.3 FUEL CELL ELECTRIC VEHICLES

Figure 1-13 shows the evolution in unadjusted fuel consumption for FCEVs. Fuel consumption in 2045 is about 17–31% lower than the reference case for laboratory year 2015. This decrease is attributable to advances in technology and better component efficiencies over time.

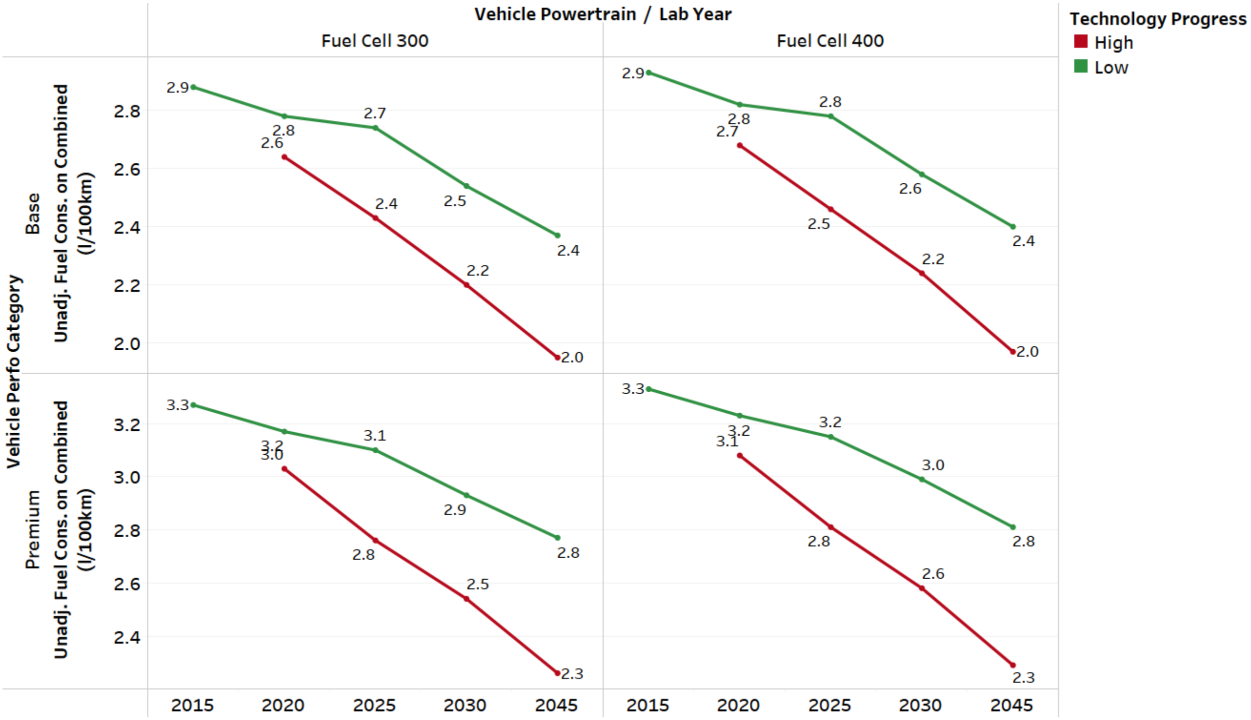


FIGURE 1-13 Unadjusted fuel consumption for small SUV FCEVs

5.4 BATTERY ELECTRIC VEHICLES

As with the preceding fuel consumption results, electrical consumption results for BEVs are presented for the U.S. combined drive cycle, which includes both of the two drive cycles used in the simulations: UDDS and HWFET. Future improvements in lightweighting and component sizing lead to a significant decrease in electrical consumption over time.

Figure 1-14 illustrates the electrical consumption for small SUV BEVs. The values, expressed in watt hours per mile (Wh/mi), represent the average energy provided by the battery to drive the vehicle for 1 mi. While not shown in the figure, 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 recovery of a great deal of the energy. On the other hand, 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 increase energy consumption.

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

6 VEHICLE MANUFACTURING COSTS

In addition to the two technology performance uncertainty cases, the study computes two technology cost uncertainty cases (low and high). The technology performance/technology cost uncertainty cases 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 costs provided in this section represent manufacturing costs, not sale prices.

6.1 CONVENTIONAL VEHICLES

Figure 1-15 illustrates manufacturing costs for conventional small SUV 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 from 2030 (but overall increases from 2015 reference case). The increase in costs compared with the reference 2015 laboratory year can be explained by several factors, including the cost of lightweighting. The reduction in vehicle weight is accompanied by an increase in material cost resulting from escalating use of aluminum or carbon fiber and advanced component technologies. The eventual drop in vehicle manufacturing cost is driven by a decrease in engine (attributable to lower displacements from sizing) and transmission costs, as well as 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.

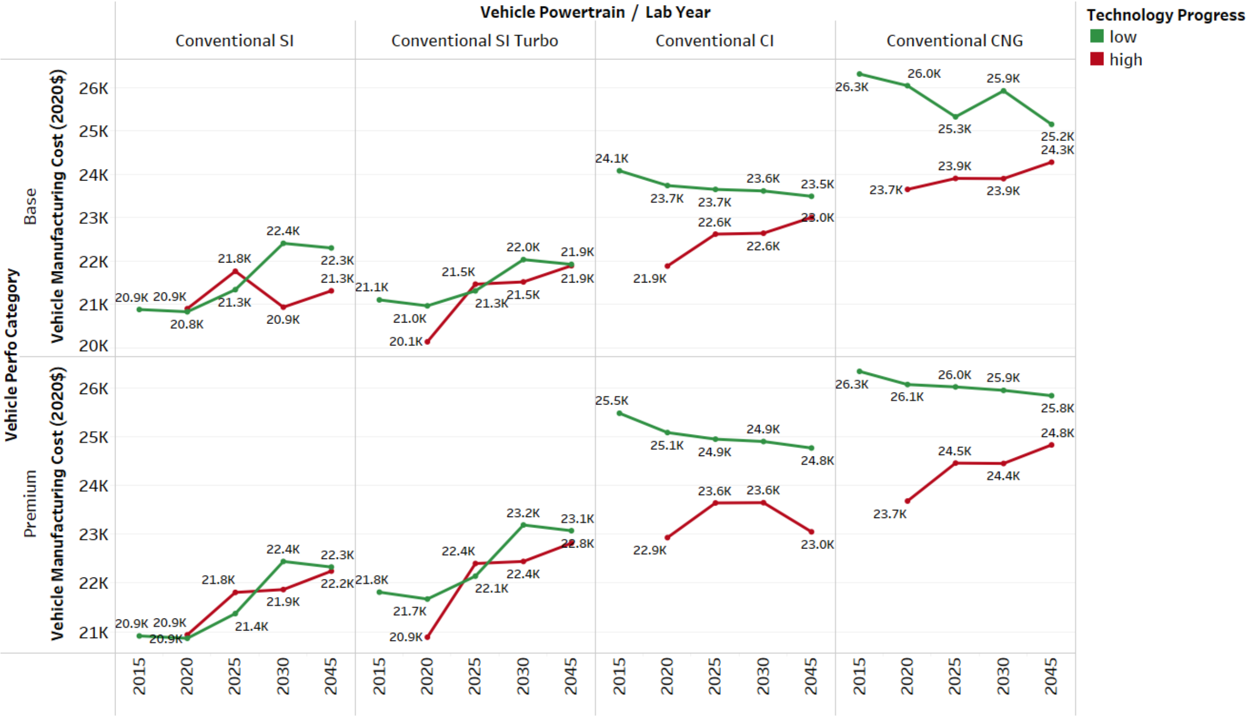


FIGURE 1-15 Manufacturing cost (2020 USD) of small SUV conventional vehicles

6.2 POWER-SPLIT HEVs

Figure 1-16 shows the vehicle-manufacturing costs for small SUV power-split HEVs. Over time, manufacturing costs decrease for these vehicles 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.

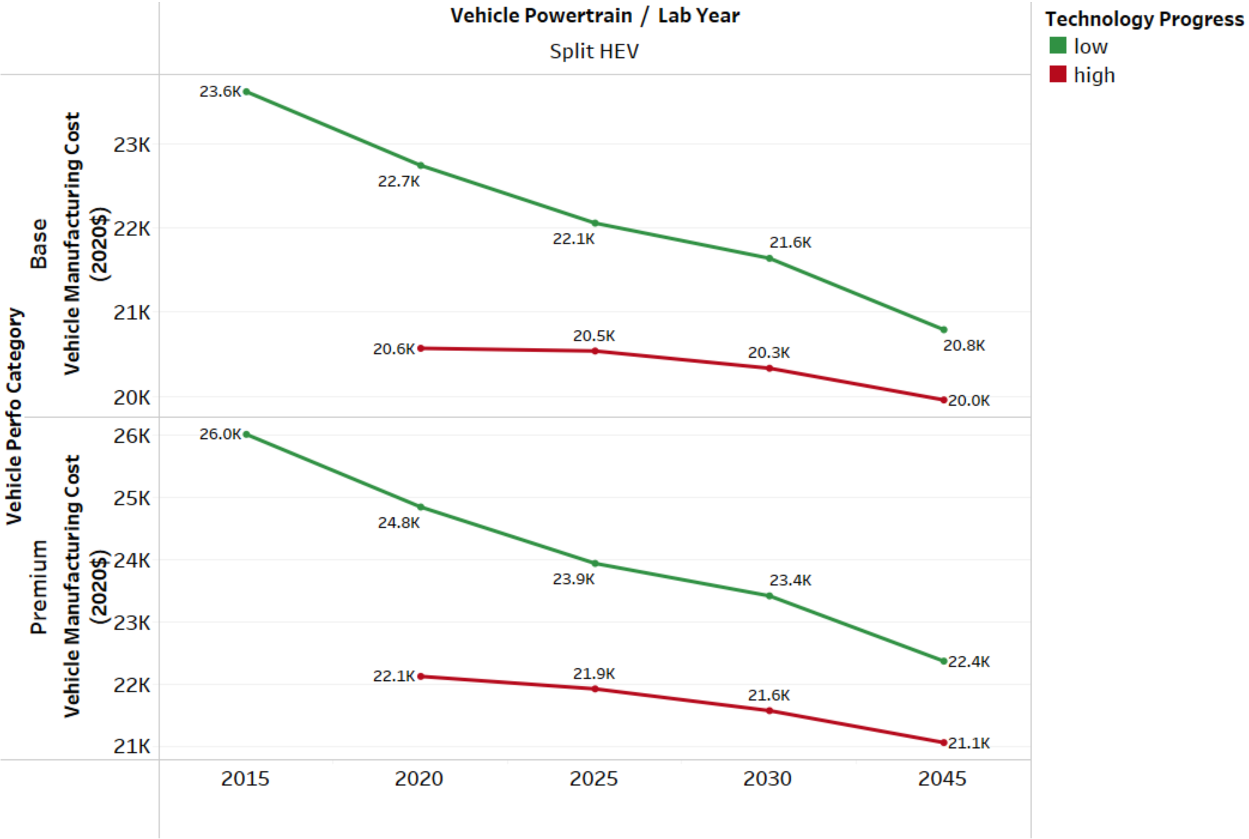


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FIGURE 1-16 Manufacturing cost of small SUV power-split HEVs

6.3 FUEL CELL ELECTRIC VEHICLES

Figure 1-17 shows manufacturing costs for small SUV FCEVs. The figure shows that the difference in manufacturing costs steadily decreases over time. Compared with laboratory year 2015 low technology progress case, the manufacturing cost of small SUV FCEVs is assumed to decrease by 20%–30% by laboratory year 2045 low-high technology progress cases.

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 made for other powertrains. However, because fuel cells are not currently manufactured at high volumes, the manufacturing costs and retail prices of FCEVs today are substantially higher than those in the projections below; this difference will hold until production levels rise substantially.

FIGURE 1-17 Manufacturing cost of small SUV FCEVs

6.4 BATTERY ELECTRIC VEHICLES

Figure 1-18 illustrates the evolution of BEVs in terms of manufacturing cost. Lightweighting affects battery sizes and decreases battery costs in future years. Battery size, in turn, affects the major manufacturing cost of BEVs. The impact on manufacturing costs in future years is greater for higher-range BEVs.

FIGURE 1-18 Manufacturing cost of small SUV 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 and across time. 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 and CNG 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: mid-size vehicles, small SUVs, and mid-size SUVs cluster closely together, while compact and pickup classes lie at the two extremes. The trend line in the plot also confirms this observation.

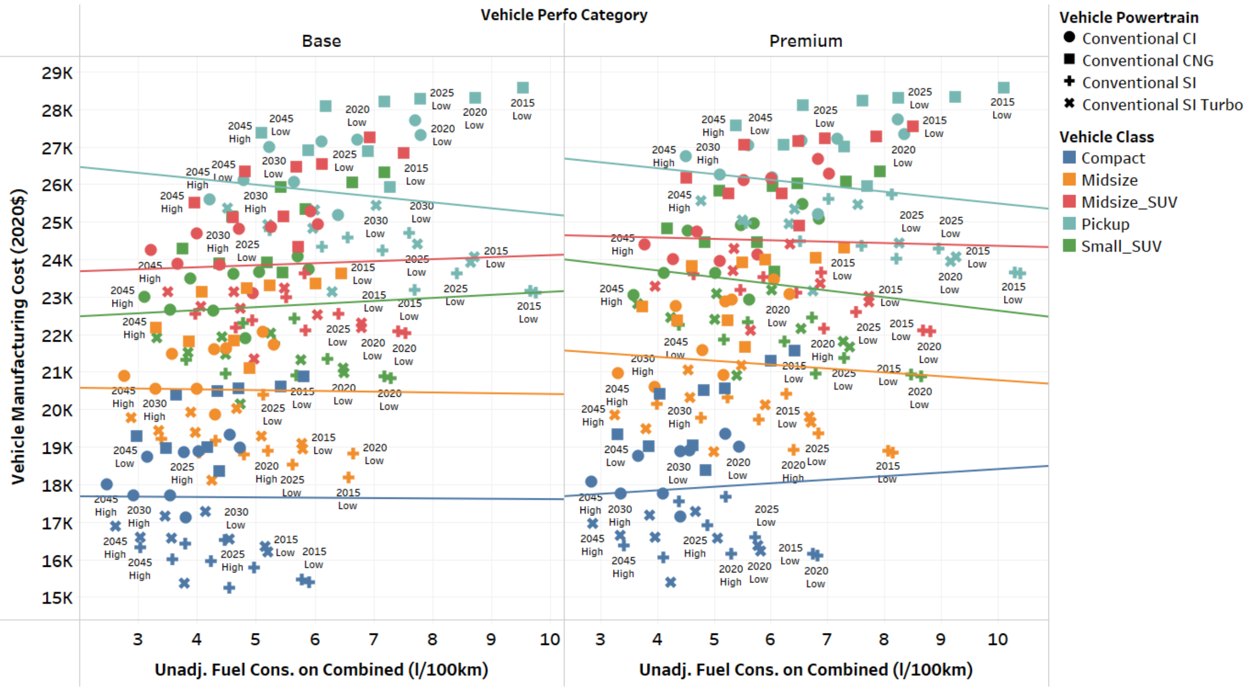


FIGURE 1-19 Vehicle manufacturing cost versus fuel consumption for conventional vehicles

The figure shows that, over time, fuel consumption decreases as a result of various VTO improvements (e.g., engine efficiency, lightweighting). However, the cost for additional lightweighting increases 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 power-split HEVs across multiple vehicle classes and over time. 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, in direction, to that observed for conventional vehicles. The figure 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 the manufacturing cost. The trend line also confirms the clustering of mid-size vehicles, small SUVs and mid-size SUVs, as with the conventional vehicles.

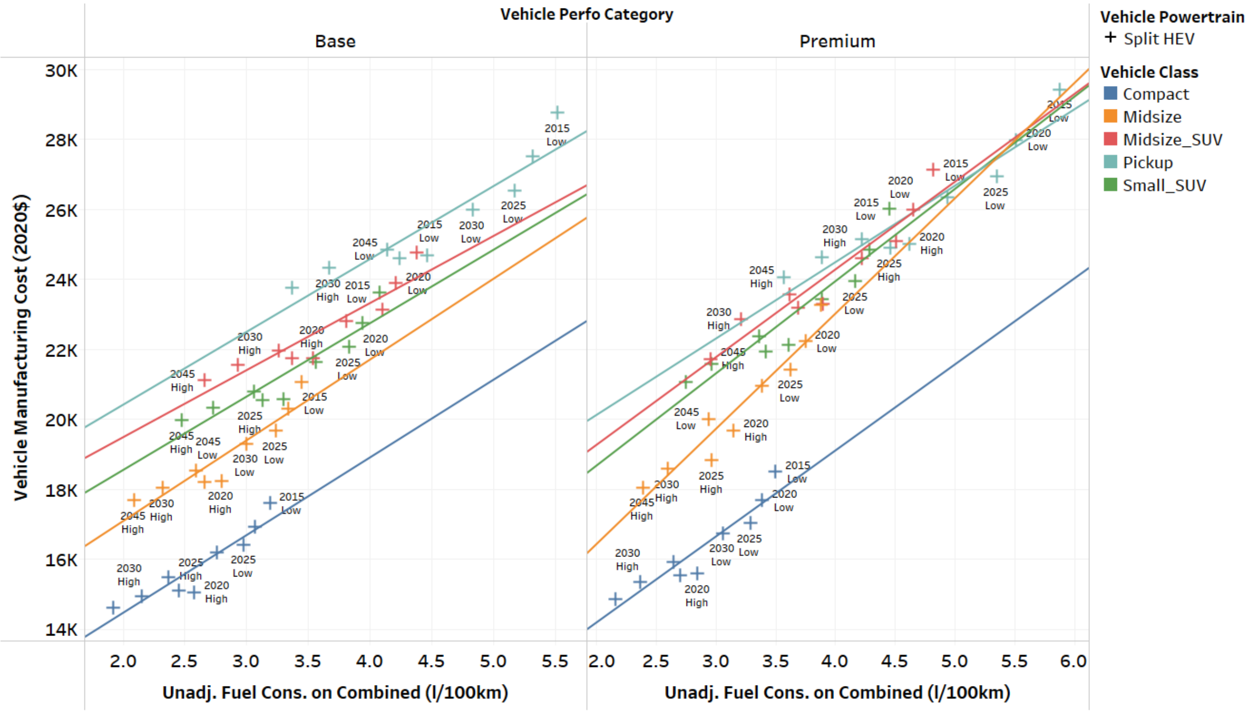


FIGURE 1-20 Vehicle manufacturing cost versus fuel consumption for power-split HEVs

7.3 FUEL CELL ELECTRIC VEHICLES

Figure 1-21 compares vehicle manufacturing cost and fuel consumption for FCEVs across multiple vehicle classes and across time. The different-colored lines represent the trend lines of vehicle manufacturing cost versus fuel consumption for different vehicle classes. Over time, both fuel consumption and manufacturing costs decrease as 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 simplicity, only the FCEV300 and FCEV4000 illustration is shown below. The other FCEV powertrains follow a similar pattern.

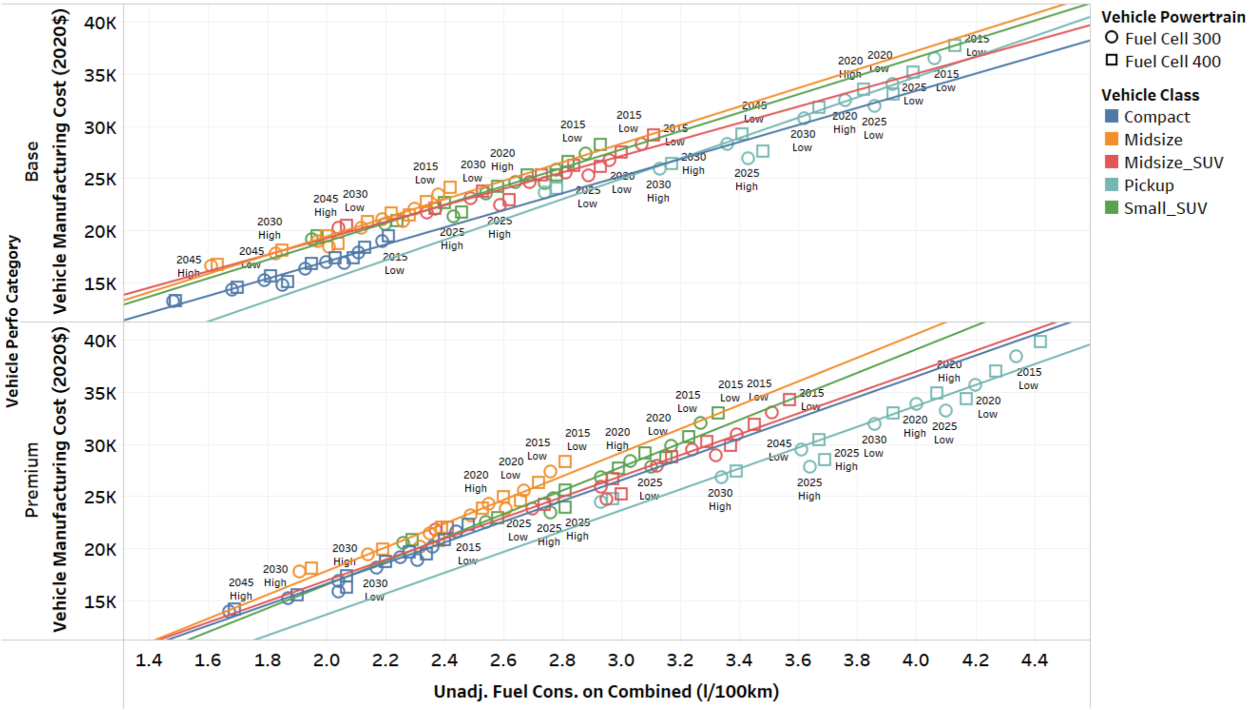


FIGURE 1-21 Vehicle manufacturing cost versus fuel consumption for FCEVs

7.4 BATTERY ELECTRIC VEHICLES

Figure 1-22 compares vehicle manufacturing cost and electrical energy consumption for BEVs across multiple vehicle classes and over time. 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 AER increases (powertrain range is BEV200 through BEV500), manufacturing costs increase (as a result of larger battery sizes) and electrical energy consumption increases. The effect of technological improvements over the years can be seen in the reduction in energy consumption and manufacturing cost from laboratory years 2015 to 2045 across the technology progress cases. Further, the trend lines show an aggressive decline in manufacturing costs associated with improved energy consumption, over time, for BEVs with higher AERs. This cost decrease can be explained by the improvement in vehicle component specifications (e.g., battery energy density, lightweighting) followed by a decrease in battery costs over time.

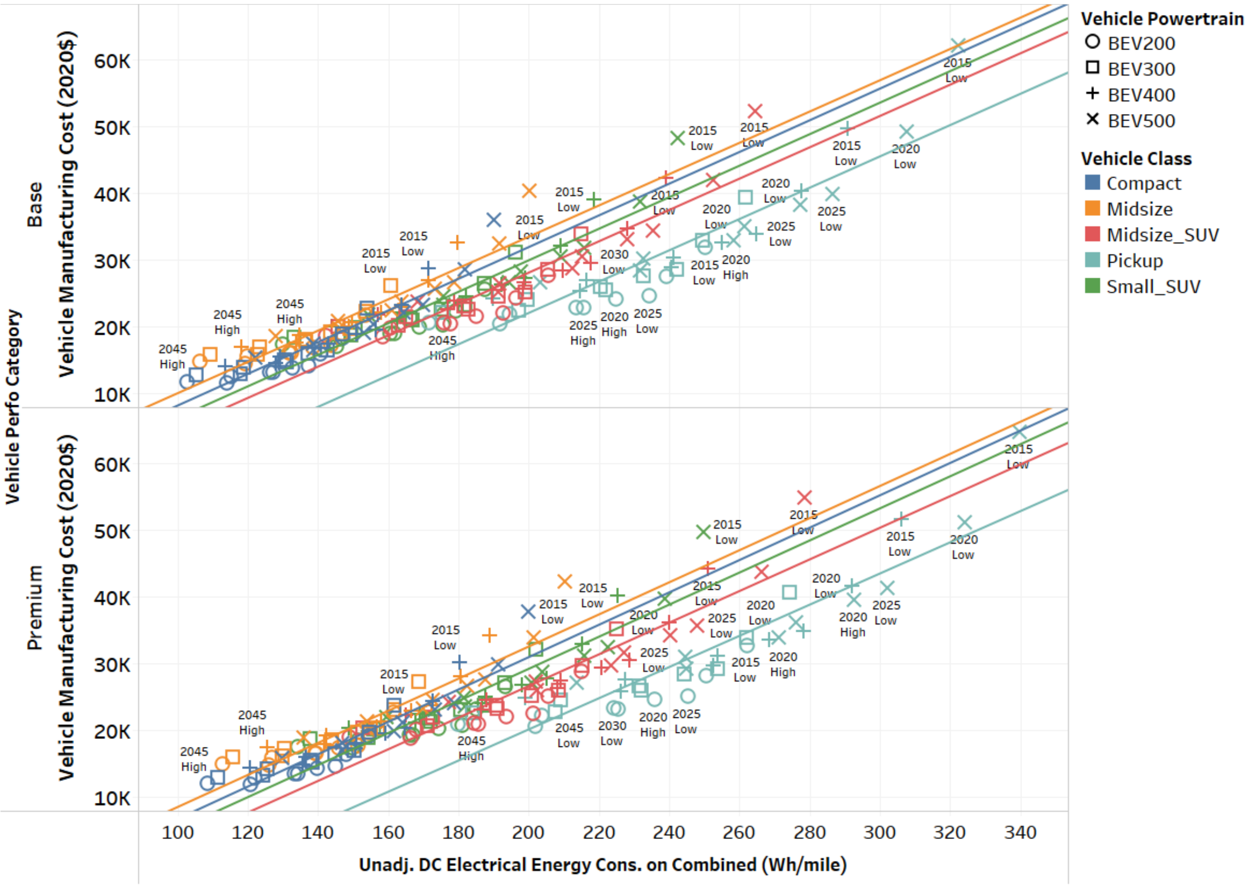


FIGURE 1-22 Vehicle manufacturing cost versus electrical energy consumption for BEVs

8 LEVELIZED COST OF DRIVING

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

Tables 1-13 and 1-14 list the primary assumptions. The fuel and electricity price assumptions are consistent with the Annual Energy Outlook 2021 (EIA 2021), as well as Burnham et. al. (2021).

TABLE 1-13 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 1-14 Fuel and electricity price assumptions

Lab Year		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	3.221
	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 LCOD for small SUV conventional vehicles across different laboratory 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 as a result of increasing lightweighting costs, as observed earlier. Higher manufacturing costs cause the levelized cost of driving to increase in future periods in most of the scenarios and could vary across the different conventional powertrains, 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.

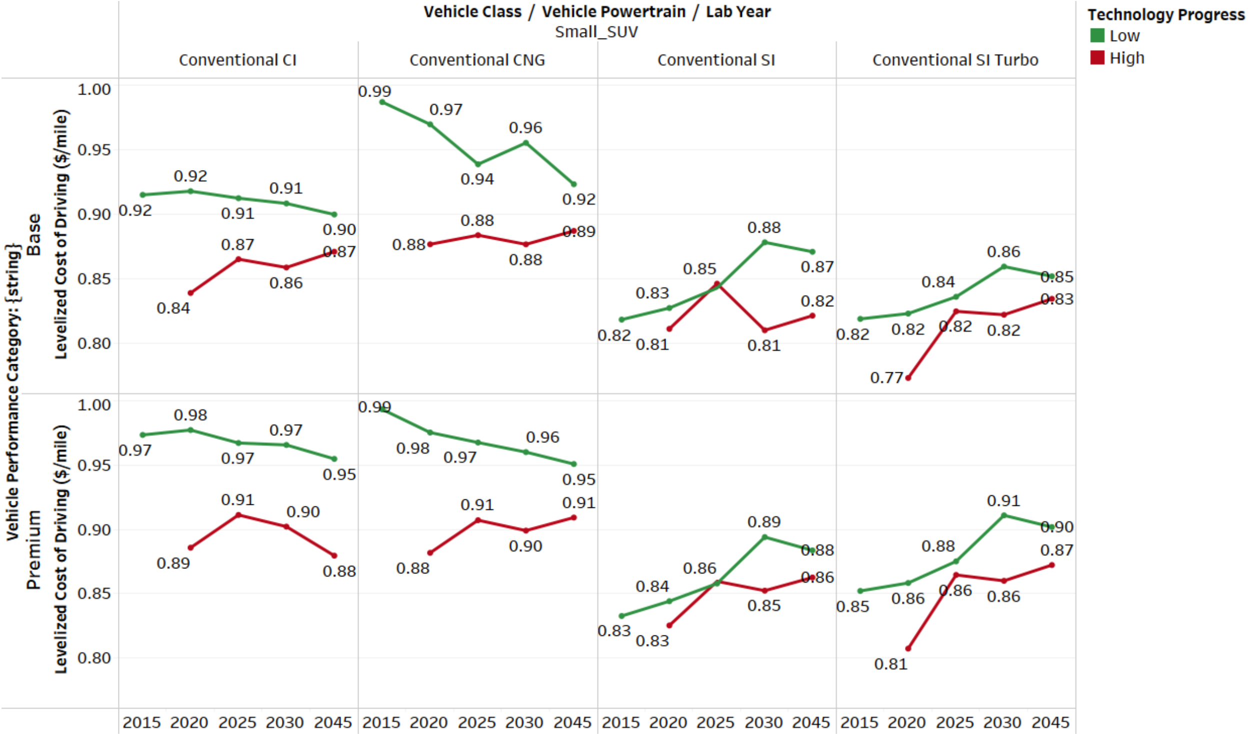


FIGURE 1-23 LCOD, small SUV conventional vehicles

8.2 POWER-SPLIT HEVs

Figure 1-24 shows the LCOD for small SUV power-split HEVs across different laboratory years. With decreasing vehicle manufacturing costs and reduced fuel consumption over time, the LCOD is reduced by 11–18% by 2045. In future periods, the aggressive lightweighting costs and targets counter the cost benefits achieved through accelerating improvements in other VTO target areas (e.g. battery costs, motor costs), 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.

FIGURE 1-24 LCOD, small SUV power-split HEVs

8.3 FUEL CELL ELECTRIC VEHICLES

Figure 1-25 illustrates the LCOD for small SUV FCEVs across different laboratory 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 LCOD is reduced by 29–39% 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). While this effect is not as pronounced as with the conventional powertrains and power-split HEVs, the lowest-cost technology progress case is, again, the high-technology progress case.

FIGURE 1-25 LCOD, small SUV FCEVs

8.4 BATTERY ELECTRIC VEHICLES

Figure 1-26 illustrates the LCOD for small SUV BEVs across different laboratory 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 LCOD is reduced by 26–47% by 2045 high technology progress case from 2015 low technology progress case across the different BEVs, with the greater reductions seen among the higher-range 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), particularly in the near- to mid-term. As a result, the optimal technology progress case is—as for the other powertrain types—the high-technology progress case, which demonstrates an increasing advantage over the low-technology progress case as BEV range increases.

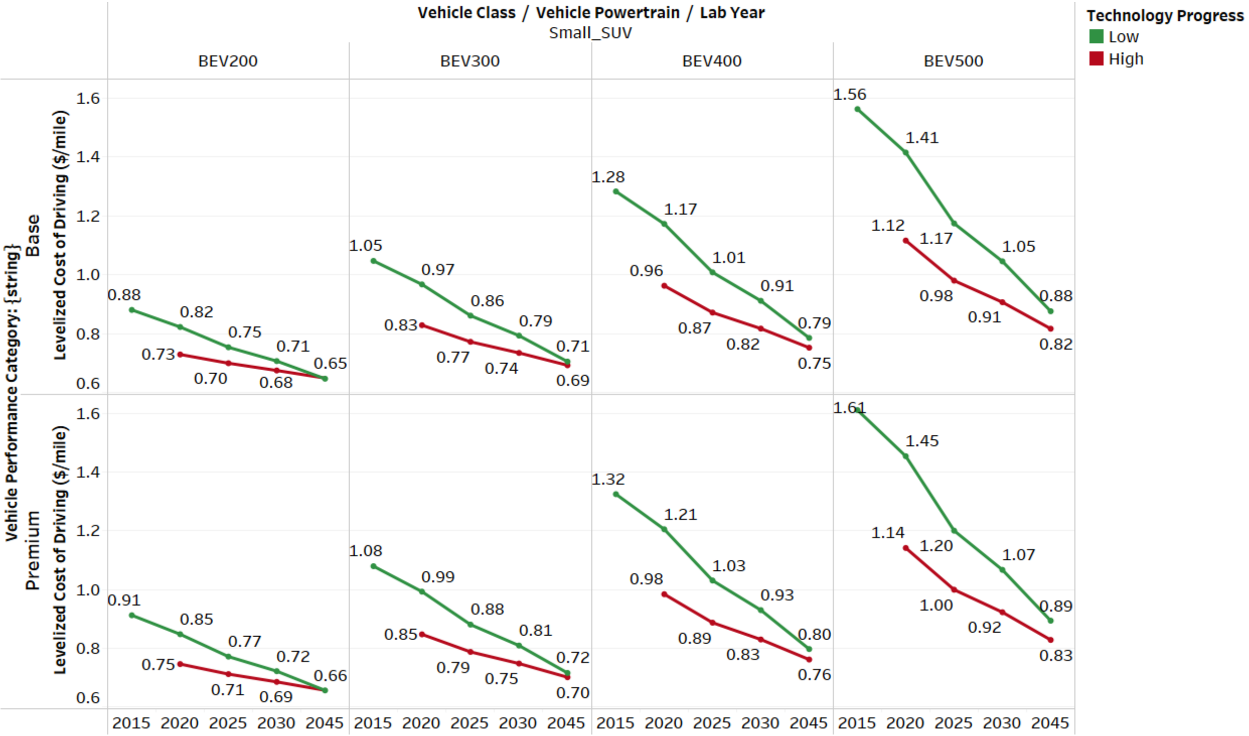


FIGURE 1-26 LCOD, small SUV BEVs

9 TOTAL COST OF OWNERSHIP

The total cost of ownership (TCO) is an indicator that comprises depreciation (residual value), maintenance, repair, insurance, and financing costs. Unlike the LCOD, it also includes taxes and fees and the sale of the vehicle at the end of its lifetime based on depreciation. TCO can be calculated on a yearly basis ($/year) or averaged over the total miles traveled ($/mile). Detailed assumptions and calculations for the TCO are available in Burnham et al. (2021).

9.1 CONVENTIONAL VEHICLES

Figure 1-27 shows the TCO of small SUV conventional vehicles across laboratory years and performance categories. Over time, the TCO has different impacts across different engine technologies, across technology progress scenarios, because of the combined effect of increases in manufacturing costs (e.g., from engine improvements, lightweighting) and fuel consumption reductions that accompany the acceleration of VTO targets. For example, the TCO of gasoline and gasoline-turbo small SUV conventional vehicle increases by 0.1-3.5% by 2045 across the different technology scenario; however, the TCO of a small SUV conventional CNG vehicle is reduced by almost 11% in the high technology scenario. The figure demonstrates that lightweighting plays a significant role, as seen for LCOD as well.

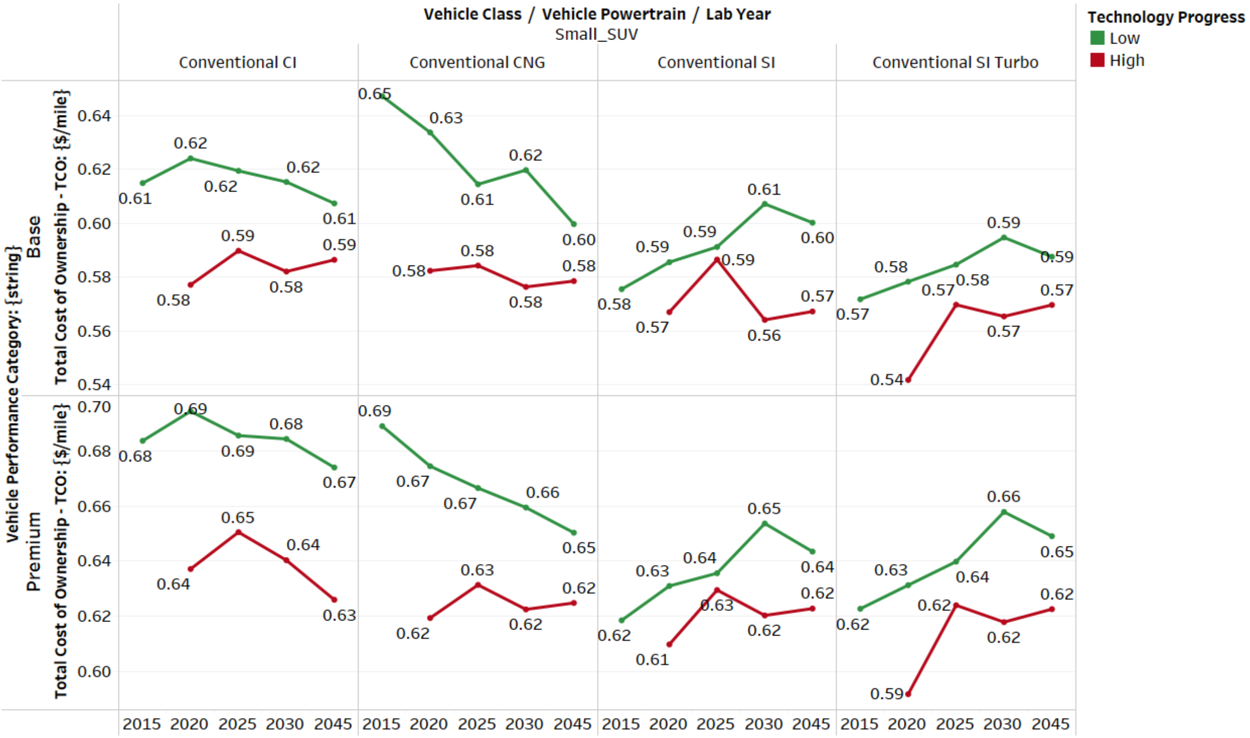


FIGURE 1-27 TCO, small SUV conventional vehicles

9.2 POWER-SPLIT HEVs

Figure 1-28 shows the TCO of small SUV power-split HEVs across different laboratory years and performance categories. The TCO of power-split HEVs is reduced by 7–11% by 2045 as a result of accelerating improvements in several VTO target areas (e.g. battery costs, motor costs).

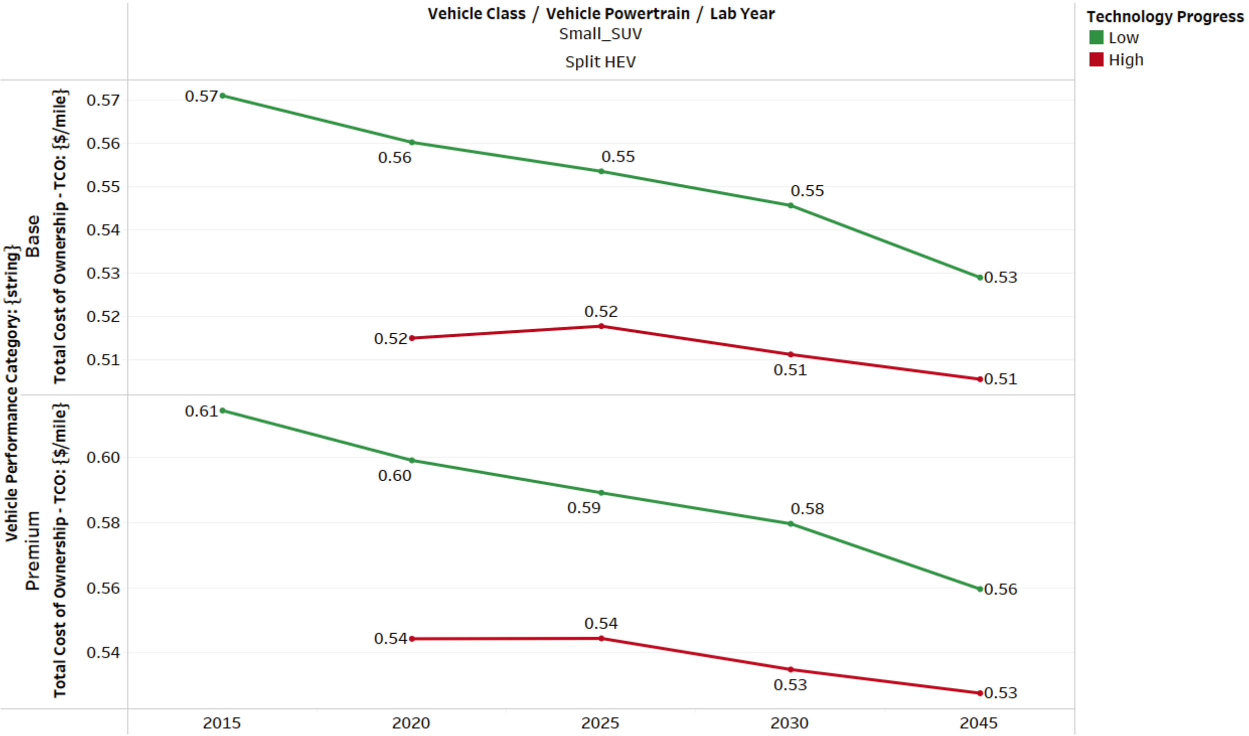


FIGURE 1-28 TCO, small SUV power-split HEVs

9.3 FUEL CELL ELECTRIC VEHICLES

Figure 1-29 shows the TCO of small SUV FCEVs across different laboratory years and performance categories. The TCO of FCEVs is reduced by 29–38% by 2045 as a result of accelerating improvements in HFTO and VTO target areas (e.g., fuel cell costs, hydrogen storage costs, battery costs, motor costs).

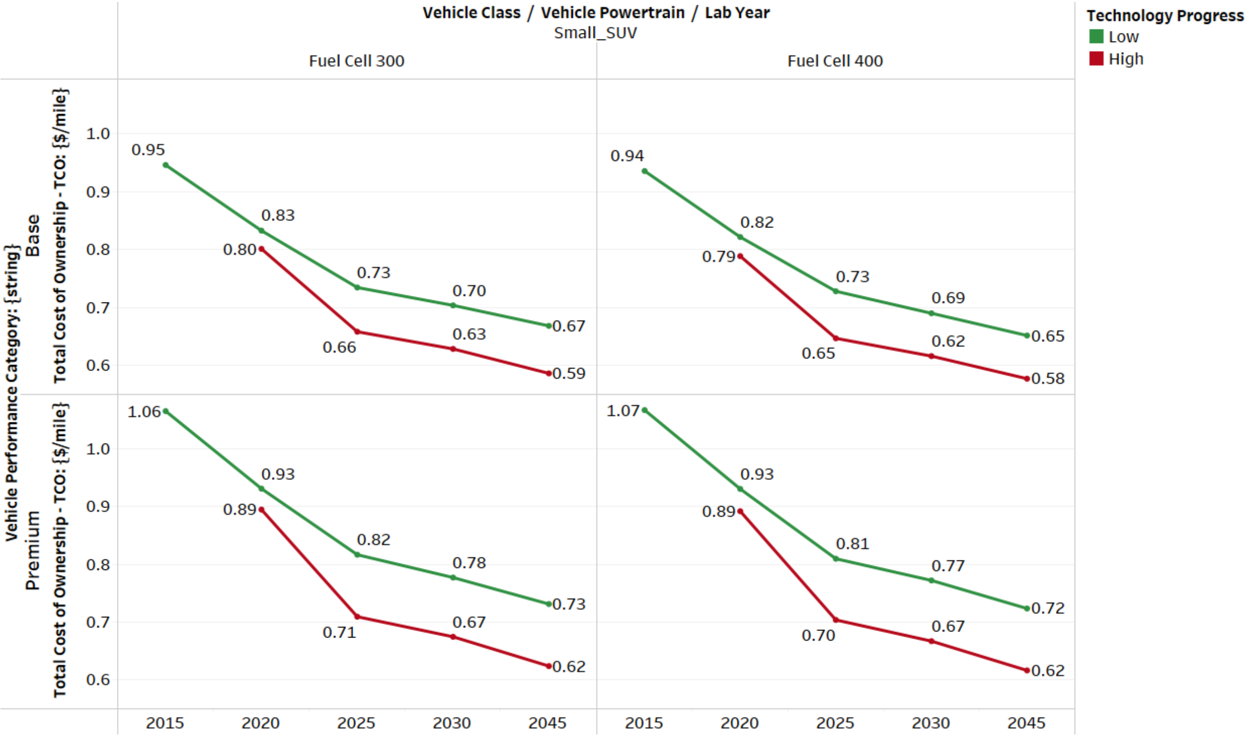


FIGURE 1-29 TCO, small SUV FCEVs

9.4 BATTERY ELECTRIC VEHICLES

Figure 1-30 shows the TCO of small SUV BEVs across different laboratory years and performance categories. The TCO of BEVs is reduced by 21–41% by 2045—with greater reductions for higher-range BEVs, as seen with LCOD—due to accelerating improvements in several VTO target areas (e.g., battery costs, motor costs). As was the case with LCOD, the high-technology progress case has an increasing advantage as BEV range increases.

FIGURE 1-30 TCO, small SUV 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, LCOD, and TCO were estimated for ten vehicle classes, five powertrains, and six timeframes with upper and lower limits for three different technology progress cases. Detailed results are reported in the complementary Excel worksheets.

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

PART TWO. Analysis of Medium- and Heavy-Duty Vehicles

1 INTRODUCTION

Under the umbrella of EERE's Office of Sustainable Transportation, the U.S. Department of Energy's (DOE) Vehicle Technologies Office (VTO) and Hydrogen and Fuel Cell Technologies Office (HFTO) seek to develop sustainable, affordable, and efficient technologies for passenger and freight movement by advancing DOE investments in advanced transportation technologies that translate to potential vehicle-level fuel savings. In Part 1 of our study, we quantified the potential costs and benefits of these technologies in light-duty vehicles. In part 2, we examine the potential costs and benefits for medium- and heavy-duty vehicles given potential advancements over the next several decades.

We focus on technologies funded by VTO and HFTO that we expect to see implemented in vehicles during this timeframe. Our analysis included simulation of more than 20 types of trucks, ranging from Class 2 (the smallest medium-duty trucks, spanning Class 2b–Class 6) to Class 8 (i.e., the largest heavy-duty trucks, including Classes 7 and 8).

The study provides the fuel consumption, estimated purchase price, and a simplified TCO for trucks that employ advanced technologies. A more detailed TCO analysis for these trucks was completed using a technology/economic benefit analysis tool called BEAN (Argonne 2022). The study results offer a vehicle-level perspective and estimated projections about the future of advanced-technology medium- and heavy-duty trucks, as well as cost and performance data pairs that can inform other advanced transportation studies.

The system modeling and control group at Argonne developed a series of integrated tools and processes to efficiently evaluate the impacts of advanced vehicle and transportation technologies from a mobility and energy perspective. Argonne's Autonomie, described in Section 2.2, is the primary tool for evaluating vehicle energy consumption. Originating from the collaborative efforts of Argonne and General Motors, this tool has the level of fidelity required to analyze the fuel economy benefits of vehicle technologies and 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 it is widely used in these sectors. Autonomie provides inputs to life cycle analysis (LCA) tools such as the Greenhouse gases, Regulated Emissions, and Energy use in Technologies model (GREET^{TM}) model (Argonne 2019), multi-laboratory TCO calculations, and the Transportation Energy and Mobility Pathway Options model (TEMPO^{TM}) (NREL 2022).

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 in trucks over the next few decades, so our projections extend from 2021 to 2050.

Section 2 documents the assumptions and methods used to define vehicles and estimate cost and energy consumption rates. Section 3 discusses the results of vehicle-level modeling and analysis. Detailed information on vehicle assumptions and simulation results is available in the spreadsheets accompanying this report.

2 METHODOLOGY

This section describes the simulation techniques used to translate component-level technology changes to vehicle-level fuel consumption or cost differences. Figure 2-1 illustrates the scope of work and boundaries for our study.

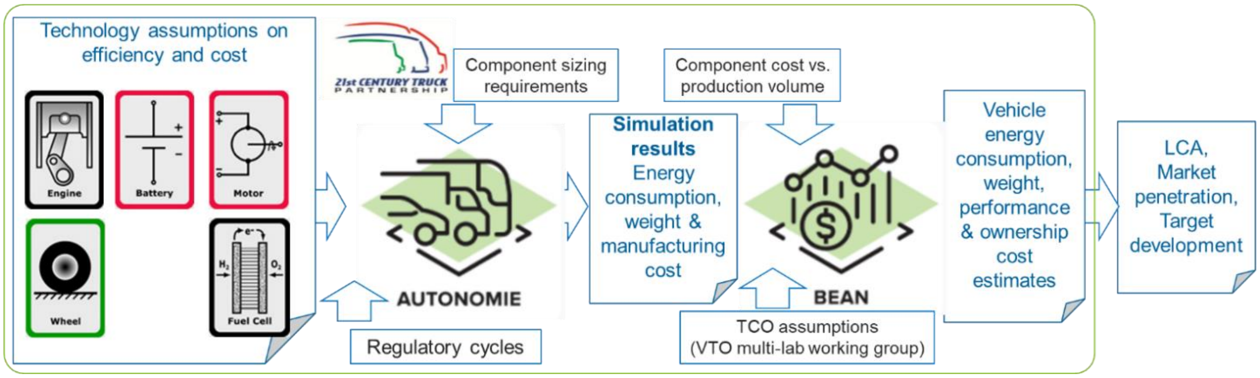


FIGURE 2-1 Scope of the work for analysis of medium- and heavy-duty vehicles

The first step in the analysis was compiling input from stakeholders and developing our assumptions regarding technology progress levels. Primary stakeholders—including DOE technology managers and researchers at the national laboratories and other agencies that work on technology forecasts—provided guidance on the vehicles of interest. Section 2.1 describes the input collection effort and 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. Following an overview of the types of trucks included and the models used, this section details vehicle specifications, drive cycles, and component technology assumptions.

The selection of vehicles has not been altered significantly from work done in 2020 (Ehsan et al. 2021), which was well received by stakeholders. The body type for delivery trucks is specified in a more descriptive way (e.g., a generic classification, such as "delivery truck," is categorized as a step van or box truck), and helpful feedback, including suggestions to add more vehicle details in the accompanying excel sheet, has been incorporated. A new techno economic benefit analysis tool (BEAN) is also included as an accompanying file. BEAN will allow wider research community to evaluate the benefits from these vehicles with their own component cost, fuel cost, vehicle usage, and ownership assumptions.

Because medium- and heavy-duty truck configurations are customized to suit their specific purposes, many different types of trucks operate on America's roads today. This analysis examines 23 truck types, as listed in TABLE 2-1. Each truck type was modeled with multiple powertrain choices (i.e., conventional, mild hybrid, parallel hybrid, series plug-in hybrid, battery electric and two types of fuel cell hybrids) using Autonomie. To keep the analysis manageable, only a subset of representative vehicles are analyzed in detail in subsequent sections.

Classes 2–6 are categorized as medium-duty vehicles, and classes 7 and 8 are categorized as heavy-duty vehicles. Because each truck type has its own specified test procedure, these classifications are used in Autonomie in accordance with the test procedures specified by the U.S. Environmental Protection Agency (EPA 2016).

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) (U.S. Census Bureau undated), 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.

TABLE 2-1 Summary of truck types modeled in Autonomie

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

2.1.1 Model Overview

Autonomie is used to evaluate the energy consumption and cost of advanced powertrain technologies. The model has been validated for several powertrain configurations and vehicle classes using Argonne's AMTL 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 in multiple studies conducted for U.S. government departments; results have been used to set targets for future research. Technology target-setting activities carried out by consortiums such as the U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability (U.S. DRIVE) and 21st Century Truck Partnership (21CTP) also use Autonomie for vehicle simulations. 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 21CTP, representatives from truck manufacturers, and fleet operators.

Each truck is unique in its functional requirements. The performance capabilities that determine 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 OEMs. We estimated performance capabilities through simulations for each category of vehicle. Based on feedback from many of our industry partners, we identified the following parameters to enforce performance parity between conventional and more advanced powertrains:

1. 0- to 30-mph acceleration time
2. 0- to 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, we determined the performance requirements for various types of vehicles (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 truck type should meet or exceed these minimum requirements. For the fuel economy measurements, we selected cargo mass based on prior collaborative work with various OEMs and Tier1 suppliers that represent the real-world cargo needs. Using the real-world cargo-carrying requirements helps researchers determine whether a hybrid or electric truck can provide the same usefulness to the fleet.

TABLE 2-2 Summary of medium-and heavy-duty vehicle classes, functions, and performance requirements

Class	Purpose	0-30 mph (s)	0- 60 mph (s)	6% Grade Speed (mph)	Cruise Speed (mph)	Max. Speed (mph)	Cruise Grade (%)	Max grade at launch (%)	Daily driving range (mi)
2	Van	7	18	50	70	75	2	15	150
3	Box	7	30	50	65	70	2	15	150
3	Van	7	24	50	65	70	1.5	15	150
3	School	7	20	50	55	60	1.5	15	150
3	Pickup	6	12	65	70	75	1.5	15	150
4	Box	9	30	50	55	60	1.5	15	150
4	StepVan	9	35	40	55	65	1.5	20	150
4	Service	7	18	60	70	75	1.5	20	200
5	Utility	9	24	50	55	60	1.5	20	150
6	StepVan	14	40	40	55	70	1.5	15	150
6	Box	14	40	45	65	70	1.5	20	150
6	Construction	12	50	40	60	65	1.5	20	150
7	Tractor	18	60	30	65	70	1.25	15	250
7	Vocational	18	60	30	60	65	1.25	15	200
7	Box	18	60	30	55	60	1.25	15	150
7	School	19	60	30	55	60	1.25	15	150
8	Longhaul	18	80	30	65	70	1.25	15	500
8	Beverage	20	66	30	65	70	1.25	15	250
8	Drayage	20	80	30	65	65	1.25	15	200
8	Vocational	20	120	25	60	55	1	15	200
8	Transit	17	120	25	50	55	1	15	200
8	Refuse	20	120	25	50	55	1	20	80
8	Regional	18	80	30	50	70	1.25	15	250

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

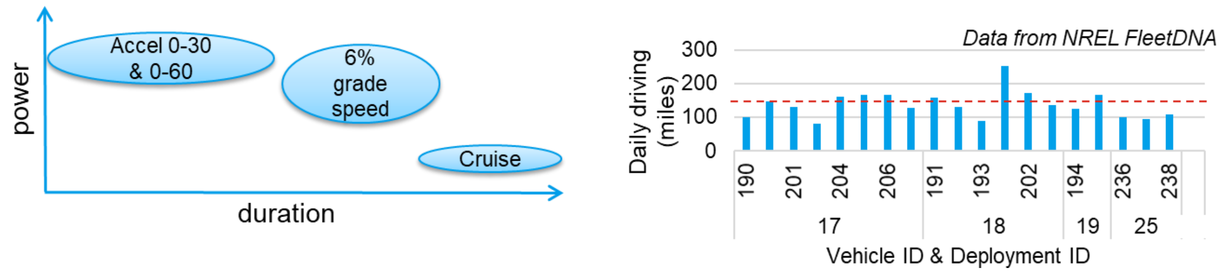


FIGURE 2-2 Overview of the performance parameters for medium- and heavy-duty vehicles

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

2.2.2 Drive Cycles

The EPA and NHTSA have issued compliance procedures for medium- and heavy-duty vehicles (EPA and NHTSA, 2016a) that specify the three drive cycles that should be used to evaluate different operational conditions (Figure 2-3).

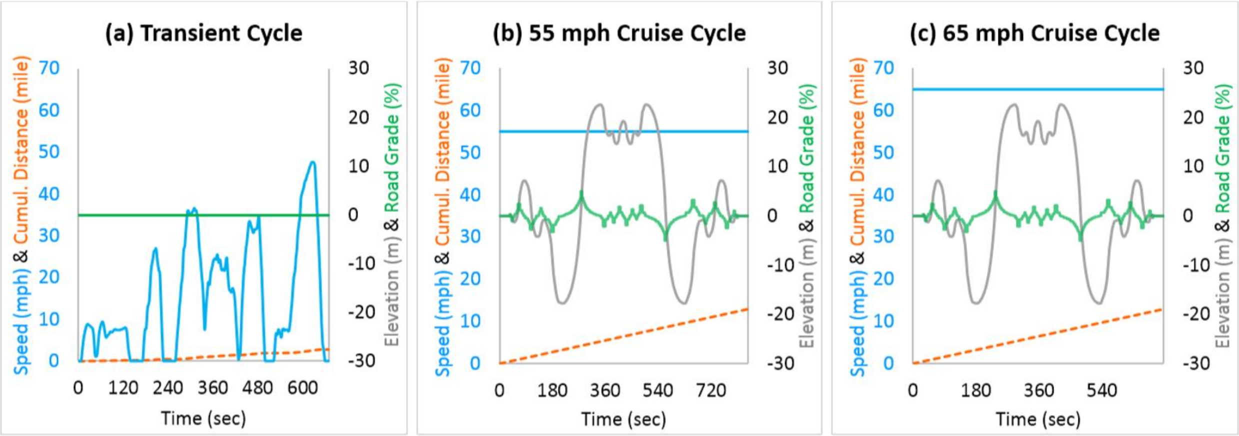


FIGURE 2-3 Drive cycles used for evaluating fuel consumption of medium and heavy-duty cycles

In addition to these cycles, we simulated other driving conditions for sizing tests, including a grade test using a proxy for 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.

We simulated acceleration tests to determine the time needed for the vehicle to achieve speeds of 30 and 60 mph. Acceleration times for heavy vehicles are much longer than those for light-duty vehicles.

We recognize that the prescribed regulatory cycles are different for classes 2 and 3 (light heavy-duty vehicles). In the future, we expect to include gasoline-powered class 2 and 3 vehicles to this analysis; at that time, we will include the new drive cycles.

2.2.3 Powertrains

This analysis examines 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. Figure 2-4 shows the component layouts of those powertrains. Conventional vehicles used in our analysis are similar to today’s diesel trucks. The mild hybrid (integrated starter/generator [ISG]) adds start-stop functionality to avoid idling. Parallel pre-transmission architecture allows for more regenerative braking, effective assistance to the engine by the motor, or even an electric-only launch or coast, if the battery and motor conditions permit.

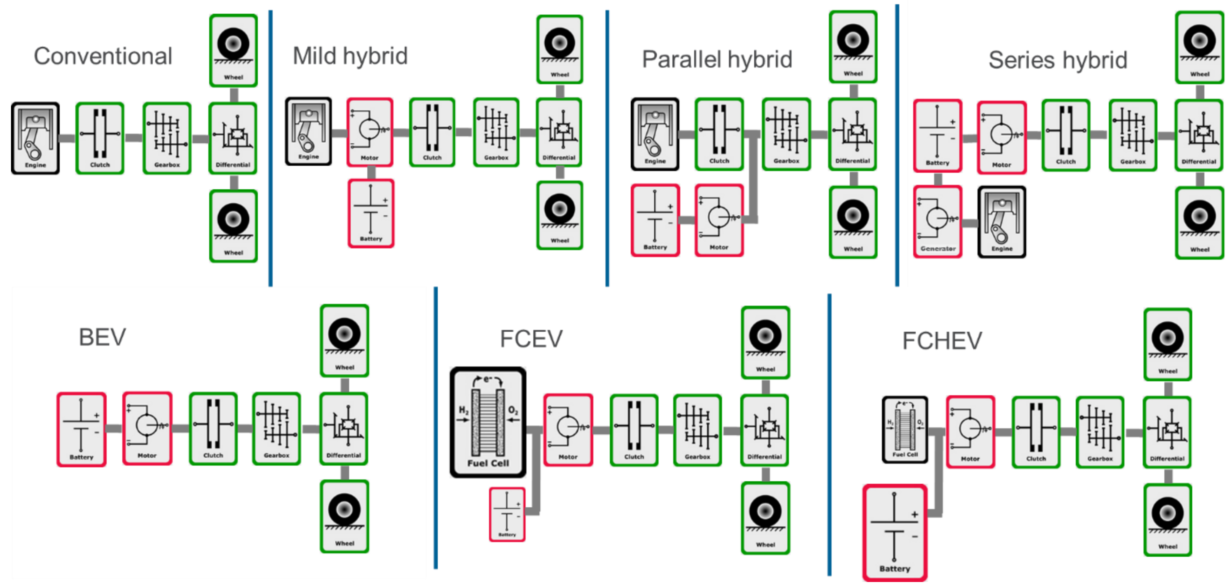


FIGURE 2-4 Component layout in powertrain architectures for medium- and heavy-duty vehicles

The PHEV, BEV, and fuel cell architectures may use a gearbox where necessary to meet 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 (e.g., grade climbing, launch, cruise).
    - 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 desired battery 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 requirements).

Due to charging infrastructure requirements and the need for two energy sources, option 3 is not considered in this analysis. Options 1 and 2 are evaluated strictly in a charge-sustaining mode for fuel economy estimates.

2.2.4 Component Technologies

We identified key performance parameters for each component on the basis of its impact on the overall energy consumption of the vehicle. Figure 2-5 summarizes these parameters; some are discussed in more detail in subsequent sections.

Technology managers at DOE, each responsible for specific research areas, provided their best estimates on how their respective technology areas could evolve over the next few decades. Their input resulted in (1) a "business-as-usual" (low) scenario, in which technology will progress at a slow pace given limited future R&D success, and (2) a "program success" (high) case to demonstrate the level of improvement targeted by DOE through various R&D initiatives.

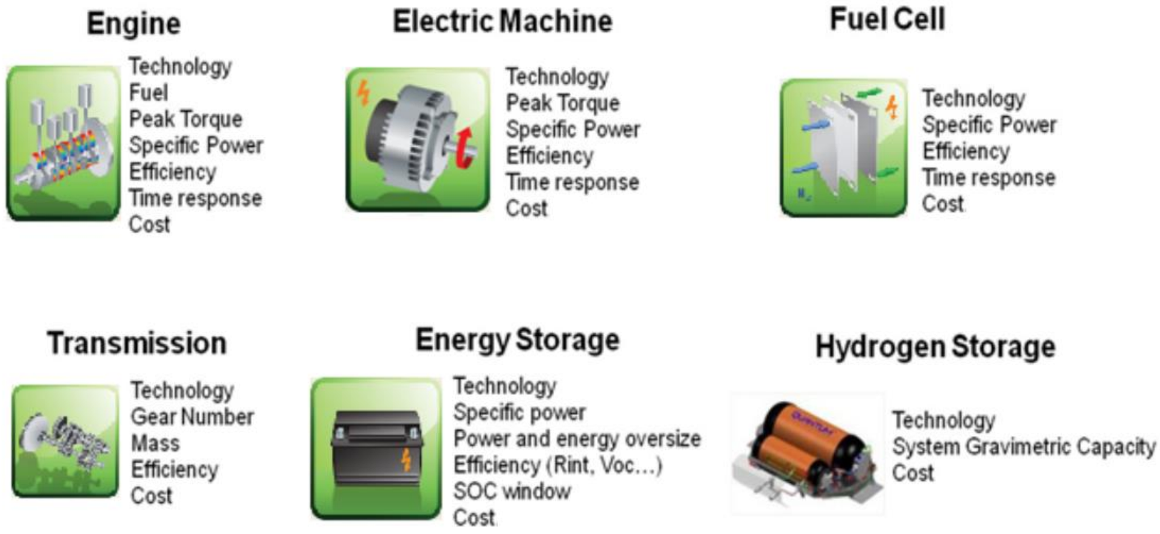


FIGURE 2-5 Component-specific parameters that affect energy consumption and operating cost estimation

2.2.4.1 Engine

This study focuses on diesel engines, consistent with what has been DOE's engine research program for heavy trucks and its associated goals. (Recently, these goals have shifted slightly away from diesel ICE technology.)

VTO R&D 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 demonstration at a 65-mph cruise point on a dynamometer (EERE-VTO 2016). DOE has, historically, anticipated 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 soon and will also help improve the efficiency of smaller engines. On the basis of these targets and the goals set for smaller diesel engines by the VTO’s U.S. DRIVE Partnership (U.S DRIVE 2018), we developed assumptions for engines needed for different types of trucks. Figure 2-6 shows the assumed peak engine efficiencies and incremental engine costs for vehicles in each size class and application. Cases are shown for the two scenarios described above, with the high level of technology progress envisioned by DOE 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 because of the higher cost of meeting consumer demands for better fuel economy. Therefore the program success scenario assumes higher efficiency gains for the same cost increase.

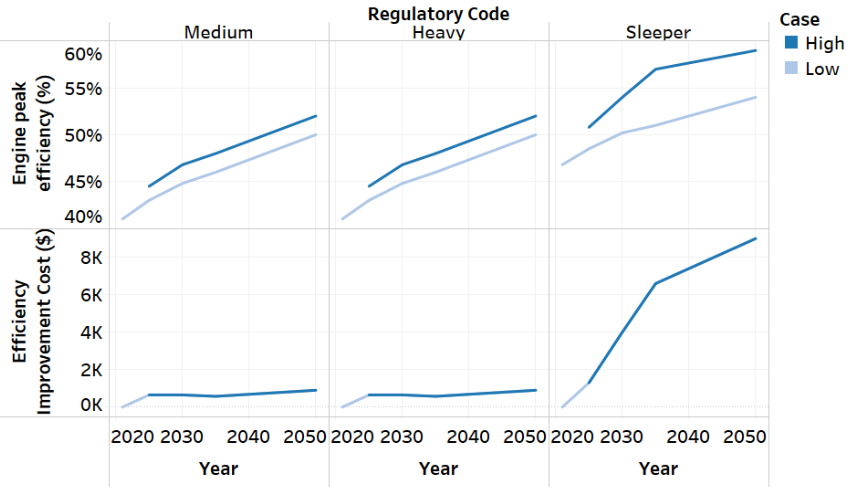


FIGURE 2-6 Efficiency and incremental cost estimates for medium and heavy-duty engines

In addition to the cost increase to improve vehicle efficiency, the cost of the engine itself changes with engine size. We estimated the engine cost based on its peak power output. The International Council on Clean Transportation (ICCT) analyzed 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 laboratories, the Argonne Autonomie team chose the cost assumptions shown in Figure 2-7.

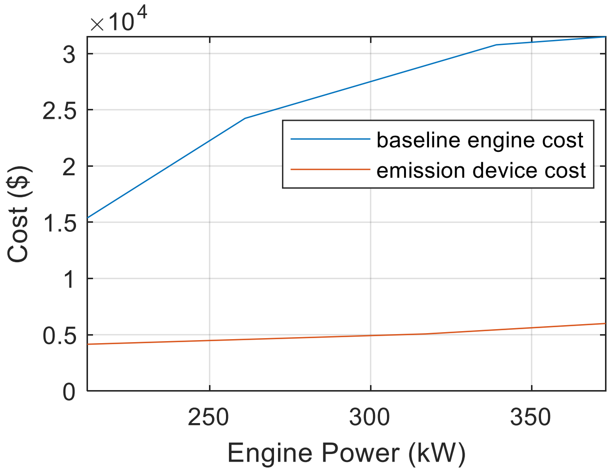


FIGURE 2-7 Estimated cost of diesel engine system as a function of engine power

These estimates provide the base cost to manufacture an engine. As technology improves, we expect to see higher costs associated with the devices and materials used to achieve higher engine efficiency (Figure 2-6).

2.2.4.2 Electric Traction Drive

VTO expects electric traction drive system cost ($/kW) to decrease significantly in the near future. Figure 2-8 illustrates our assumptions regarding efficiency and costs of future electric traction drive systems. The system efficiency and cost assumptions are the cumulative values for electric machine and power electronics components needed to operate the machine.

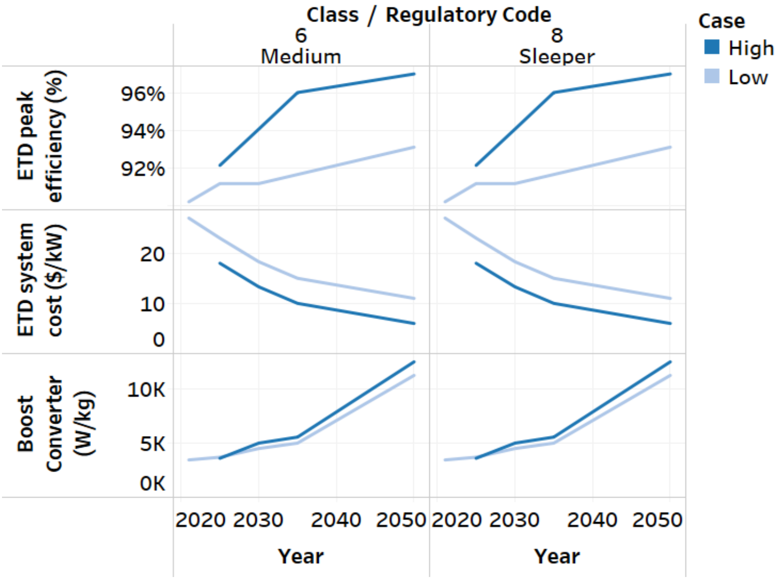


FIGURE 2-8 Cost and efficiency assumptions for electric traction drive system

We relied on data from the A2Mac1 database (A2Mac1 2019) and feedback from other national laboratories that work on this topic to estimate the efficiency and power density (kW/kg) values.

2.2.4.3 Transmission

VTO does not set specific goals regarding the number of gears needed for vehicles. These values have been chosen based on the transmission choices available in present-day production vehicles (and remain constant over the time period examined). Figure 2-9 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, FCEV and FCHEV) can achieve their performance requirements even with a direct-drive system. Heavier (class 6–8) electric vehicles, on the other hand, require a transmission with at least 2-speed ratios to meet performance requirements.

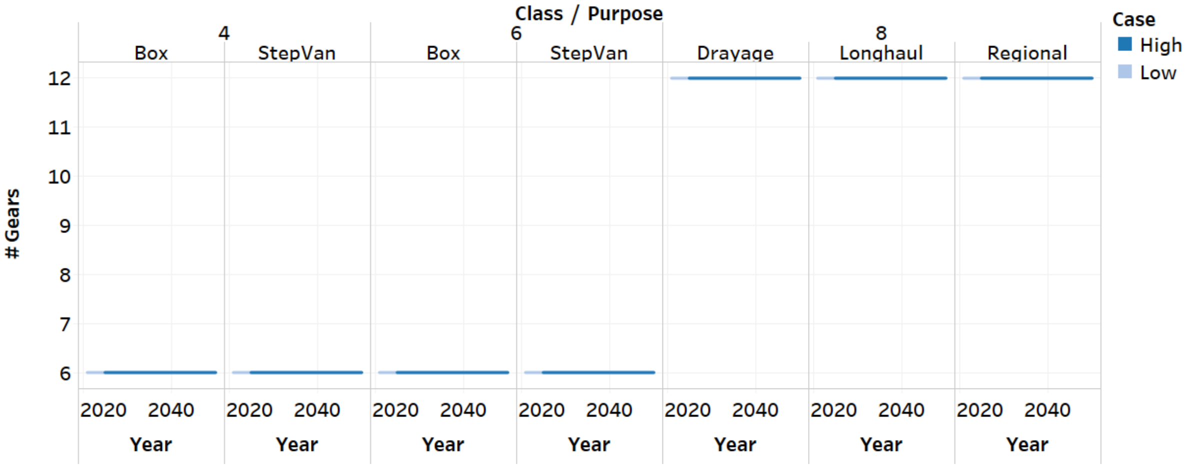


FIGURE 2-9 Assumed number of gears in conventional truck transmissions

2.2.4.4 Energy Storage

VTO supports research on batteries for light-duty vehicles, although no roadmaps had been developed 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, we assumed that the light-duty HEV battery goals will be applicable for ISG systems in the heavy-duty domain, HEV trucks will likely use technologies developed for light-duty PHEVs, and trucks with plug-in and electric powertrains are assumed to use battery technologies developed for light-duty BEVs.

Figure 2-10 summarizes the battery characteristics for all trucks simulated. Battery packs for FCEVs were assumed to be very similar to HEV packs, so the same assumptions were made for both. Costs for PHEV, FCHEV, and BEV battery packs were assumed to depend on energy, not power, and no power cost coefficient was used.

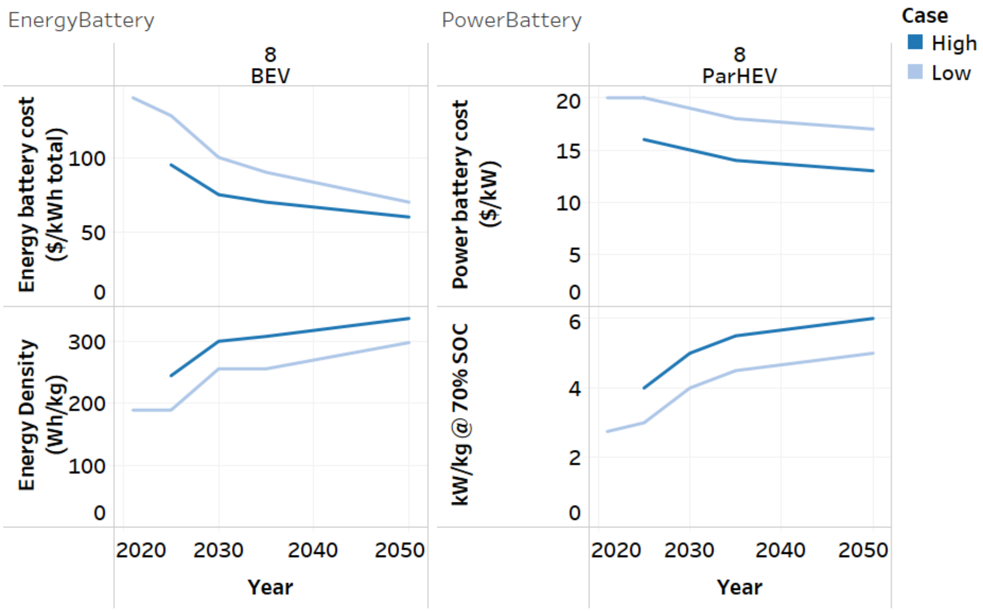


FIGURE 2-10 Battery assumptions for plug in hybrid and electric trucks (left) and charge sustaining hybrid trucks (right)

The power and energy capacity of the cell will determine the cost of the energy storage system. In the case of hybrid vehicles, where a high-power battery is employed, the cost of the battery is determined by the $/kW assumption. The cost of high 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 a 2C rate to ensure safe operating conditions for the battery.

2.2.4.5 Fuel Cells

In 2019, HFTO established fuel cell targets specific to heavy-duty vehicles (Marcincoski et al. 2019). Many factors that affect the fuel cell design would be different in heavy-duty vehicles than in light-duty to meet the rigorous requirements for trucks. Sustained higher power operation and durability requirements are expected to increase the cost of manufacturing fuel cells for trucks.

This year, HFTO provided inputs on fuel cell efficiency and cost for medium-duty trucks as well. Fuel cells for these smaller trucks are less efficient when compared to those used for long-haul sleeper trucks. Figure 2-11 shows the shape of the fuel cell efficiency curve assumed for medium- and heavy-duty applications.

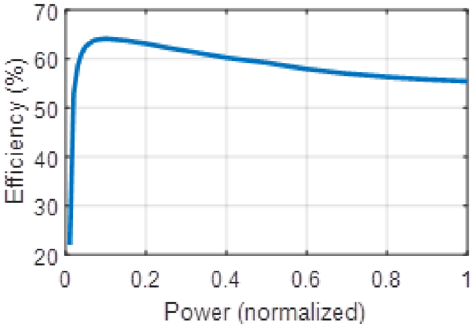


FIGURE 2-11 Operating efficiency of the fuel cell plotted against the normalized net power output

Figure 2-12 shows assumptions for fuel cells in medium- and heavy-duty applications. We scale the efficiency curve shown in Figure 2-11 to obtain an assumed peak efficiency value for each year and technology progress case. By 2050, this peak efficiency is assumed to reach 70% for the fuel cells designed for medium-duty trucks and 72% (i.e., in the "High" scenario) for the ones designed for long-haul sleeper trucks. 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 et al. 2019). Most of this cost reduction is targeted in the interim period, primarily by 2030.

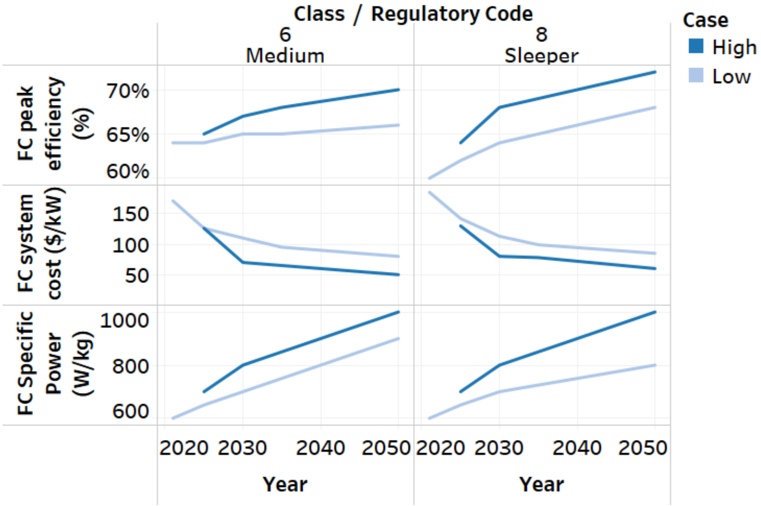


FIGURE 2-12 Fuel cell system efficiency and cost coefficients for trucks

Fuel cell components are sized such that the beginning-of-life performance characteristics are consistent with the assumptions used for BEVs. We assume that performance or efficiency degradation will not be significant enough to affect vehicle operation.

2.2.4.6 Hydrogen Storage

For simplicity, Figure 2-13 displays the assumptions made on fixed cost for a hydrogen tank and the cost associated with storing each kg of hydrogen. The figure also shows the combined production and delivery cost of hydrogen assumed for this work.

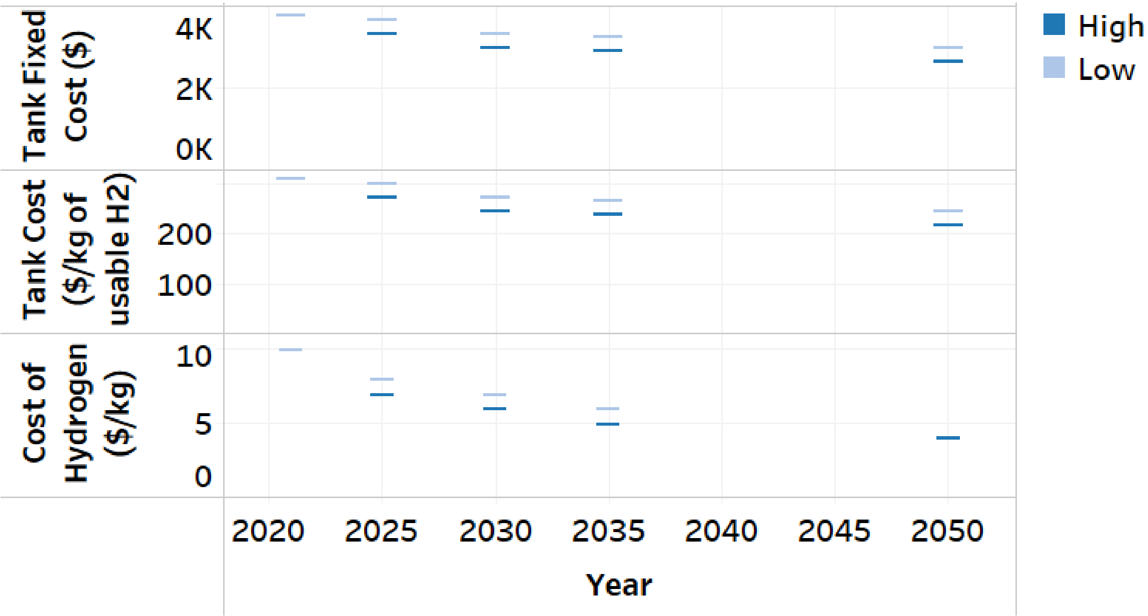


FIGURE 2-13 **Hydrogen cost & storage cost assumptions**

2.2.4.7 Lightweighting

Use of advanced materials and optimized design can reduce 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 eliminated from the truck (DOE-VTO 2013). Since 2014, some of the lightweighting approaches mentioned in that report (e.g., the use of fiber-reinforced plastics in Class 8 tractor bodies) have been deployed. Cost-effective technologies tend to be adopted quickly in this segment. Figure 2-14 shows values assumed for future glider weight reduction.

DOE predicts that truck lightweighting will approach 30% compared to the baseline established in the 2013 report. About 13% lightweighting (compared with that baseline) has already been achieved. For this analysis, we use the present-day truck as the baseline. Thus the values in Figure 2-14 reflect the improvement expected from the present-day trucks. The cost of lightweighting is assumed in our analysis to be $5/kg based on DOE guidance.

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 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.

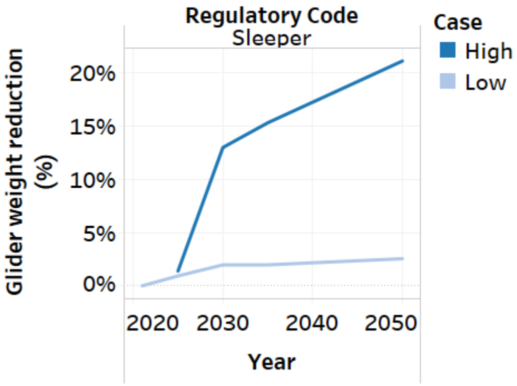


FIGURE 2-14 Assumptions regarding glider weight reduction in trucks and cost of lightweighting

In a prior year's work, the second option was chosen, providing a way to reduce the load-specific fuel consumption (gal/mi/ton). Based on feedback from various stakeholders, this year's analysis uses 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 technological options available to improve vehicle fuel economy 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. We developed the assumptions shown in Figure 2-15 for conventional trucks, and applied them to all other powertrains.

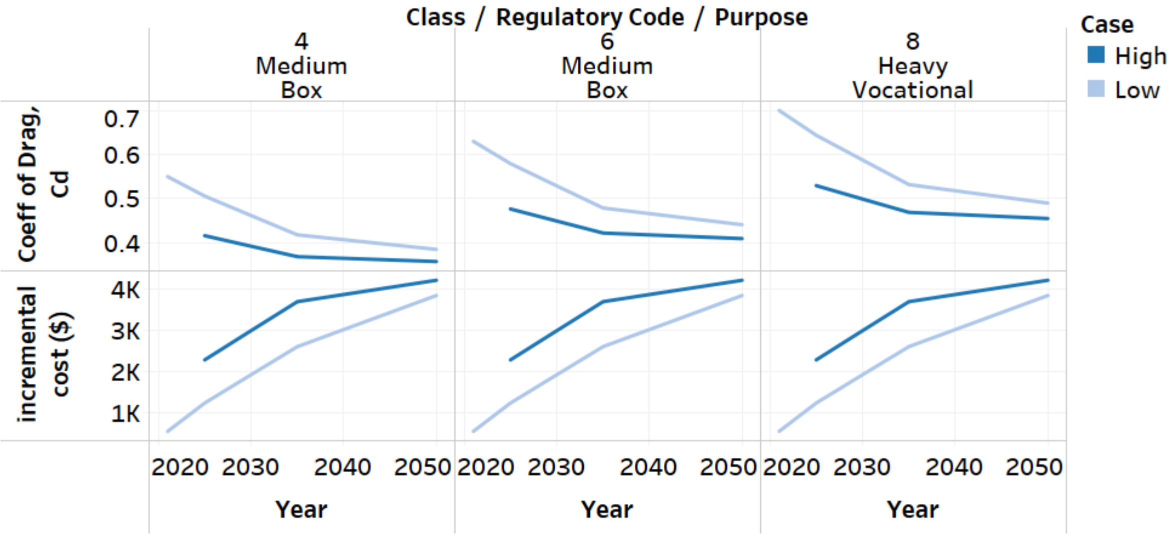


FIGURE 2-15 Aerodynamic improvement and associated incremental cost assumed for different truck types

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. We estimated vehicle prices 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 report, accessible at https://vms.es.anl.gov/case-studies/u-s-doe-vto-hfto-r-d-benefits/. The detailed plots provided in this report 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 during 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-mi range and regional trucks are designed for a 250-mi range. Comparing these two cases shows how BEVs and fuel cell-powered trucks may 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

For this analysis, we estimated fuel consumption simulations over the 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 the EPA 65 cycle, 9% to the EPA 55 cycle, and the remainder to the fuel consumption observed in the ARB transient cycle. For vocational trucks, the multi-purpose weightage used in this study assigns 54% of the weightage to the ARB transient cycle, with the remainder shared between the other two cycles. This is as prescribed in the heavy duty regulatory documents for these type of vehicles. (EPA and NHTSA 2016).

Figure 2-16 provides a summary of the fuel consumption of present-day trucks over the regulatory test procedure.

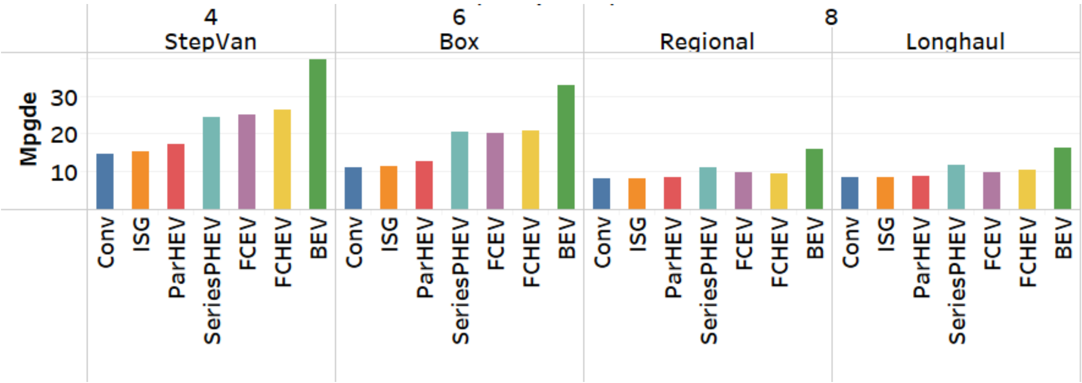


FIGURE 2-16 Overview of energy consumption of present-day trucks (expressed as miles per gallon diesel equivalent [mpgde])

Figure 2-16 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 some 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, also included in the figure, 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.

Figure 2-17 shows the percentage of fuel savings potentially realized by each powertrain for various types of trucks. The figure 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 timeframe 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.

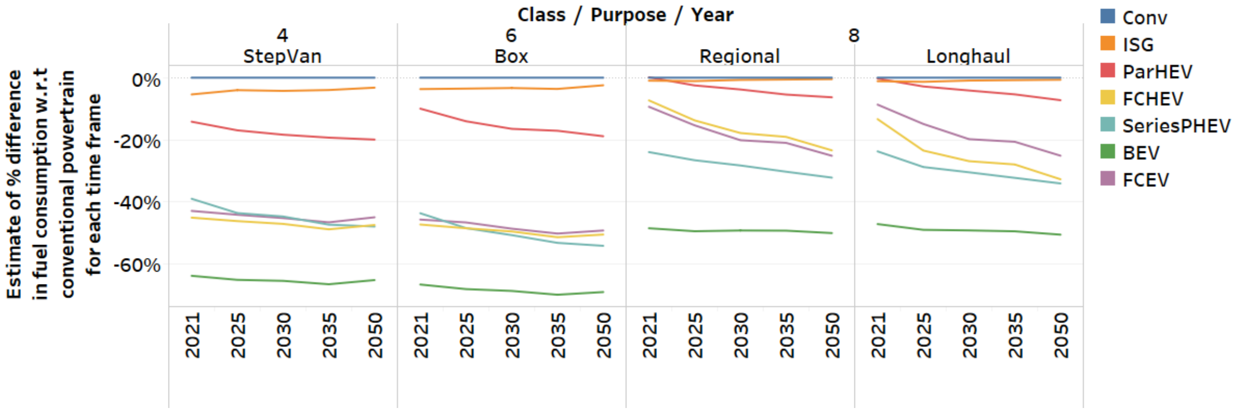


FIGURE 2-17 Comparison of diesel-equivalent fuel consumption for various powertrains

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 during highway driving because of a combination of drive cycle properties and vehicle design attributes. Long-haul trucks are designed for steady operation at highway speeds, so they operate very close to their peak efficiency under these conditions. In regulatory tests, highway driving provides 95% of the weightage for such trucks. Electrified trucks display the greatest advantage under the transient driving conditions considered in 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.

In addition to the fuel economy estimates, this analysis examines the cost and mass estimates for the vehicles. Figure 2-18 shows that, in the near term, advanced powertrains have cost and weight penalties compared with 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 and ownership costs.

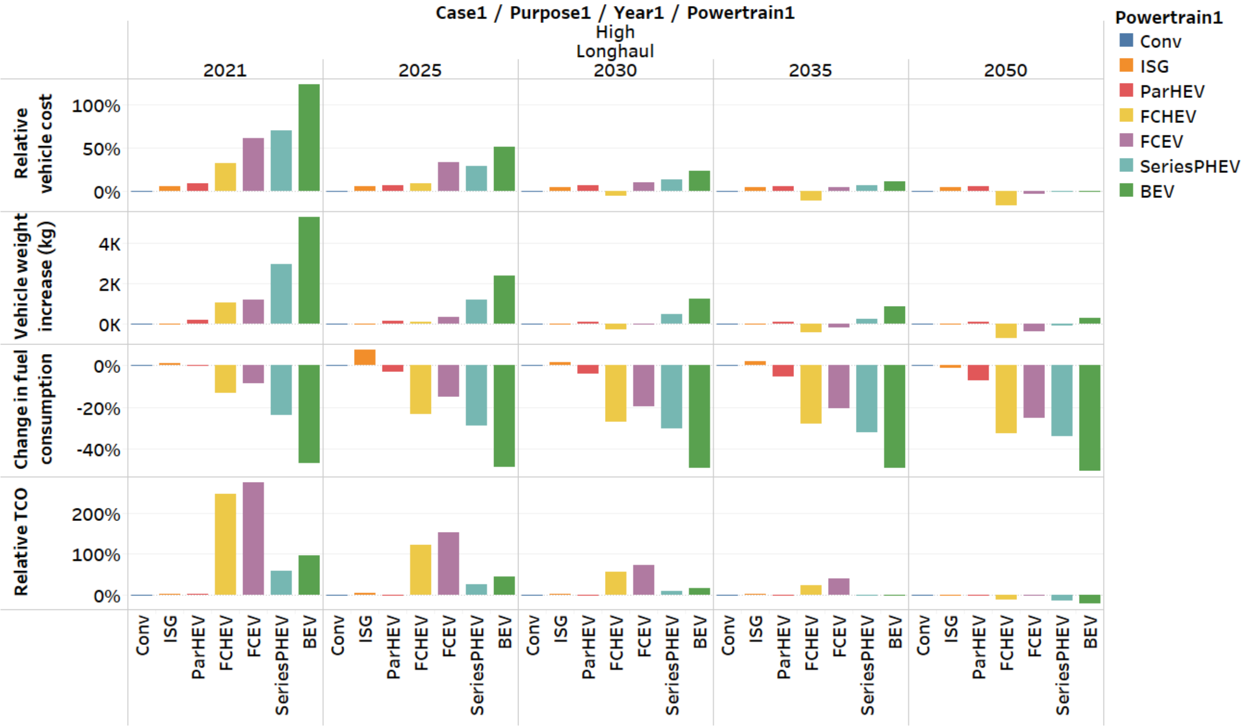


FIGURE 2-18 Evolution of vehicle cost, weight, and energy consumption for long-haul trucks that use advanced powertrains (all percentages are computed based on the conventional truck parameters for that year)

Similar plots for three more truck types are provided in the Appendix. The data shown in these plots are available for all trucks and are shared from our website as Excel sheets accompanying this report.

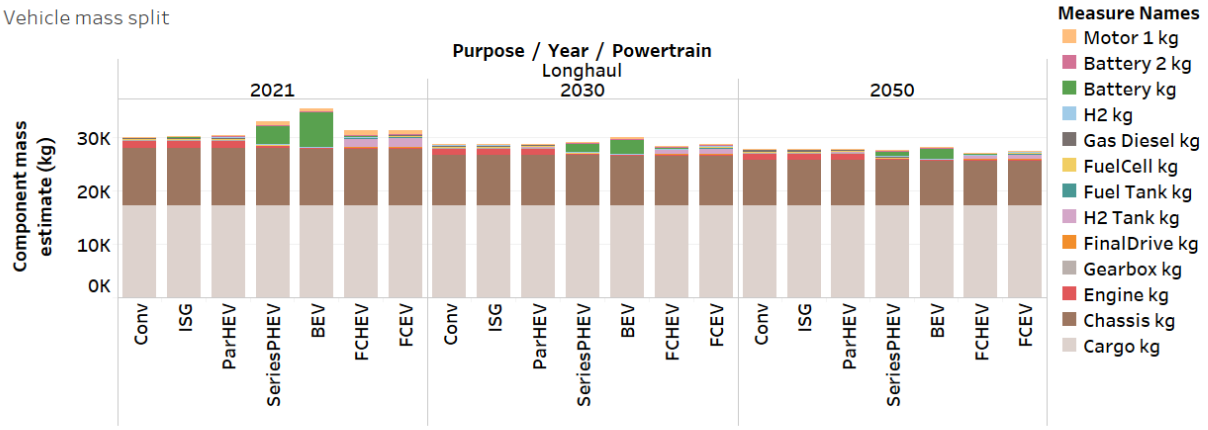
Fuel economy values for advanced trucks are used as inputs for other VTO-funded projects that estimate life-cycle cost and well-to-wheel (WTW) carbon dioxide (CO_2) emissions from trucks.

3.2 MASS AND 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 2030. This increase in component weight could reduce the cargo-carrying capacity of these vehicle variants; however, battery technology improvements are expected to reduce the vehicle weight penalty as we get closer to 2050, as indicated clearly in the powertrain-specific mass split shown at the bottom of the figure.

The appendix provides a more detailed view of the mass associated with energy storage in electric and fuel cell trucks.

Vehicle mass split



Powertrain mass split

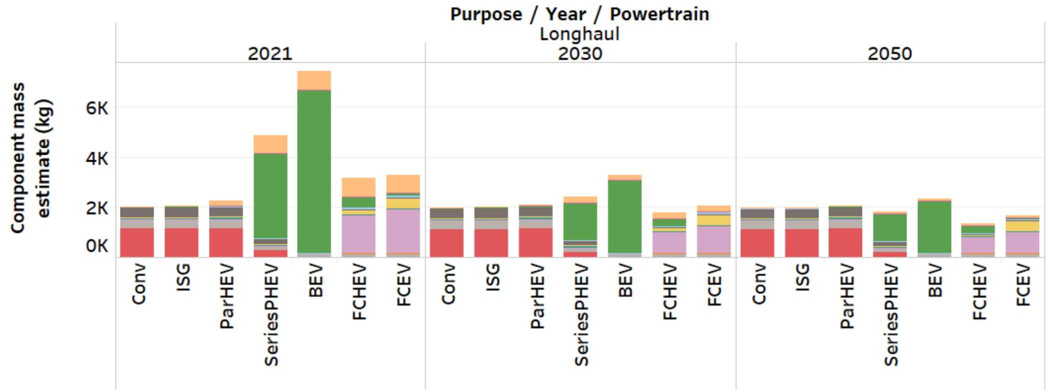


FIGURE 2-19 The top plot shows vehicle-level split of all component masses; The bottom plot provides a powertrain-specific split for components aside from the cargo and chassis (which dominate the vehicle mass).

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 in the manufacture of 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 each component. Figure 2-20 shows that, in the near term (2021–2030), 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 over time, our results demonstrate the battery cost becoming a relatively smaller part of the overall vehicle cost and, at the vehicle level, electric and plug-in hybrid long-haul trucks becoming cheaper to manufacture than their conventional counterparts

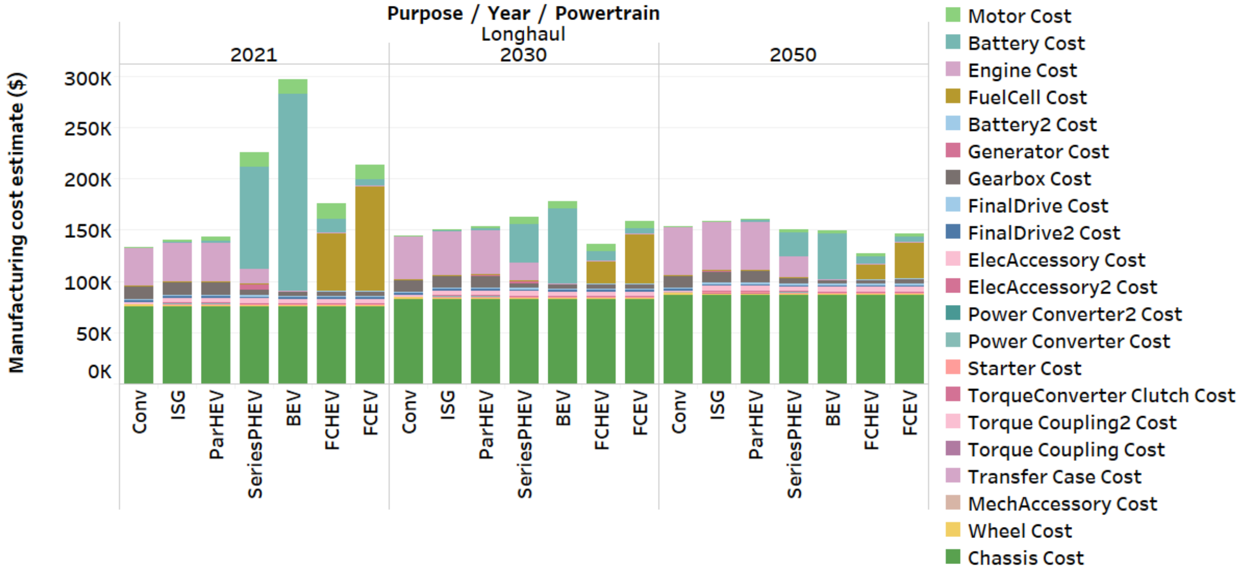


FIGURE 2-20 Cost of each component in long haul-trucks that employ advanced powertrains

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.

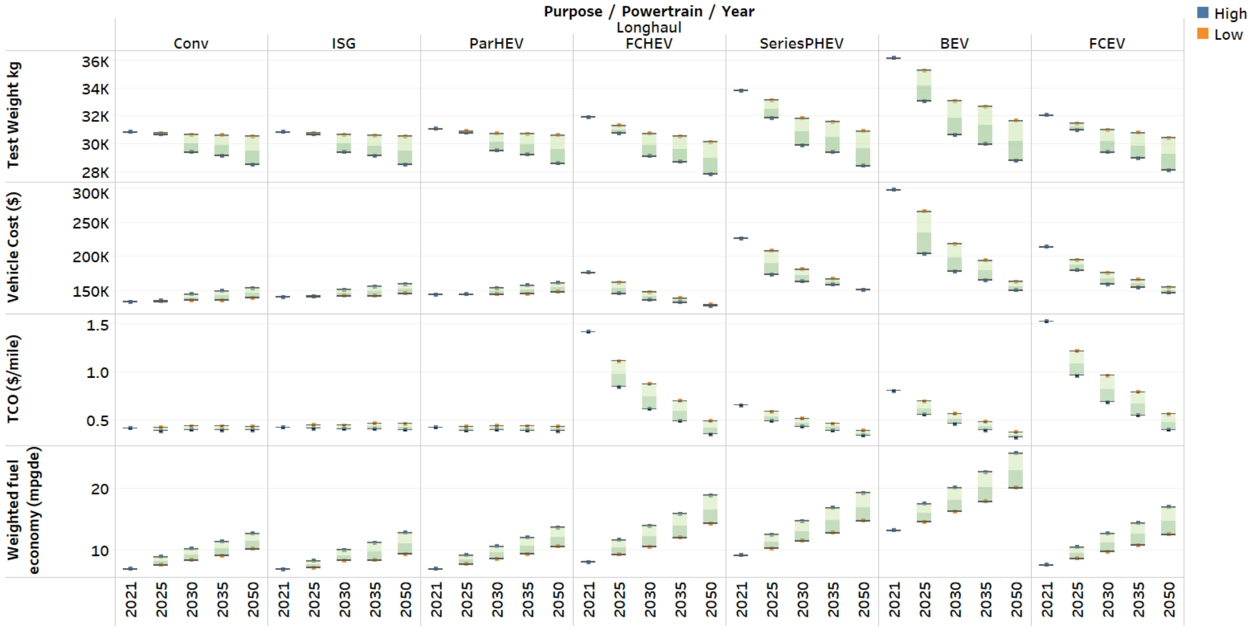


FIGURE 2-21 Direct impacts on fuel economy, vehicle cost, and overall ownership cost of trucks resulting from varying levels of technology progress (seen here for a long-haul truck)

The figure shows that lower levels of technology progress have impacts on vehicle cost, energy consumption, and ownership cost, 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.

The appendix provides similar plots for three more trucks. The data needed to plot the above figures are available for all types of trucks in Table 2 and in Excel sheets 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 ownership cost 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 study, but the data provided may be used by other agencies and national laboratories to predict the market adoption of advanced powertrains.

3.3 TOTAL COST OF OWNERSHIP ANALYSIS

TCO is an important criterion for wider adoption of new technologies by fleet managers. Argonne uses a techno-economic analysis tool called BEAN to analyze TCO. During the last year, we updated BEAN to process Autonomie results. Light-duty- and heavy-duty-specific BEAN files are also shared with this report.

BEAN provides the flexibility to update the cost assumptions for components and fuels, providing an easy way for technology analysts to assign their own component or fuel cost assumptions and see how the TCO for vehicles change under those circumstances. Operating costs such as driver wages, insurance costs, registrations costs, tolls, penalties associated with loss of cargo, and downtime are all factored into BEAN. The tool uses the assumptions and methodologies from a multi-laboratory report on TCO calculation (Burnham et. al. 2021).

BEAN was updated with more analysis plots to visualize the results described in this report. All the vehicle information needed for TCO, LCA, and market penetration analysis is provided through accompanying Excel sheets.

To quickly check the benefits and costs of powertrains, we can use a simpler comparison of TCO based on capital expenses and operating expenses directly attributable to the technology. This approach follows the guidance provided by 21CTP on the economic analysis used in their target-setting process.

This section specifies how Autonomie carries out the simpler TCO analysis. The main factors considered in this analysis are initial purchase price and fuel/energy cost spread over the service period of the truck.

As previously indicated, a retail price equivalent (RPE) factor of 1.2 is used to estimate the vehicle purchase price from the estimated manufacturing cost. Cost associated with maintenance and dwell time during recharging or refueling the vehicle are added based on the multi-laboratory TCO report (Burnham et. al. 2021). BEAN provides a convenient way to view and update these assumptions.

Fuel price is an important factor in determining the competitiveness of various powertrains. BEAN uses these fuel cost values as the default ones but allows users to update them to evaluate a different scenario.

Figures 2-22 shows the cost of delivering and dispensing hydrogen assumed for this work.

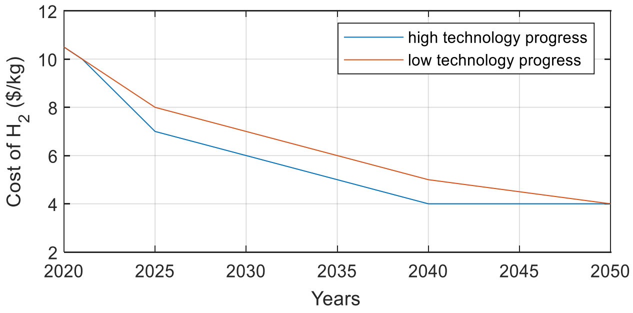


FIGURE 2-22 Estimated cost of H_2 under low and high technology progress assumptions

Diesel price estimates are taken from the Annual Energy Outlook 2021 report. The taxes associated with diesel are deducted from the price to make the fuel cost comparable to that of hydrogen. The variation in diesel prices and taxes over time are shown in Figure 2-23.

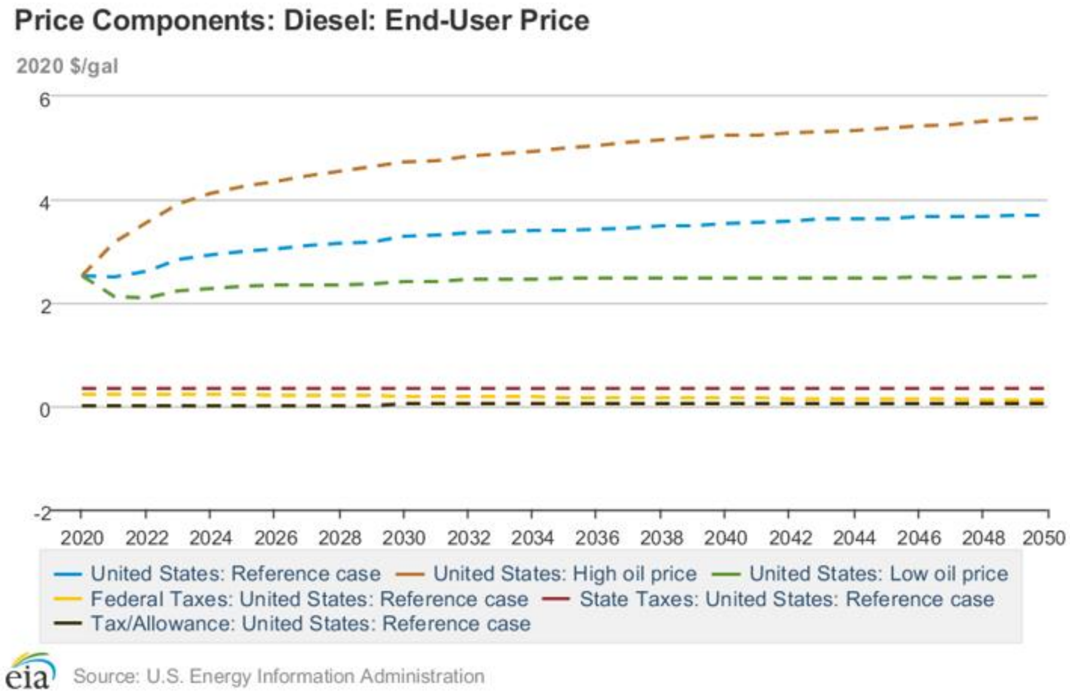


FIGURE 2-23 Projected diesel fuel prices from EIA Annual Energy Outlook 2021 (Taxes are subtracted from the end-user price to estimate the cost of diesel fuel)

There is an ongoing effort by DOE to quantify the break-even cost for high-power chargers for trucks. The relevant values are not publicly available yet, so, for this year, we are continuing with our estimate of the charging cost, as shown in Figure 2-24. The initial years assume a high cost due to investment needed in setting up chargers. We expect this cost to decrease over time as electric vehicles gain wider acceptance.

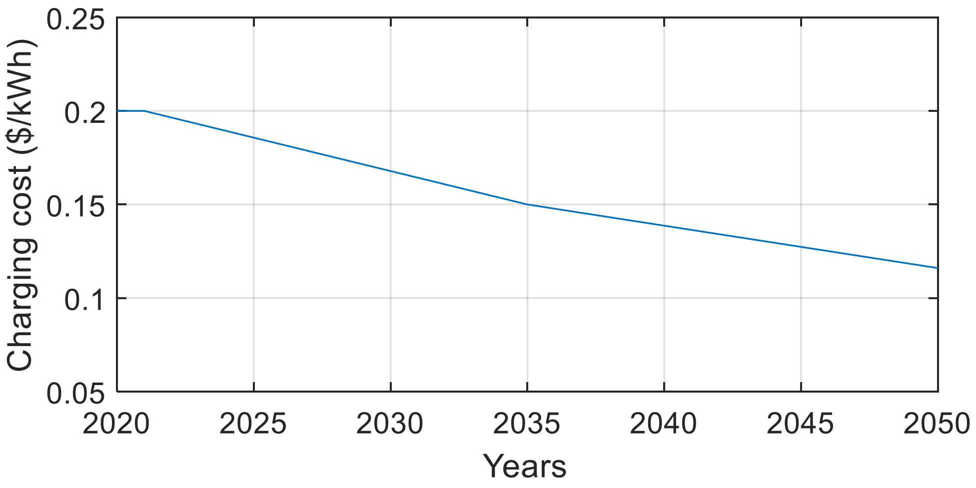


FIGURE 2-24 Assumed electricity cost for the next three decades

The resale value of the vehicle is estimated based on the plot shown in Figure 2-25. BEAN can use specific residual value assumptions for each type of truck.

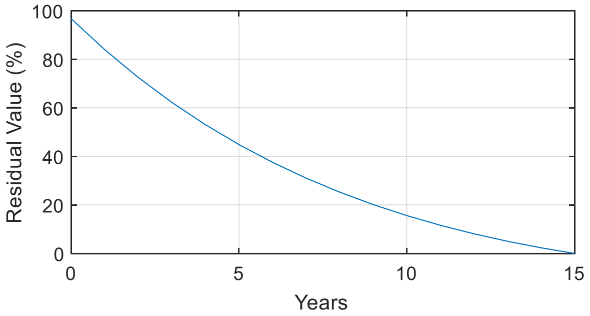


FIGURE 2-24 Residual value assumption for TCO calculation in Autonomie

TCO analysis provides a quick glimpse into how advanced powertrains will emerge in the medium and heavy-duty segment.

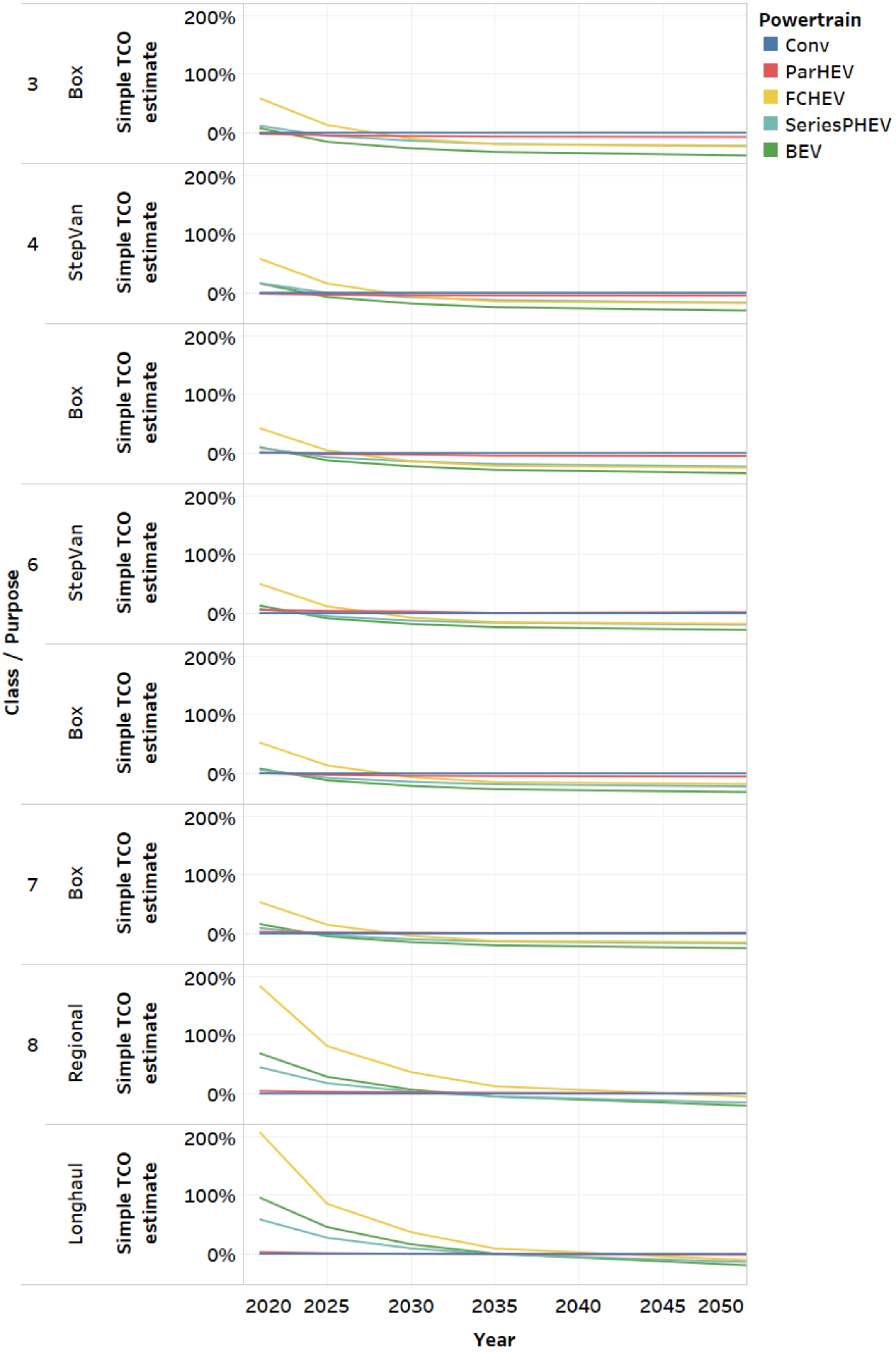


FIGURE 2-25 Comparison of TCO for multiple types of trucks and powertrain choices

Figure 2-26 shows that the smaller electric trucks and fuel cell trucks are expected to achieve TCO parity with conventional trucks between 2025 and 2035. Electric trucks and fuel cell trucks designed for longer-range applications are likely to see TCO parity in the long term, between 2035 and 2050.

BEAN allows us to expand this analysis to consider greenhouse gas (GHG) emissions associated with the vehicle energy consumption. BEAN uses emissions factors from another ANL tool, the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model, which can be used to evaluate well-to-pump (WTP), pump-to-wheel (PTW) and well-to-wheel (WTW) greenhouse gas (GHG) emissions in user-defined scenarios of fuel type and vehicle efficiency.

4. MEDIUM AND HEAVY-DUTY REPORT SUMMARY

This analysis outlines the input assumptions (including performance requirements and sizing process assumptions) and modeling processes used to estimate future vehicle-level fuel economy, weight, and manufacturing cost for medium- and heavy-duty trucks. The sample plots shown 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 five timeframes, 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, life-cycle cost analysis (GREET^{TM}), cradle-to-grave analysis, and market acceptance analysis work (ATB, TEMPO^{TM}) carried out by various agencies, including other national laboratories (Ledna et. al. 2022; Iyer et al. 2021; Wang et al. 2021; NREL 2020).

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 fuel cell-powered electric trucks economically attractive compared with conventional diesel powertrains.

The vehicles and processes modeled as a part of this analysis have been used to support many DOE efforts, including target-setting processes both within DOE and as associated with DOE partnership efforts. Representative vehicles for more than 20 conventional trucks are included in the upcoming release of Autonomie. For four of the truck types, we share seven powertrain examples to ensure that the new capabilities developed as part of this project are widely distributed. Future iterations of this work will include more vehicles, features, and analyses based on the feedback of stakeholders and DOE guidance.

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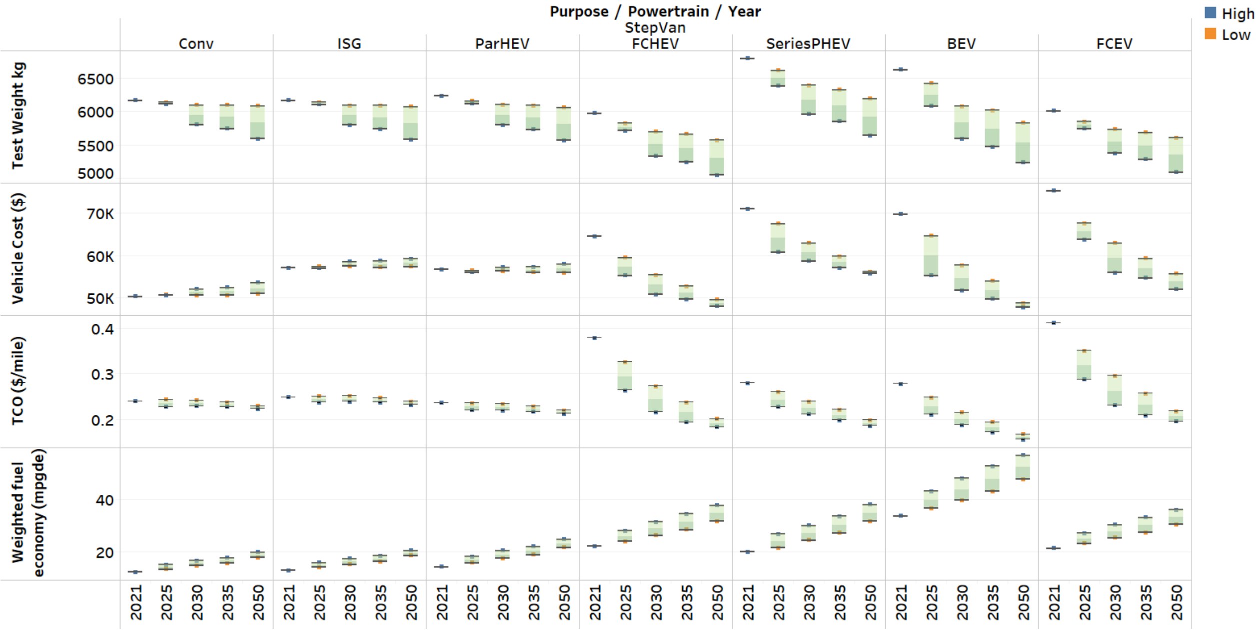
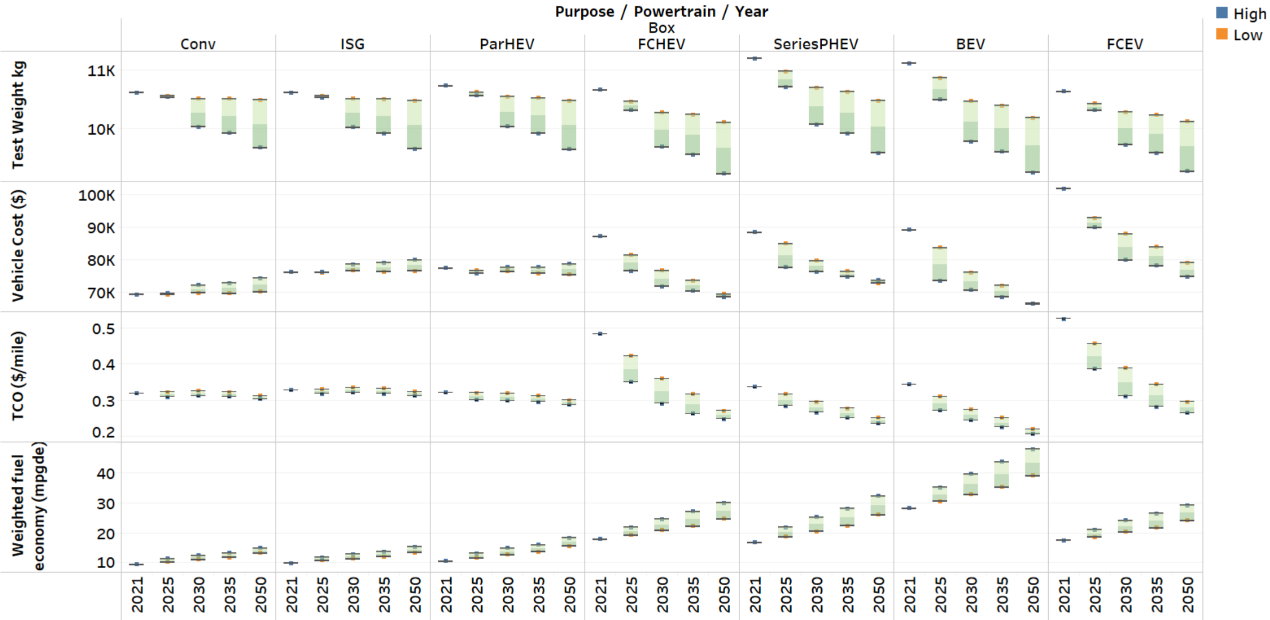
APPENDIX

Class4 WalkIn

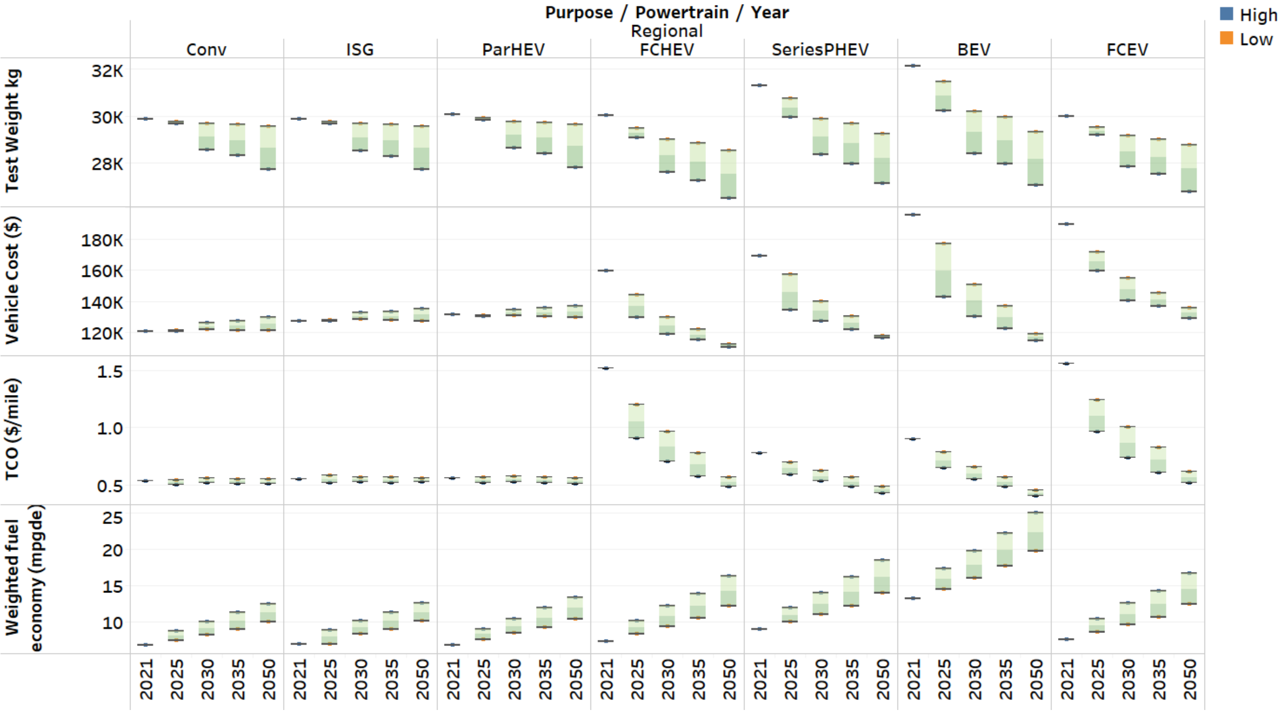


Class 6 Box

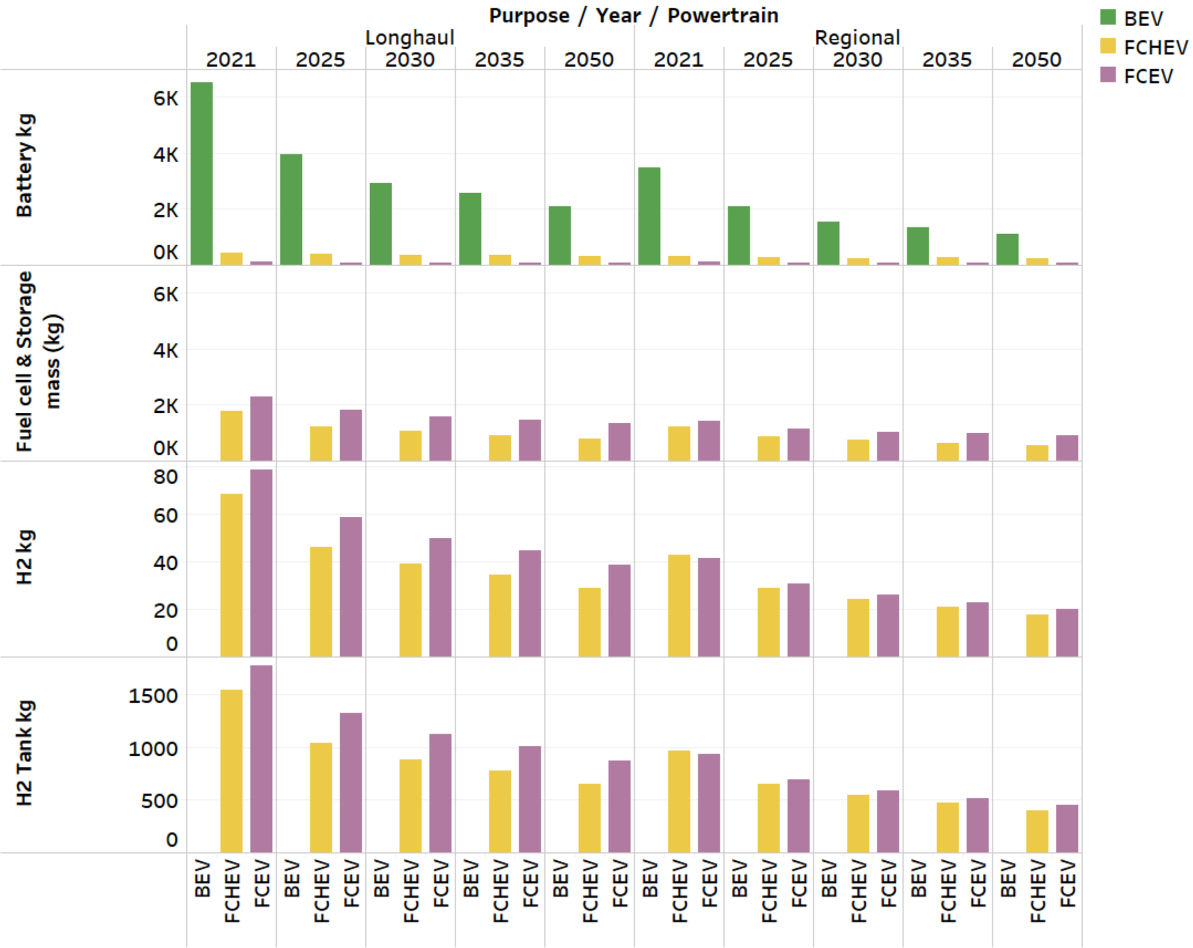

Case / Purpose / Year / Powertrain
High
Box
2021
2025
2030
2035
2050
Powertrain
Conv
ISG
ParHEV
FCHEV
FCEV
SeriesPHEV
BEV
Difference in vehicle cost
40%
20%
0%
Vehicle weight increase (kg)
500
0
Difference in energy consumption
-20%
-40%
-60%
Relative TCO
50%
0%
Conv
ISG
ParHEV
FCHEV
FCEV
SeriesPHEV
BEV


Purpose / Powertrain / Year
Box
Conv
ISG
ParHEV
FCHEV
SeriesPHEV
BEV
FCEV
High
Low
Test Weight kg
11K
10K
Vehicle Cost ($)
100K
90K
80K
70K
TCO ($/mile)
0.5
0.4
0.3
0.2
Weighted fuel economy (mpgde)
40
30
20
10
2021
2025
2030
2035
2050

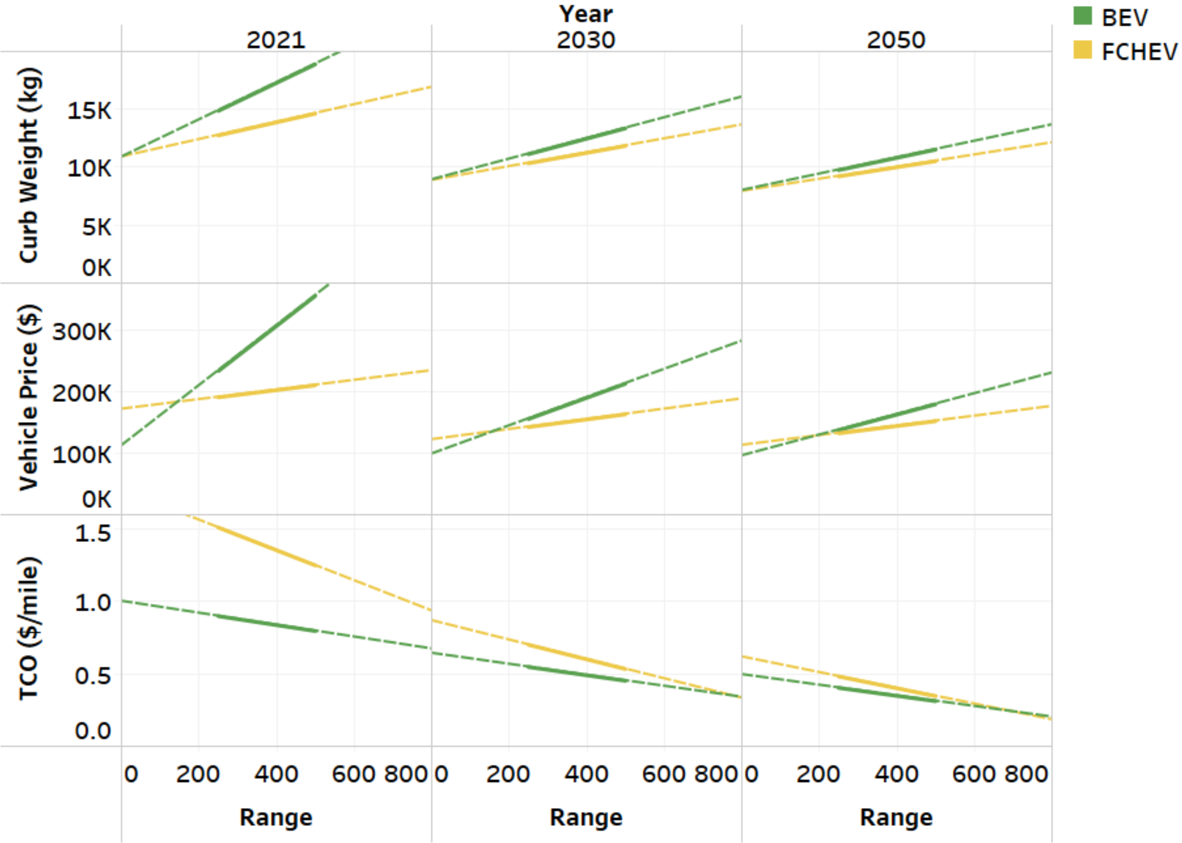
Class 8 Regional



Among the vehicles considered in this analysis, onboard energy storage requirement is highest for class 8 long-haul trucks. This figure shows the evolution of battery, hydrogen, and tank mass for a long-haul truck and regional truck over the future years. A 500-mi driving range is assumed for the long-haul truck; a 250-mi range is assumed for the regional truck. For the simple TCO calculation, we assume these vehicles are operated over their full driving range for 240 days in a year.



The preceding figure shows that BEVs can compete in class 8 tractor segments where payload and daily driving range requirements are lower. For cases where payload and driving range requirements are more aggressive, FCHEVs can provide a good alternative. The next figure shows the vehicle curb weight, estimated purchase price, and TCO as a function of range. Regional (250-mi driving range) and long-haul (500-mi driving range) trucks are quite similar in powertrain size. The energy storage size is the main difference between them. Extrapolation of the trend seen from the two cases shows that for shorter-range vehicles, BEVs are cheaper to purchase and operate. But as the range increases, FCHEVs become more competitive.



These results can change with the assumptions made about component cost, fuel cost, VMT, ownership duration, etc. BEAN provides the flexibility to change those parameters to complete such analyses.

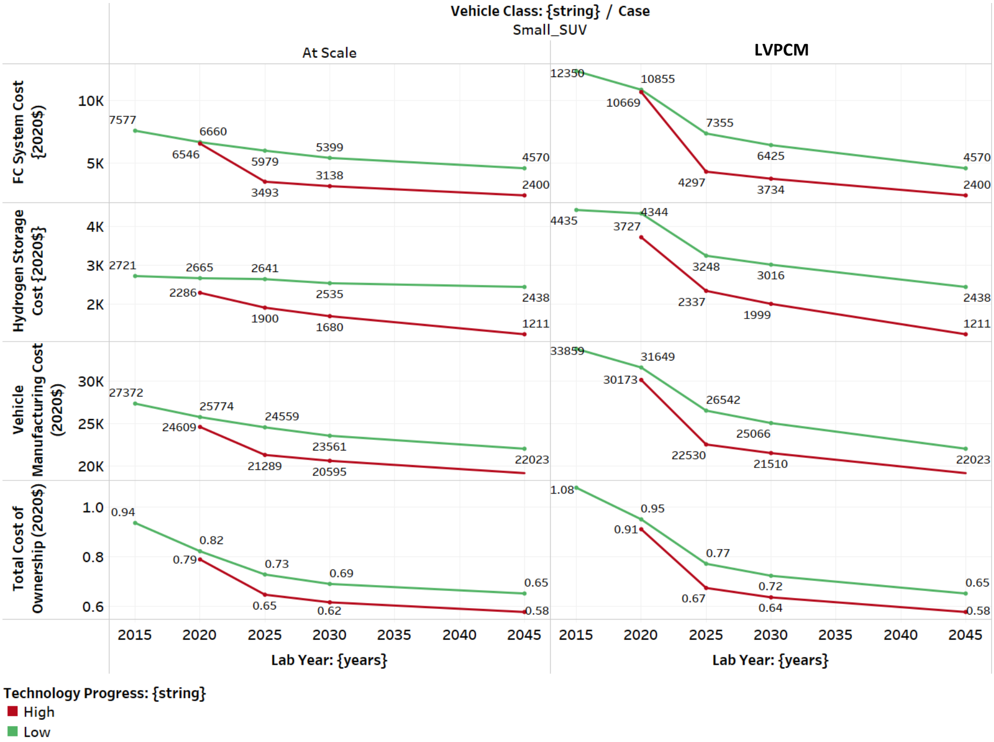
<u>HFTO Low Volume Production Cost Multiplier (LVPCM) Effects</u>

The report had outlined the fuel cell and hydrogen storage costs when produced at scale. In addition, an additional analysis has been conducted to evaluate the impact of low-production cost assumptions for fuel cell and hydrogen storage tanks.

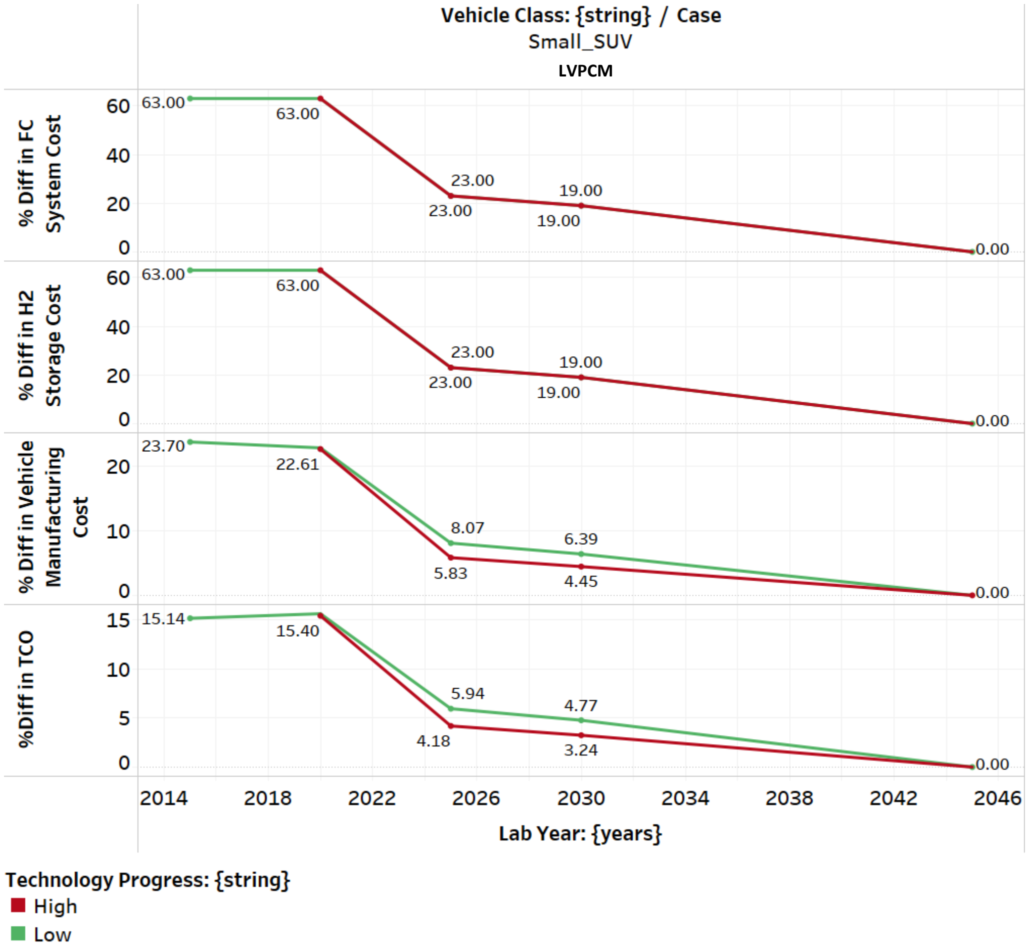
To develop the low cost impact, the sales weighted vehicle market penetration from external tools had been used to determine the LVPCM for fuel cell costs and hydrogen storage tank costs. These resulting costs are outlined below for light-duty vehicles:

Lab Year	Model Year	Technology Progress Case	Fuel Cell cost ($/kw) at scale	Tank Cost slope ($/usable kg of H2) at scale	Tank Cost (fixed) ($) at scale	LVPCM Multiplying Factor	Fuel Cell Cost ($/kW) at LCM	Tank Cost slope ($/usable kg of H2) at LCM	Tank Cost (fixed) ($) at LCM
2015	2020	Low	76	338	1087	1.63	123.9	551	1772
2020	2025	Low	68	338	1087	1.63	110.8	551	1772
2020	2025	High	68	282	1033	1.63	110.8	460	1684
2025	2030	Low	60	338	1087	1.23	73.8	416	1337
2025	2030	High	40	224	981	1.23	49.2	276	1207
2030	2035	Low	57.5	338	1087	1.19	68.4	402	1294
2030	2035	High	37.5	199.5	933	1.19	44.6	237	1110
2045	2050	Low	50	338	1087	1	50.0	338	1087
2045	2050	High	30	124	799	1	30.0	124	799

For Small SUV Fuel Cell 300 vehicles as an example, the figure below shows the trendline as an effect of the LVPCM assumptions:



As a result of the LVPCM assumptions, the % difference (increase) in FC system costs are evaluated below:


Vehicle Class: {string} / Case
Small_SUV
LVPCM
% Diff in FC System Cost
60
40
20
0
63.00
63.00
23.00
23.00
19.00
19.00
0.00
% Diff in H2 Storage Cost
60
40
20
0
63.00
63.00
23.00
23.00
19.00
19.00
0.00
% Diff in Vehicle Manufacturing Cost
20
10
0
23.70
22.61
8.07
5.83
6.39
4.45
0.00
%Diff in TCO
15
10
5
0
15.14
15.40
5.94
4.18
4.77
3.24
0.00
2014
2018
2022
2026
2030
2034
2038
2042
2046
Lab Year: {years}
Technology Progress: {string}
🟥 High
🟩 Low

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