ANL/ESD-19/10

Energy Consumption and Cost Reduction of Future Light-Duty Vehicles through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050

Energy Systems Division

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Energy Consumption and Cost Reduction of Future Light-Duty Vehicles through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050

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NOTATION

ACRONYMS AND ABBREVIATIONS

AER	all-electric range
AMTL	Advanced Mobility Technology Laboratory
BaSce	Benefits and Scenario Analysis
BEV	battery-powered electric vehicle
BEV200	BEV with 200 mi of all-electric range (end-of-life) on combined driving cycle (adjusted)
BEV300	BEV with 300 mi of all-electric range (end-of-life) on combined driving cycle (adjusted)
BEV400	BEV with 400 mi of all-electric range (end-of-life) on combined driving cycle (adjusted)
BISG	belt-integrated starter generator (mild hybrid vehicle)
CI	compression ignition
CO_2	carbon dioxide
CVT	continuously variable transmission
DCT	dual-clutch transmission
DM	discrete manual transmission
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DRIVE	U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability
EDV	electric drive vehicle
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
E-REV	extended-range electric vehicle
EV	electric vehicle
FTP	Federal Test Procedure
GPRA	Government Performance and Results Act

HEV	hybrid electric vehicle
HFTO	Hydrogen & Fuel Cell Technologies Office
HWFET	Highway Federal Emissions Test
ICE	internal combustion engine
IVM	initial vehicle movement
Li-ion	lithium ion
MY	model year
NEMS	National Energy Mobility System
NHSTA	National Highway Safety Transportation Administration
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PEV	pure electric vehicle
PHEV	plug-in hybrid electric vehicle
PHEV20	PHEV with 20 mi of all-electric range (end-of-life) on combined driving cycle (adjusted)
PHEV50	PHEV with 50 mi of all-electric range (end-of-life) on combined driving cycle (adjusted)
R&D	research and development
SAE	Society of Automotive Engineers
SEDS	State Energy Data System
SI	spark ignition
SOC	state of charge
SUV	sport utility vehicle
UDDS	Urban Dynamometer Driving Schedule
USD	U.S. dollars
US06	EPA US06 cycle
VCR	variable compression ratio
VTO	Vehicle Technologies Office
VTS	vehicle technical specifications
VVL	variable valve lift
VVT	variable valve timing

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
sec	second(s)
V	volt(s)
W	watt(s)
Wh	watt hour(s)

PREFACE

This report is the fifth revision of a continuous improvement study on Benefits and Scenario Analysis (BaSce) from the U.S. Department of Energy Vehicle Technologies Office and Hydrogen and Fuel Cell Technologies Office. Past reports are as follows:

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

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

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

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

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

With each revision of the study, changes were made to the assumptions, control strategies at the vehicle level, methodologies, and powertrain selections.

1 INTRODUCTION

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

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

These various technologies are assessed for six different timeframes: laboratory years 2015 (reference), 2020, 2025, 2030, and 2045. A delay of 5 years is assumed between laboratory year and model year (year technology is introduced into production). Finally, uncertainties are included for both technology performance and cost aspects by considering two cases:

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

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

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

2 METHODOLOGY

2.1 VEHICLE CLASSES AND POWERTRAINS

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

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

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

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

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

- *Two technology progress uncertainty levels*: low and high cases. These correspond to low uncertainty (aligned with original equipment manufacturer [OEM] improvements based on regulations), average uncertainty, and high uncertainty (aligned with aggressive technology advancement based on DOE VTO & HFTO programs). Low-technology progress represents a very small uncertainty in achieving the target; that is, the manufacturers would achieve this target without the advancement of DOE VTO & HFTO programs. The high-technology progress represents a very high uncertainty in achieving the target by the manufacturers as they respond to DOE VTO & HFTO targets for the corresponding technology and laboratory year. These uncertainties do not necessarily entail to predicting future performances.

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

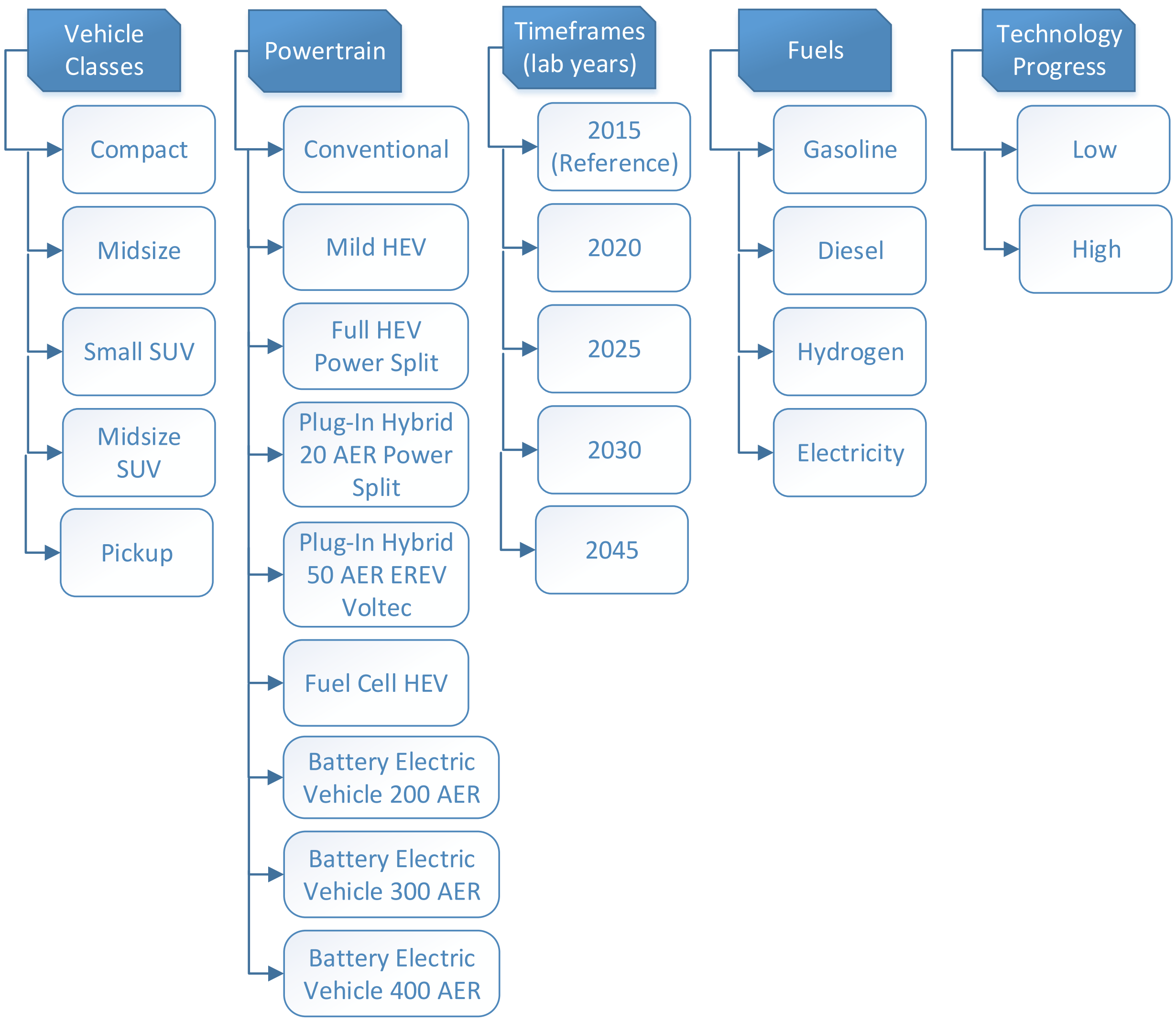


FIGURE 1 Vehicle classes, timeframes, configurations, fuels, and technology progress level.

2.2 AUTONOMIE OVERVIEW

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

- Estimate the energy, performance, and cost impact of advanced vehicle and powertrain technologies
- Support proper methods, from model-in-the-loop, software-in-the-loop (SIL), and

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

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

- Simulate subsystems, systems, or entire vehicles;
- Predict and analyze fuel efficiency and cost;
- Perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms;
- Support system hardware and software requirements;
- Link to optimization algorithms; and
- 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

The energy consumption was simulated using the Urban Dynamometer Driving Schedule (UDDS) and Highway Federal Emissions Test (HWFET) (U.S. EPA, 2019). The vehicle costs are calculated from individual component characteristics (e.g., power, energy, weight).

3 ASSUMPTIONS

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

3.1 ENGINE

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

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

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

Instead of analyzing individual engine technologies, the approach is to consider baskets of advanced technologies consistent with expectations of engine performance over time. The peak and part-load efficiencies have been selected for each fuel type and timeframe after discussions with experts and literature review. Table 1 illustrates the engine peak and part-load efficiencies for a conventional powertrain across the different laboratory years. The low, and high labels correspond to the different technology performance cases.

TABLE 1 Engine peak and part-load efficiency assumptions

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
Naturally Aspirated GASOLINE for Conventional									
IC Engine eff	36	38	43	40	43	42	45	44	47
Engine eff at 2bar at 2000rpm	24	25	29	26	30	28	30	30	35
Engine eff at 20% at 2000rpm	24	25	29	26	30	29	32	31	35
Engine eff at 3bar at 1300rpm			33	31	35	34	37	36	39
DIESEL									
IC Engine eff	42	43	50	44	50	47	51	48	52
Engine eff at 2bar at 2000rpm	26	27	31	29	33	30	33	32	35
Engine eff at 20% at 2000rpm	30	33	40	37	42	39	44	41	46
Engine eff at 3bar at 1300rpm	32		36	35	39	37	41	39	43
Downsized, Boosted, Gasoline Engine Pathway (Turbo)									
IC Engine eff	36	39	43	39	43	40	44	42	46
Engine eff at 2bar at 2000rpm	24	25	26	25	28	26	32	28	33
Engine eff at 20% at 2000rpm	29	30	35	32	36	34	39	36	41
Engine eff at 3bar at 1300rpm	27	28	35	29	38	32	38	34	40
GASOLINE for HEVs based on Atkinson Cycle									
IC Engine eff	39	40	46	41	46	43	48	45	50
Engine eff at 2bar at 2000rpm	25	26	30	27	31	30		31.6	35.5
Engine eff at 20% at 2000rpm	24	25	29	26	30	30	32	31	35
Engine eff at 3bar at 1300rpm			33	31	35	34	37	36	39

3.2 FUEL CELL SYSTEM

Table 2 illustrates the power density of fuel cell systems and shows that, between the reference case of laboratory years 2015 and 2045, the power density increases from 650 W/kg for the low scenario to up to 1,000 W/kg for the high scenario. The low and high labels correspond to the two different technology performance cases considered in the study. It is important to note that these estimates are based on the best available data in 2018. Since conclusion of this study, more recent estimates of fuel cell specific power, efficiency, and cost have been published by the DOE's Hydrogen and Fuel Cell Technologies Office.[1] It is also important to note that these estimates assumed that fuel cells are manufactured at high volumes, and therefore experience cost reductions due to economies of scale. The cost of fuel cells given current manufacturing volumes ranges from $160-$210/kW.

[1] For current information on HFTO estimates of hydrogen and fuel cell costs, please see publications available here: https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-information-resources

TABLE 2 Fuel cell power density assumptions

	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
Specific Power FC system	W/kg	650.0	659.0	675.0	659.0	800.0	675.0	900.0	700.0	1000.0
Peak Fuel Cell System Efficiency	%	61.0	62.0	63.0	63.0	65.0	65.0	68.0	65.0	68.0
Fuel Cell System Specific Cost	$/kw	*53.0*	*50.0*	*50.0*	*47.0*	*40.0*	*44.0*	*37.0*	*37.0*	*30.0*

The fuel cell system simulated has been sized to a range of 320 mi on the adjusted combined cycle. In addition, 100% of the hydrogen present in the tank is referred to as usable. The fuel cell peak efficiency is assumed to be at 61% for reference laboratory year 2015, which increases to 68% for laboratory year 2045.

3.3 ELECTRIC MACHINE

Two different electric machines are used as references in this study:

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

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

TABLE 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	Camry EM1 data from Oak Ridge National Laboratory (ORNL) (Burress et al. 2008)	
Parallel HEV	Sonata HEV data from ORNL (Olszewski 2011)	
Split HEV and blended PHEV	Camry EM1 data from ORNL (Burress et al. 2008)	Camry EM2 Data from ORNL (Burress et al. 2008)
EREV PHEV	Camry EM1 data from ORNL (Burress et al. 2008)	Sonata HEV Data from ORNL (Olszewski 2011)
BEV	Chevrolet Bolt EM data (Momen 2018)	
Fuel cell HEV	Nissan Leaf data from ORNL (Olszewski 2011)	

For the study, the peak efficiency of electric machines for the different powertrains was scaled as shown in Table 4.

TABLE 4 Efficiency scaling of electric machines

Vehicle Powertrain	Peak Efficiency Scaled (%)
Micro-HEV / mid-hybrid BISG	96
Power-split HEV	96
Blended PHEV20 AER / EREV PHEV50 AER	96

3.4 ENERGY STORAGE SYSTEM

The battery performance data used in the study are provided by Argonne, Idaho National Laboratory, and major battery suppliers (Francfort 2014). A scaling algorithm developed by Argonne is used for the high-energy cases (Nelson et al. 2007).

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

TABLE 5 Battery assumptions

	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
High Power APPLICATIONS										
Specific Power @ 70% SOC	W/kg	2750	3000	4000	4000	5000	4500	5500	5000	6000
Power Term	$/W	20	20	16	19	15	18	14	17	13
	Lab Year	2015	2020		2025		2030		2045	
Parameter	Tech Progress	Low	Low	High	Low	High	Low	High	Low	High
High Energy APPLICATIONS (PHEV)										
Energy Density (Wh/kg) - Blended PHEV	Wh/kg	60	80	100	105	125	110	140	115	170
Energy Density (Wh/kg) - EREV PHEV	Wh/kg	70	95	105	105	125	110	140	115	170
Energy Term - based on USABLE Energy - Blended PHEV	$/kWh	530	460	300	210	160	185	130	160	120
Energy Term - based on USABLE Energy - EREV PHEV	$/kWh	500	365	235	210	160	185	130	160	120
BEV										
Energy Density (Wh/kg)	Wh/kg	170	170	230	230	310	240	320	280	320
Energy Term - based on USABLE Energy - AEV	$/kWh	220	180	**170**	144	125	140	98	120	**80**

3.6 LIGHTWEIGHTING

Table 6 details the lightweighting assumptions on the glider mass across the different vehicle classes and laboratory years. The low and high cases illustrate the different technology performance cases. The glider mass reduction varies across the different vehicle classes. The assumption of reduction can be explained by the use of better materials and technologies in the future, such as aluminum unibody structures.

TABLE 6 Lightweighting across vehicle classes and laboratory years

	Model Year:	2025		2030		2035		2050	
	Lab Year:	2020		2025		2030		2045	
Technology Progress:		Low	High	Low	High	Low	High	Low	High
Cost of Lightweighting	$ / kg-saved	$17.00	$11.00	$17.00	$11.00	$17.00	$11.00	$15.00	$9.00
		Compact Car							
Vehicle Mass Reference	kg	1320							
Non-Powertrain Mass Reference (to be light-weighted)	kg	977							
Glider Cost Reference (Lab Year 2015)	$	7949							
Glider mass reduction (Lab Year 2015)	%	4%	11%	5%	18%	5%	19%	5%	19%
Total Glider Cost	$	$ 8,622	$ 9,111	$ 8,847	$ 9,837	$ 8,847	$ 9,982	$ 8,741	$ 9,612
Total Vehicle mass reduction	%	3%	8%	4%	13%	4%	14%	4%	14%
		Midsize Car							
Vehicle Mass Reference	kg	1595							
Non-Powertrain Mass Reference (to be light-weighted)	kg	1194							
Glider Cost Reference (Lab Year 2015)	$	10671							
Glider mass reduction (Lab Year 2015)	%	8%	16%	10%	25%	10%	30%	10%	32%
Total Glider Cost	$	$ 12,295	$ 12,772	$ 12,701	$ 13,955	$ 12,701	$ 14,611	$ 12,462	$ 14,110
Total Vehicle mass reduction	%	6%	12%	7%	19%	8%	22%	10%	24%
		Small SUV							
Vehicle Mass Reference	kg	1636							
Non-Powertrain Mass Reference (to be light-weighted)	kg	1205							
Glider Cost Reference (Lab Year 2015)	$	12617							
Glider mass reduction (Lab Year 2015)	%	7%	12%	10%	18%	14%	22%	18%	28%
Total Glider Cost	$	$ 14,008	$ 14,247	$ 14,564	$ 14,963	$ 15,398	$ 15,533	$ 15,807	$ 15,675
Total Vehicle mass reduction	%	5%	9%	7%	14%	10%	17%	13%	22%
		Midsize SUV							
Vehicle Mass Reference	kg	1737							
Non-Powertrain Mass Reference (to be light-weighted)	kg	1246							
Glider Cost Reference (Lab Year 2015)	$	13773							
Glider mass reduction (Lab Year 2015)	%	11%	13.0%	13%	20%	17%	24%	21%	30%
Total Glider Cost	$	$ 16,135	$ 15,555	$ 16,431	$ 16,514	$ 17,316	$ 17,076	$ 17,681	$ 17,148
Total Vehicle mass reduction	%	8%	10.2%	9%	15%	12%	18%	15%	23%
		Pick-Up							
Vehicle Mass Reference	kg	2006							
Non-Powertrain Mass Reference (to be light-weighted)	kg	1388							
Glider Cost Reference (Lab Year 2015)	$	14710							
Glider mass reduction (Lab Year 2015)	%	12%	12%	14%	21%	17%	24%	22%	28%
Total Glider Cost	$	$ 17,438	$ 16,475	$ 18,120	$ 17,901	$ 18,802	$ 18,374	$ 19,224	$ 18,245
Total Vehicle mass reduction	%	8%	8.0%	10%	15%	12%	17.0	15%	20.8

3.7 VEHICLE

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

TABLE 7 Frontal area summary table

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

Table 8 details the drag coefficient of drag reductions for all vehicle classes and performance categories across all laboratory years and technology progresses.

TABLE 8 Rolling resistance 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 9 summarizes the reference drag coefficient assumptions for the different vehicle classes.

TABLE 9 Reference drag coefficient assumptions

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

Table 10 details the drag coefficient of drag reductions for all vehicle classes and performance categories across all laboratory years and technology progresses.

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

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

4 VEHICLE POWERTRAIN SIZING

4.1 VEHICLE TECHNICAL SPECIFICATION (VTS)

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

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

TABLE 11 Vehicle classification and performance categories

Vehicle Class	Performance Category	0–60 mph time (s)
Compact	Base	10
	Premium	8
Midsize	Base	9
	Premium	6
Small SUV	Base	9
	Premium	7
Midsize SUV	Base	10
	Premium	7
Pickup	Base	7
	Premium	7

Additional performance metrics include:

- 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. If we use a battery electric vehicle as an example, increasing the required battery energy would increase the vehicle weight which would then result in an increase in electric machine power. Considering the large number of vehicle to be simulated, several automated sizing algorithms have been used to provide a fair comparison among technologies.

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

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

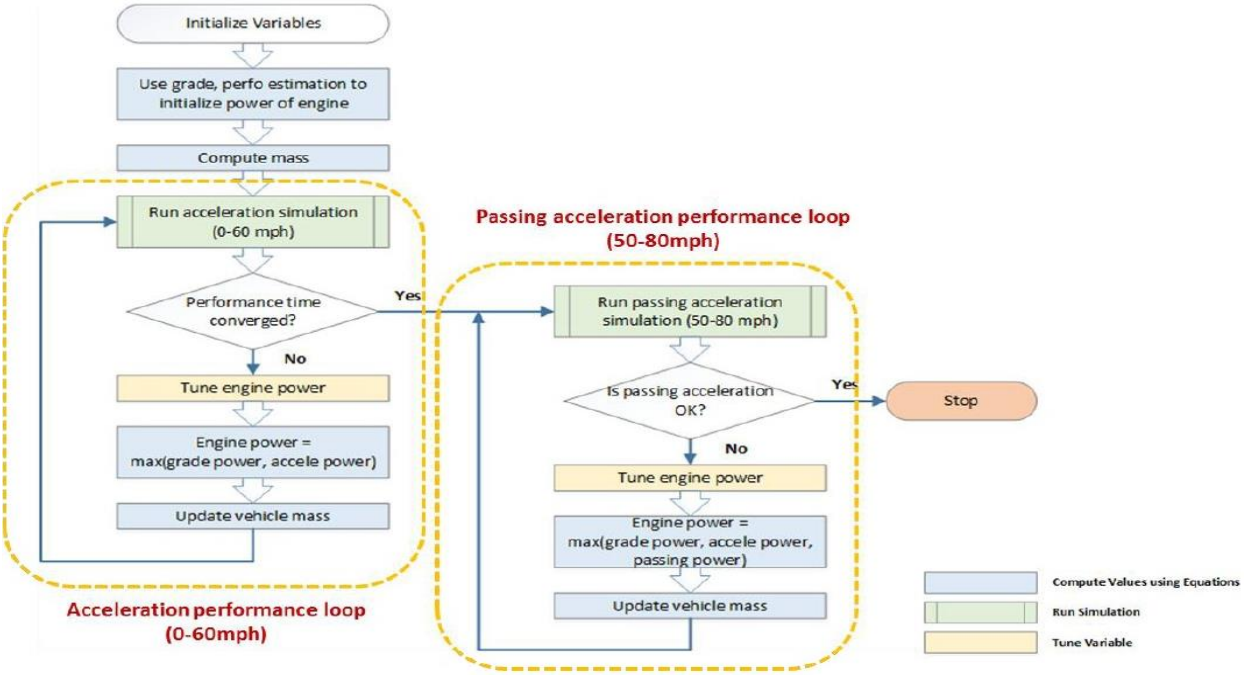


FIGURE 2 Conventional powertrain sizing algorithm

- For HEVs, the electric machine and battery powers are determined to capture all the regenerative energy from a UDDS cycle. The engine and the generator are then sized to meet the gradeability and performance requirements.
- For PHEV20s, the electric machine and battery powers are sized to be able to follow the UDDS cycle in electric-only mode (this control is used only for sizing; a blended approach is used to evaluate consumption). The battery-usable energy is defined to follow the combined drive cycle for 20 mi (adjusted). The engine is then sized to meet both performance and gradeability requirements.
- For PHEV50s, the main electric machine and battery powers are sized to be able to follow the aggressive EPA US06 drive cycle (US06, duty cycle with aggressive highway driving) in electric-only mode. The battery-usable energy is defined to follow the combined drive cycle for 50 mi (adjusted), depending on the requirements. The genset (engine plus generator) or the fuel cell systems are sized to meet the gradeability requirements.

4.3 POWERTRAIN SIZING RESULTS

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

4.3.1 Conventional Powertrain

Figure 3 illustrates the evolution in engine peak power for conventional vehicles across different laboratory years and technology progress cases for the different performance categories. Driven by light weighting and aerodynamic improvements, the engine peak power decreases.

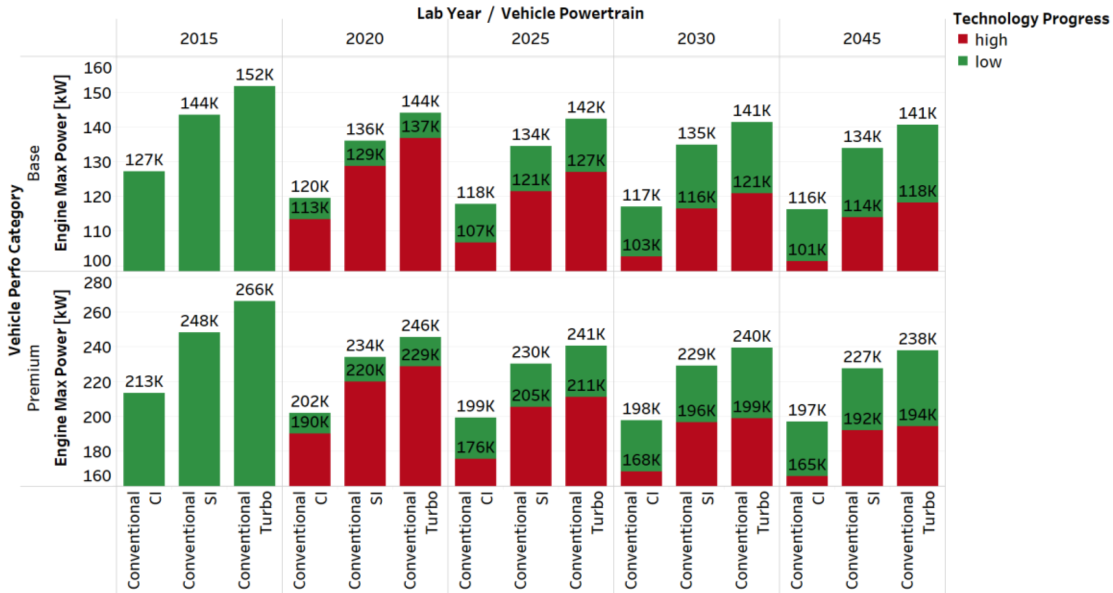


FIGURE 3 Engine maximum power for conventional midsize vehicles

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

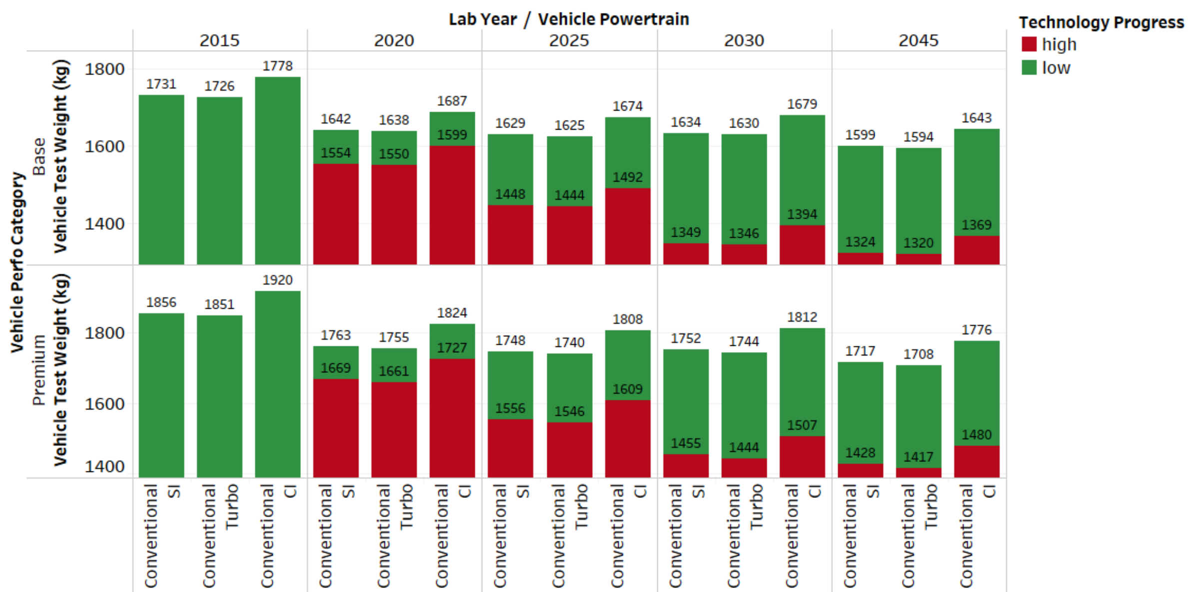


FIGURE 4 Vehicle test weight of conventional midsize vehicles

4.3.2 Power Split HEVs

Figure 5 illustrates the engine peak power for midsize HEVs. The engine power for HEVs is determined by both the performance and gradeability requirements. While performance is the primary factor for current technologies, future lightweighting makes gradeability requirements critical for some cases.

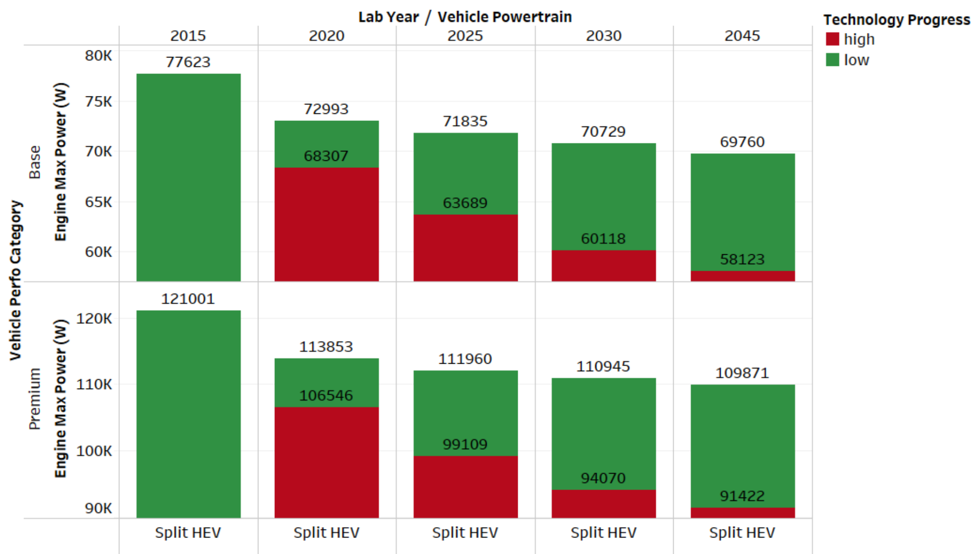


FIGURE 5 Engine peak power for split HEV for conventional powertrains

Figure 6 illustrates the evolution of electric machine peak power for HEVs with different fuel types. Electric machine peak power decreases in the future because of the effects of light weighting. Future light weighting makes the gradeability requirements critical for some cases, and hence the 2030 and 2045 low case contains an electric machine with a higher peak power than the previous years.

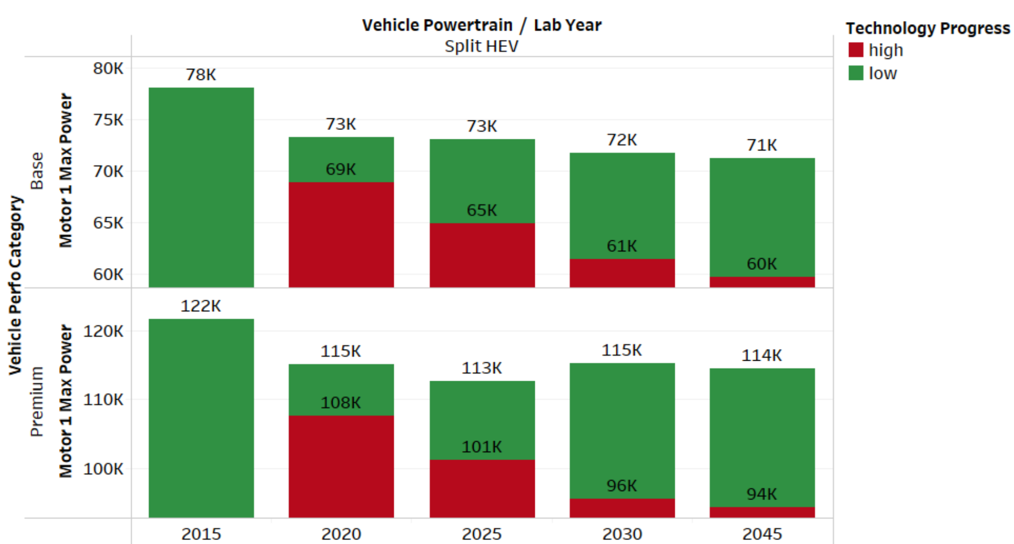


FIGURE 6 Electric machine power for midsize split HEVs

4.3.4 Fuel Cell HEVs

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

FIGURE 7 Fuel cell system power for midsize fuel cell HEVs

4.3.5 Battery Electric Vehicle

Figure 8 shows the electric machine peak power for the different BEVs of midsize vehicle class. Electric machine peak power requirements decrease over time owing to light weighting and assumptions in electric machine efficiency improvements. The decrease ranges between 22% and 38% for a BEV with 200 mi of AER (end-of-life) on combined driving cycle (adjusted) (BEV200), between 24% and 39% for a BEV with 300 mi of AER (end-of-life) on combined driving cycle (adjusted) (BEV300), and between 28% and 44% for a BEV with 400 mi of AER (end-of-life) on combined driving cycle (adjusted) (BEV400).

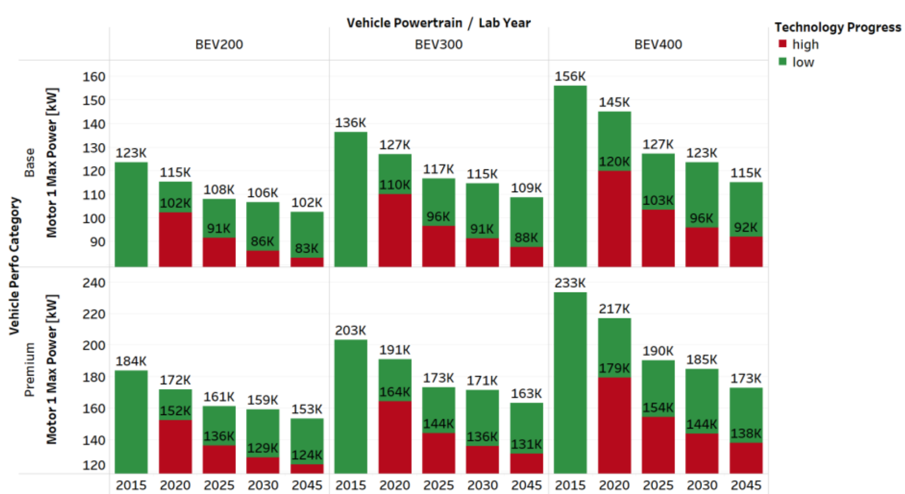


FIGURE 8 Electric machine power for midsize BEVs across powertrains

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

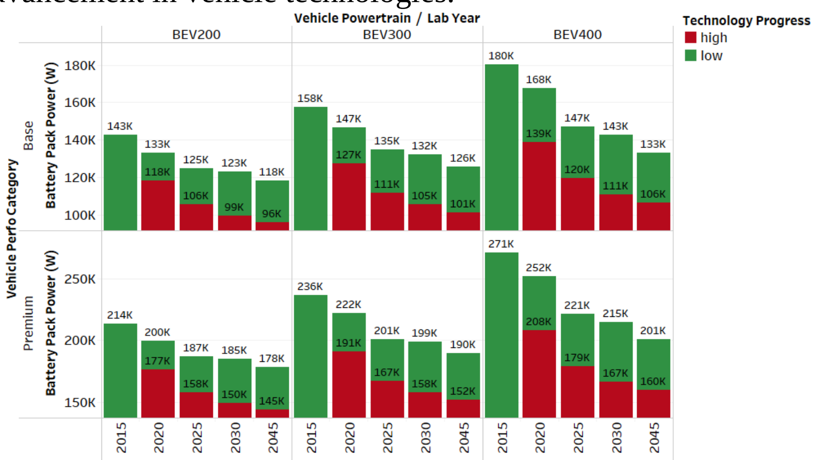


FIGURE 9 Battery pack power for midsize BEVs across powertrains

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

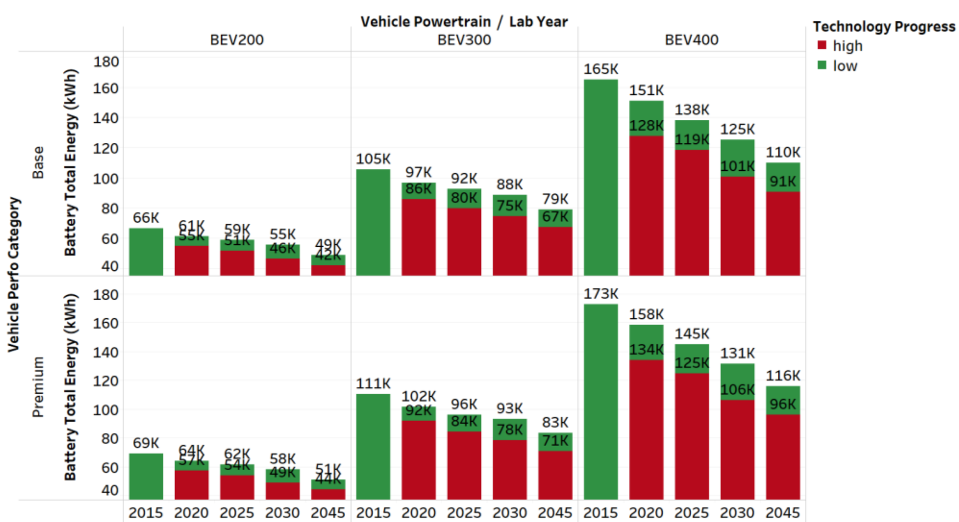


FIGURE 10 Battery pack total energy requirements for midsize BEVs across powertrains

5 ENERGY CONSUMPTION RESULTS

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

5.1 CONVENTIONAL POWERTRAIN

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

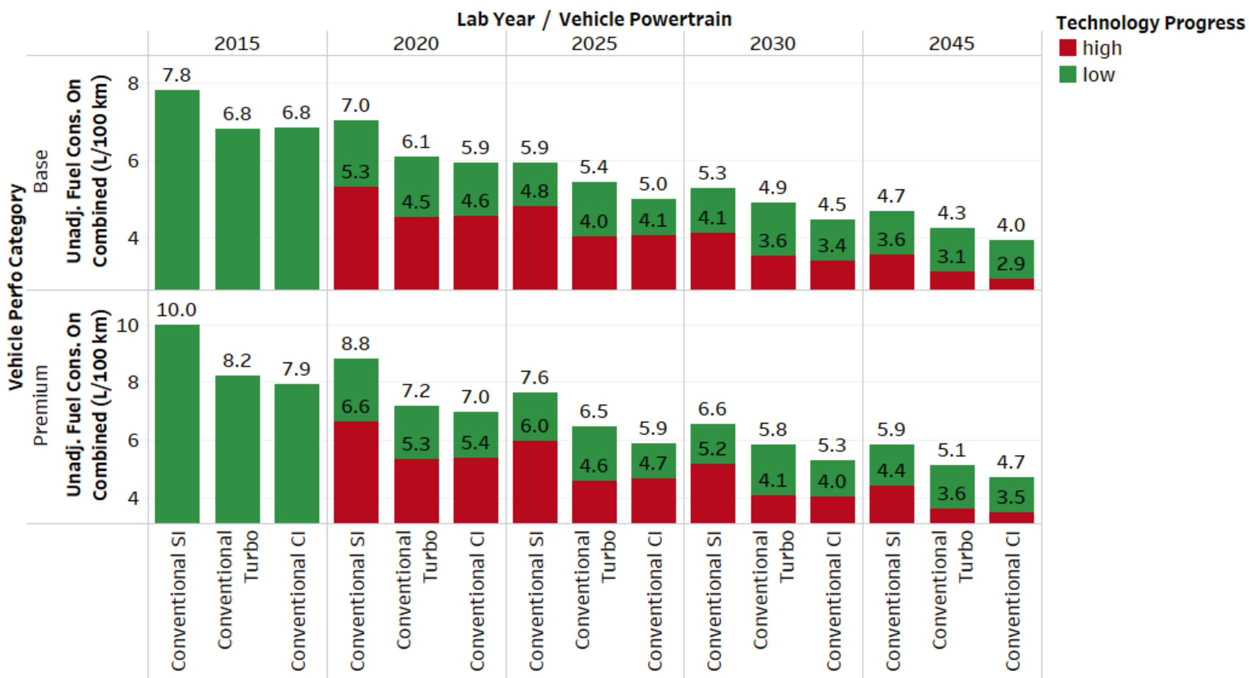


FIGURE 11 Unadjusted fuel consumption for conventional midsize vehicles

The fuel consumption evolution for the midsize mild-hybrid BISG powertrain for different gasoline and diesel fuel types is shown in Figure 12. Fuel consumption decreases over time across fuels. Gasoline conventional vehicles consume from 40% to 54% less fuel by 2045 compared with the reference (2015) laboratory year. Diesel powertrains evolve differently with decreases ranging from 41% to 57% for the base performance category. The improvement varies slightly across the different performance categories.

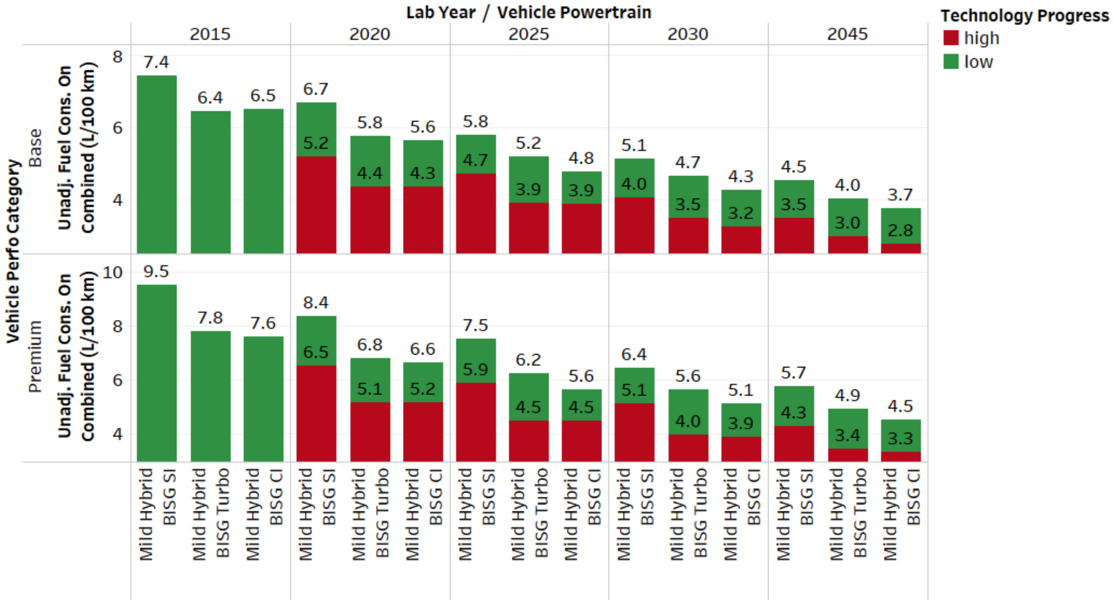


FIGURE 12 Unadjusted fuel consumption for mild-hybrid BISG midsize vehicles

5.2 POWER SPLIT HEVS

The evolution in fuel consumption for the midsize split HEVs is shown in Figure 13. 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 vehicles decreases by 30% to 48% in laboratory year 2045 for the base performance category. The improvement varies slightly across the different performance categories.

FIGURE 13 Unadjusted fuel consumption for midsize power-split HEVs

5.3 FUEL CELL HEVS

The evolution in unadjusted fuel consumption for the fuel cell HEVs is illustrated in Figure 14. Fuel consumption in 2045 is about 37% to 43% lower than the reference case of laboratory year 2015. This decrease is due to the advances in technology and better component efficiencies over time.

FIGURE 14 Unadjusted fuel consumption for midsize fuel cell HEVs

5.4 BATTERY ELECTRIC VEHICLE

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

Figure 15 illustrates the electrical consumption for midsize BEVs. The values, expressed in Wh/mi, represent the average energy provided by the battery to drive the vehicle for 1 mi. The labels low and high represent the technology performance cases. The unadjusted electrical energy consumption in HWFET cycles tends to be consistently higher than that in the UDDS cycles for the corresponding cases. The trend is explained by examining the two drive-cycle curves and the energy that is recoverable by regenerative braking. The UDDS cycle consists of many strong and steep braking periods, which allow a great deal of the energy to be recovered. However, the HWFET cycle consists of stable speeds and limited braking. Hence, the battery recovers more energy through regenerative braking during a UDDS cycle than during a HWFET cycle. HWFET cycles also consist of higher speeds, which affect energy consumption.

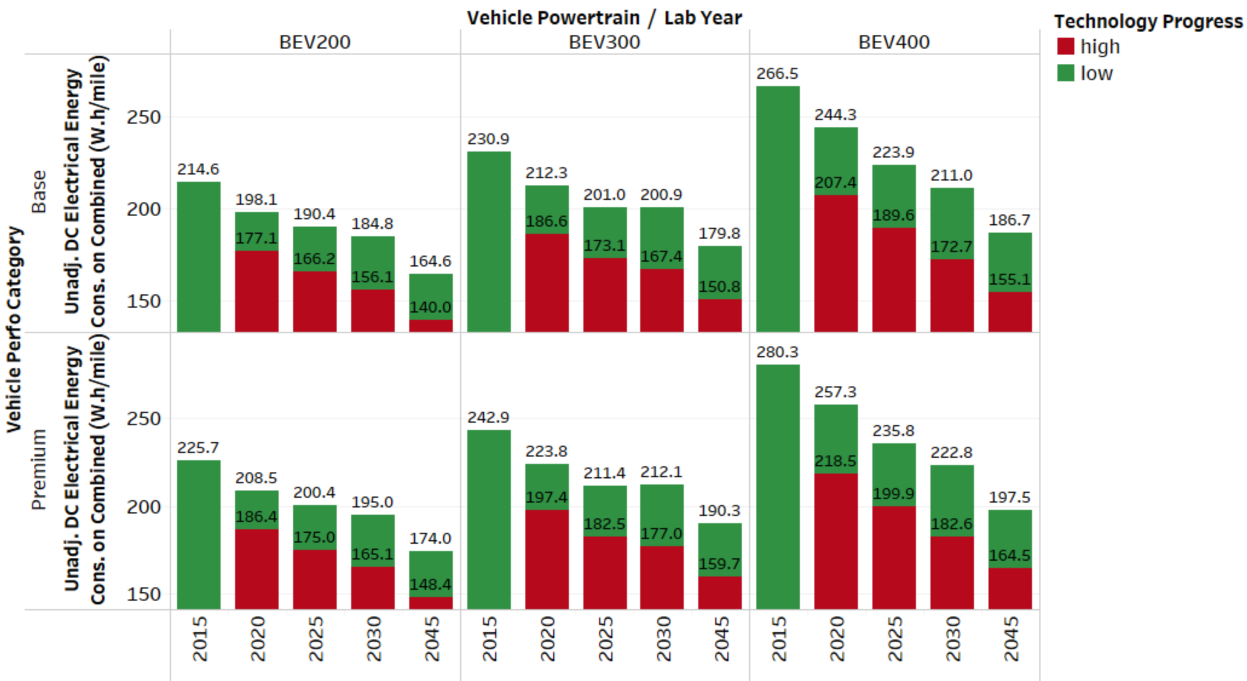


FIGURE 15 Unadjusted electrical energy consumption by midsize BEVs for combined cycle

6 VEHICLE-MANUFACTURING COSTS

In addition to the two levels of technology performance uncertainties, the study computes two levels of technology cost uncertainty cases (low and high). In other words, the technology performance/technology cost uncertainty levels are illustrated according to technology progress cases low (low-technology performance/high-technology cost case) and high (high-technology performance/low-technology cost case). All costs reported in this section are in 2019 U. S. dollars (USD). The cost values in this section represent manufacturing costs, not sale prices.

6.1 CONVENTIONAL

Figure 16 illustrates the manufacturing costs for conventional midsize vehicles. The labels high and low represent the different technology progress uncertainty cases. Vehicle prices increase from laboratory year 2015 to 2030 and then decreases by 2045. The increase in costs compared to the reference 2015 laboratory year can be explained by several factors including cost of lightweighting—the decrease in vehicle weight is accompanied by an increase in material cost brought about by escalating use of aluminum or carbon fiber and advanced component technologies. The difference in manufacturing costs between the diesel and gasoline vehicles can be explained by the differences in engine cost—diesel engine costs are much higher than gasoline vehicle engine costs, driving the difference in manufacturing costs.

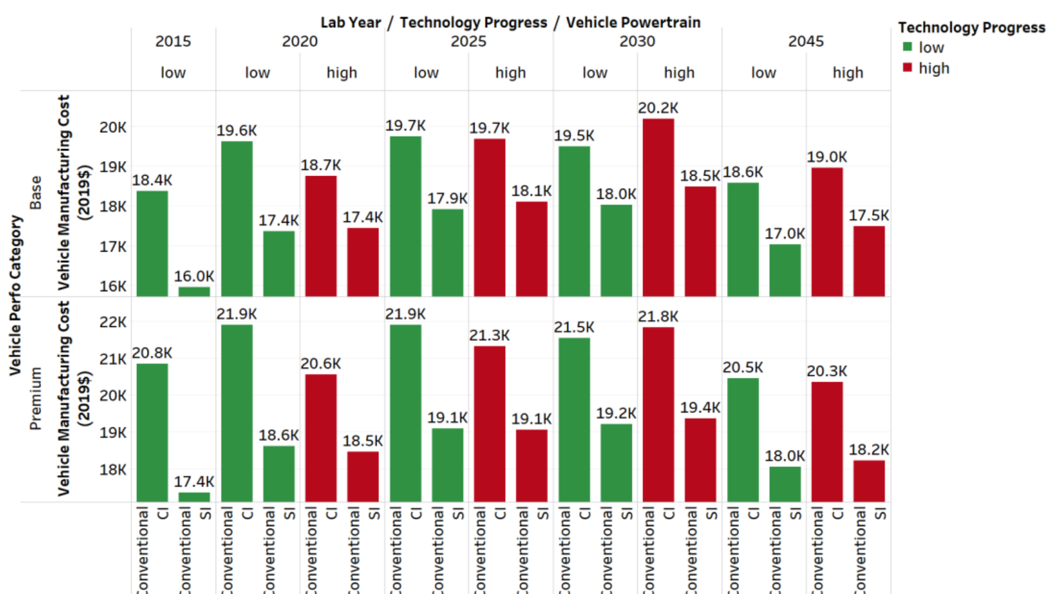


FIGURE 16 Manufacturing cost (2019 USD) of conventional vehicles

6.2 POWER SPLIT HEVS

Figure 17 shows the vehicle-manufacturing costs for power-split HEVs. Over time, manufacturing costs decrease for power-split HEVs because energy storage and electric machine costs decrease in the future. Although the glider cost increases over time, the overall effect on the manufacturing cost follows a downward trend. Similar to the explanation for the trend observed for conventional vehicles, the gasoline power-split HEVs are cheaper than the corresponding diesel HEVs.

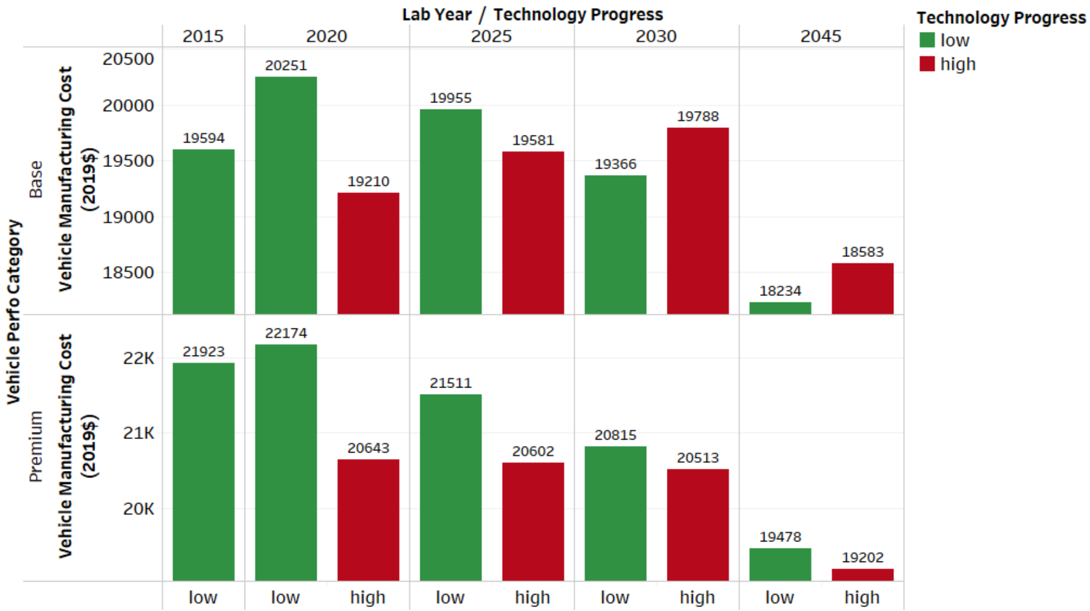


FIGURE 17 Manufacturing cost of midsize power-split HEVs

6.3 FUEL CELL HEVS

Manufacturing costs of fuel cell vehicles follow similar trends, as shown in Figure 18. Over time, the difference in manufacturing costs decreases. Compared to laboratory year 2015, the manufacturing cost of midsize vehicle is assumed to decrease by 10% to 15% by laboratory year 2045. It is important to note that these estimates assume that fuel cells are manufactured at economies of scale in all years. This assumption was made for consistency with assumptions being made in other powertrains. However, fuel cells are not currently manufactured at high volume. As a result, the manufacturing costs and retail prices of fuel cell vehicles today are substantially higher than those in the projections below.

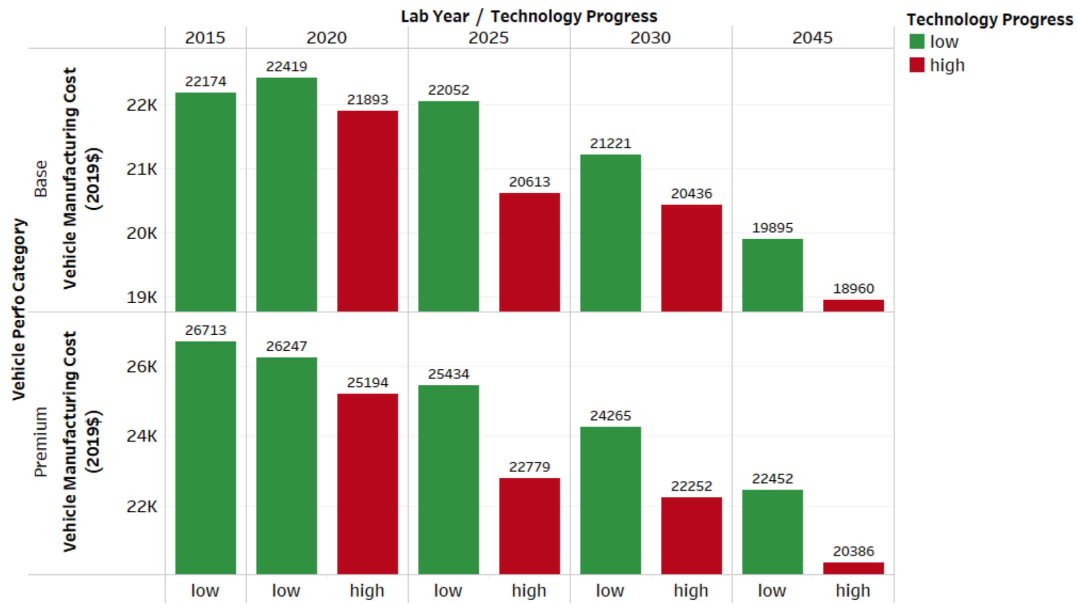


FIGURE 18 Manufacturing cost of midsize fuel cell vehicles

6.4 BATTERY ELECTRIC VEHICLE

Figure 19 illustrates the evolution of BEVs in terms of manufacturing cost. Lightweighting has an effect on battery sizes and hence decreases battery costs in future years. Battery size in turn affects the major manufacturing cost of BEVs. Higher range BEVs have a greater impact on manufacturing costs in future years.

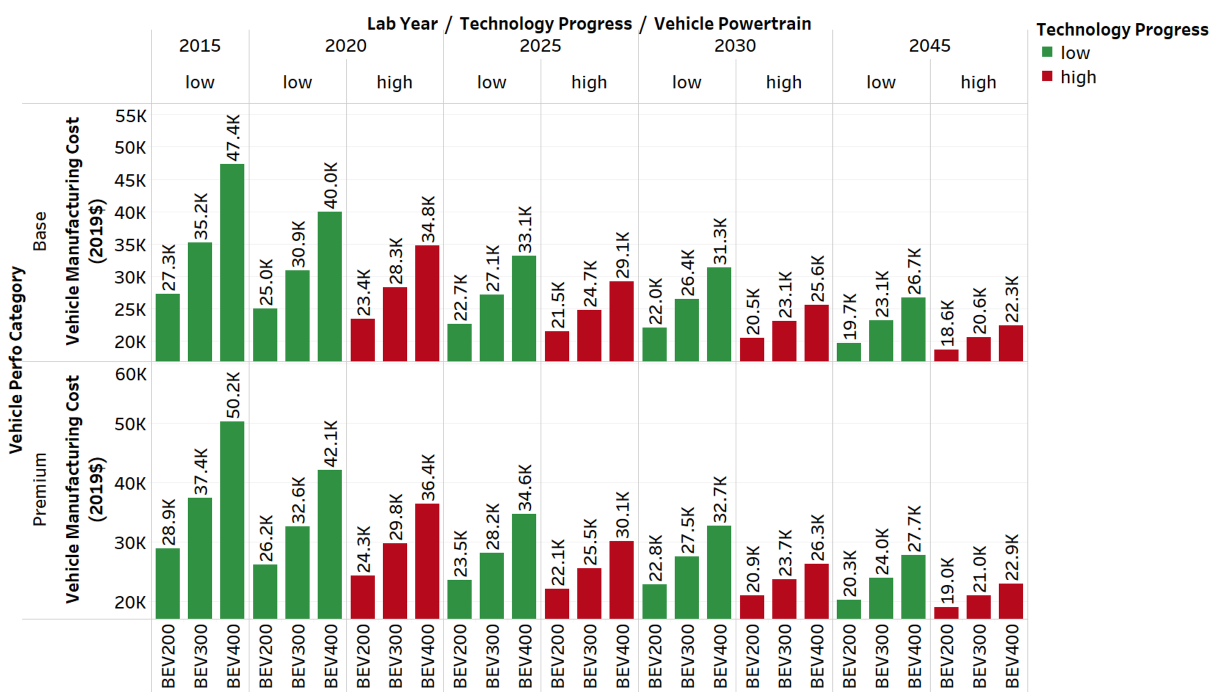


FIGURE 19 Manufacturing cost of midsize BEVs

7 VEHICLE FUEL CONSUMPTION VERSUS VEHICLE-MANUFACTURING COSTS

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

7.1 CONVENTIONAL VEHICLES

Figure 20 illustrates the comparison of vehicle-manufacturing cost versus fuel consumption for conventional vehicles across multiple vehicle classes. The different colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different vehicle classes. A key observation is that diesel vehicles have relatively higher manufacturing costs than gasoline vehicles. In addition, the figure shows the relative position of the different vehicle classes in terms of fuel consumption and manufacturing costs: midsize vehicles, small SUVs, and midsize SUVs cluster closely to each other, while compact and pickup classes lie on the two extremes. The trend line in the plot also confirms this observation.

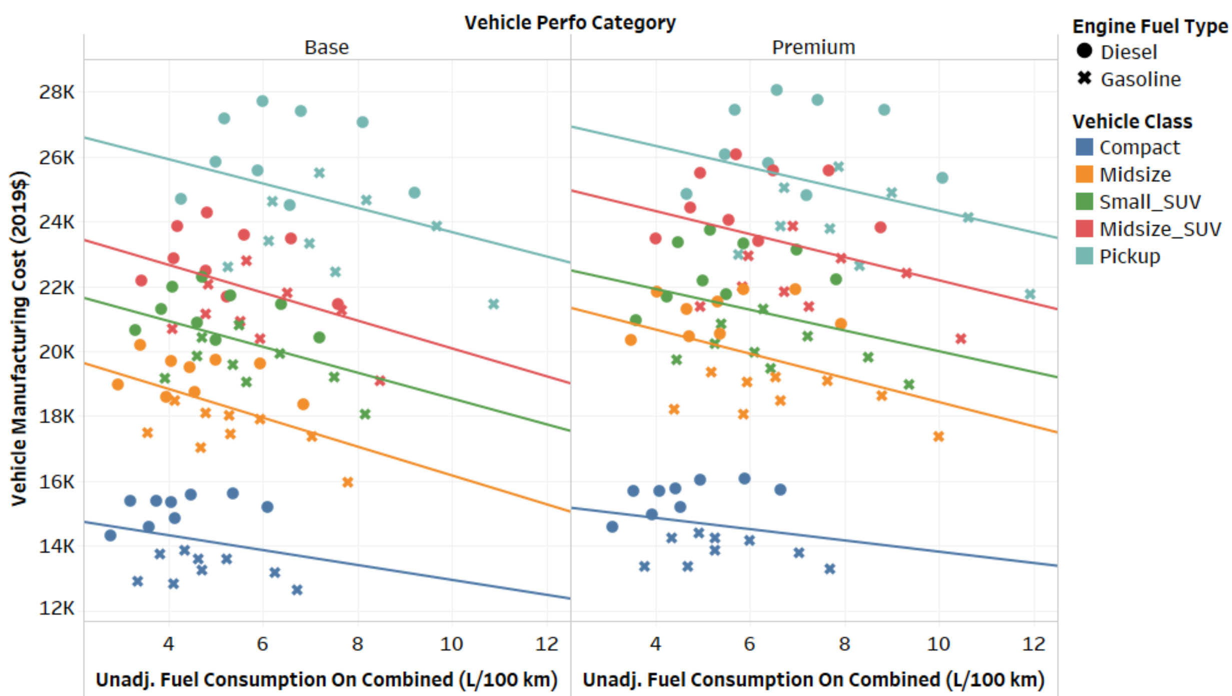
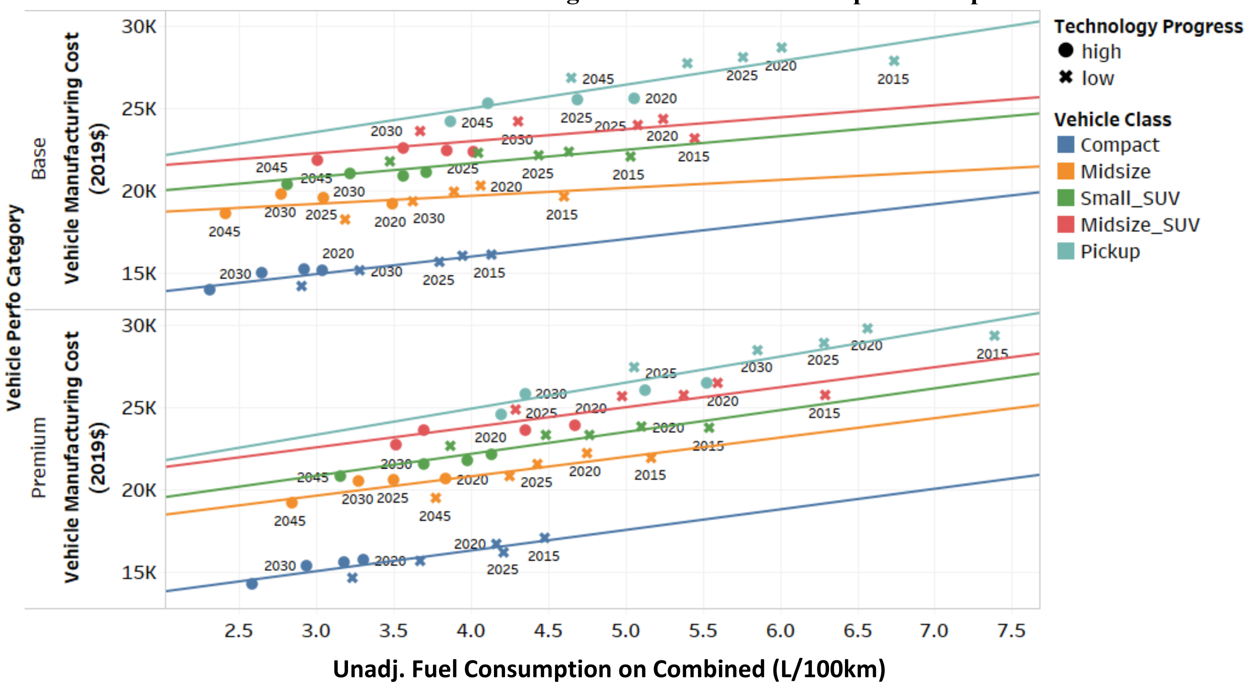


FIGURE 20 Vehicle-manufacturing cost versus fuel consumption for conventional vehicles

7.2 POWER SPLIT HEVS

Figure 21 shows the comparison of vehicle-manufacturing cost versus fuel consumption for split HEVs across multiple vehicle classes. The different colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different vehicle classes. The effect of the different vehicle classes on fuel consumption and manufacturing cost is similar to that observed earlier. The figure further shows how the fuel consumption and manufacturing costs progress across the different laboratory years. As shown by the trend lines, over time, both fuel consumption and manufacturing costs decrease. As discussed earlier, these decreases are a result of the drop in battery and electric machine costs, which play a dominant role in manufacturing cost. The trend line also confirms the clustering.

FIGURE 21 Vehicle-manufacturing cost versus fuel consumption for split HEVs



7.3 FUEL CELL HEVS

Figure 22 compares vehicle-manufacturing cost and fuel consumption for fuel cell HEVs across multiple vehicle classes. The different colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different vehicle classes. As shown by the trend lines, over time, both fuel consumption and manufacturing costs decrease. These decreases are a result of the drop in fuel cell and electric machine costs, which play a dominant role in manufacturing costs. The trend lines also confirms the clustering of the different vehicle classes.

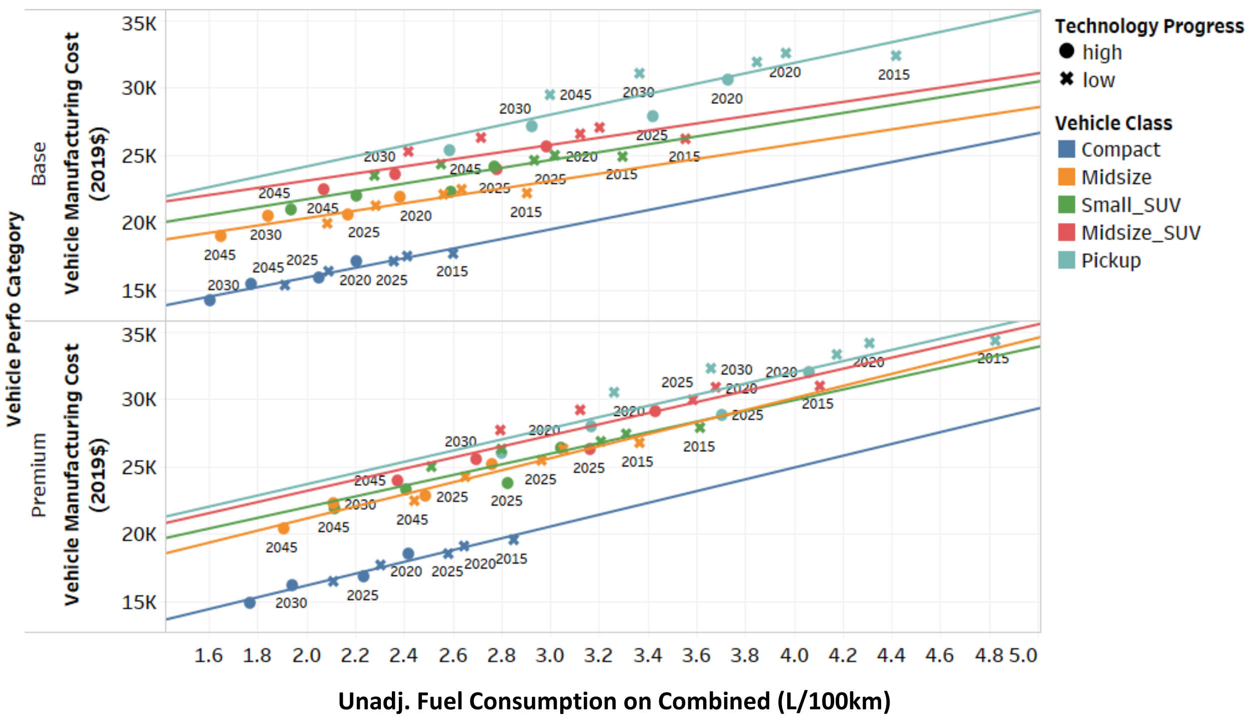


FIGURE 22 Vehicle-manufacturing cost versus fuel consumption for fuel cell HEVs

7.4 BATTERY ELECTRIC VEHICLE

Figure 23 compares vehicle-manufacturing cost and gasoline-equivalent fuel consumption for BEVs across multiple vehicle classes. The different colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different vehicle classes. The different vehicle classes follow trends similar to those previously discussed. As AER increases, manufacturing cost increases (owing to bigger battery sizes) and fuel consumption decreases. The effect of technological improvements over the years can be seen in the reduction in fuel consumption and manufacturing cost from laboratory year 2015 to 2045. Furthermore, the trend lines show an aggressive decline in manufacturing costs with respect to improved fuel consumption for BEVs with higher AERs. This cost decrease can be explained by the improvement in component specifications followed by the decrease in battery costs over time.

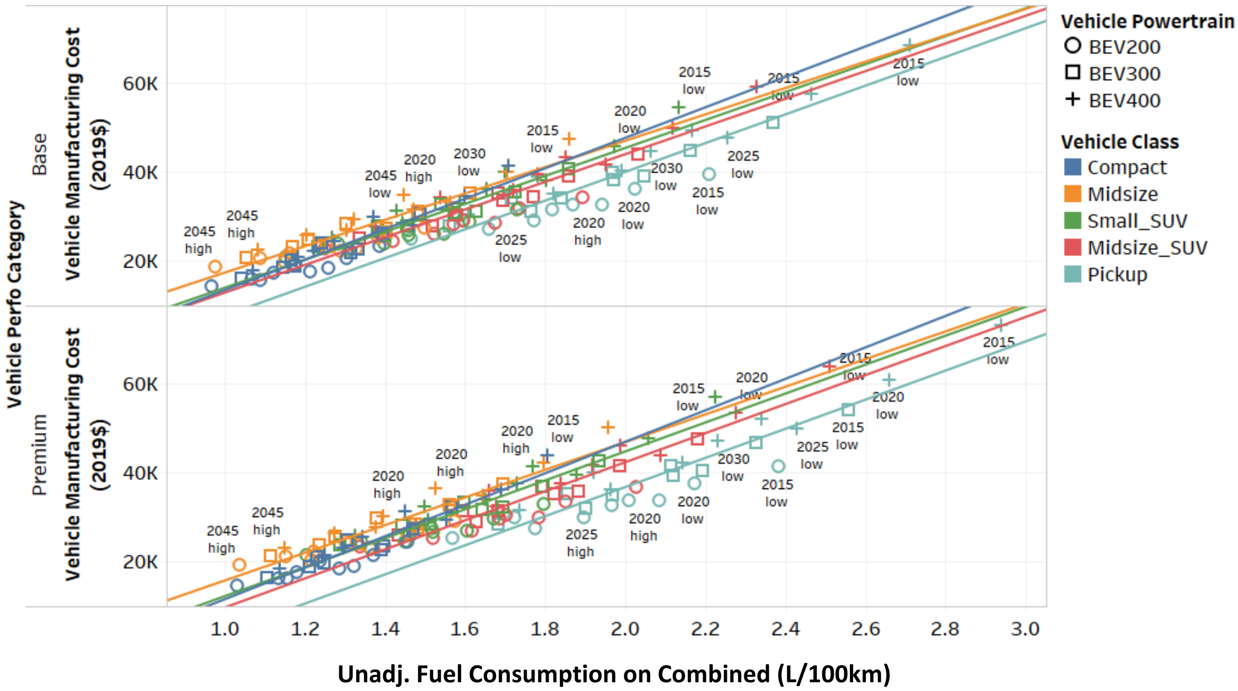


FIGURE 23 Vehicle-manufacturing cost versus fuel consumption for BEVs

8 CONCLUSION

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 and energy consumption estimates were estimated for 10 vehicle classes, five different powertrains, and six time frames with upper and lower limits for two technology progress scenarios. Detailed results are reported in the complementary Excel worksheets.

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

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