33rd Electric Vehicle Symposium (EVS33)
Portland, Oregon, June 14-17, 2020

Impact of U.S. DOE R&D on Light Duty Electrified Vehicles Efficiency and Cost

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Summary

The U.S. Department of Energy's (DOE) Vehicle Technologies Office (VTO) supports research, development (R&D), and deployment of efficient and sustainable transportation technologies that will improve energy efficiency, fuel economy, and enable America to use less petroleum. To accelerate the development and adoption of new technologies, VTO has developed specific targets for a wide range of powertrain technologies (e.g., engine, battery, electric machine, lightweighting, etc.). The objective of the paper is to quantify the impact of VTO R&D on vehicle energy consumption and cost compared to expected historical improvements across vehicle classes, powertrains, component technologies and timeframes. A large scale simulation process was used to develop and simulate tens of thousands of vehicles on US standard driving cycles using Autonomie. Results demonstrate significant additional reduction in both cost and energy consumption due to VTO R&D targets compared to historical predicted trends.

Keywords: BEV (battery electric vehicle), energy consumption, HEV (hybrid electric vehicle), PHEV (plug in hybrid electric vehicle), simulation

1 Introduction

The impact of advances in powertrain technology is evaluated using a fuel consumption (or fuel economy or CO_2 g/mile) metric on standard regulatory drive cycles [1]. Such advances include advances in engine, battery, vehicle electrification and material (light weighting). System simulation of vehicle models incorporating the technology advancements is an accepted approach to evaluate the fuel economy potential of such advanced technologies [2].

Vehicle Technologies Office, U.S. Department of Energy (U.S. DOE) generates the advancements in technology and cost targets for engines, transmissions, batteries, fuel cell technologies, vehicle electrification, light weighting, etc. over a given time frame [3]. The Vehicle System Simulation tool Autonomie [5] is used to perform simulation on vehicle models that incorporate baseline and advanced vehicle technology targets as generated by U.S. DOE. The vehicle models used for the simulation include conventional, hybrid (HEV), plug-in hybrid (PHEV) and battery-electric vehicles (BEVs) of different all-electric range (AER). The advancements in technologies are generally evaluated over standard regulatory driving cycles, for fuel economy and cost impact.

2 Procedure

The different vehicle technology targets set by the U.S. DOE-VTO are used to build the assumptions that are evaluated over a range of timeframes. This paper will cover the results from 2015, 2020, 2025, 2030, and 2045 ”lab years”, which correspond to ”model year - 5 years”. For example, a lab year 2015 vehicle would reflect a vehicle that is available in the market in 2020, and similarly, a 2045 lab year vehicle would imply a vehicle that is available in the market in 2050.

The following subsections represent the breakdown involved during the vehicle simulation. The latest report from Argonne [4] details the assumptions and procedure involved behind the vehicle modeling and simulation efforts.

3 Vehicle and Component Assumptions

This section details the different vehicle classifications and some of the major vehicle attribute selection used in the study.

Table 1 details the different vehicle classifications defined for various performance times (0-60 mph time) in seconds as well as corresponding vehicle attributes.

Table 1: Vehicle classification, performance categories and characteristics

Vehicle Class	**Performance Category**	**0-60 mph time (s)**	**Frontal Area (m^2)**	**Drag Coefficient**	**Rolling Resistance**
Compact	Base (NonPerfo)	10	2.3	0.31	0.009
Compact	Premium (Perfo)	8	2.3	0.31	0.009
Midsize	Base (NonPerfo)	9	2.35	0.3	0.009
Midsize	Premium (Perfo)	6	2.35	0.3	0.009
Small SUV	Base (NonPerfo)	9	2.65	0.36	0.009
Small SUV	Premium (Perfo)	7	2.65	0.36	0.009
Midsize SUV	Base (NonPerfo)	10	2.85	0.38	0.009
Midsize SUV	Premium (Perfo)	7	2.85	0.38	0.009
Pickup	Base (NonPerfo)	7	3.25	0.42	0.009
Pickup	Premium (Perfo)	7	3.25	0.42	0.009

Table 2 below summarizes the main target assumptions associated with the different technologies over time. The vehicle simulations (and results to follow) represent the ”lab years” 2015, 2020, 2025, 2030, and 2045 but the assumption values from years 2015, 2020, 2025 and 2045 have been provided in the table for simplicity.

Table 2: Technology Assumptions

	2015	2020		2025		2045	
	Low	Low	High	Low	High	Low	High
Conventional Engine Peak Efficiency (%)	36	38	43	40	43	44	47
Hybrid Engine Efficiency (%)	39	40	46	41	46	45	50
Electric Machine Cost ($\$/kW$)	17	13	10	10	6	6.3	4
Specific Power @ 70% SOC - HEVs (W/kg)	2750	3000	4000	4000	5000	5000	6000
Power Cost Term - HEVs ($\$/W$)	20	20	16	19	15	17	13
Energy Density (USABLE) - PHEV20 (Wh/kg)	60	80	100	105	125	115	170
Energy Density (USABLE) - PHEV50 (Wh/kg)	70	95	105	105	125	115	170
Energy Density (USABLE) - BEV (Wh/kg)	170	170	230	230	310	280	320
Energy Cost Term (USABLE) - PHEV20 ($\$/kWh$)	530	460	300	210	160	160	120
Energy Cost Term (USABLE) - PHEV50 ($\$/kWh$)	500	365	300	210	160	160	120
Energy Cost Term (USABLE) - BEV ($\$/kWh$)	220	180	170	144	125	120	80

4 Results & Observations

4.1 Component Sizes

Engine Power Figure 1 shows the engine peak power for midsize vehicles across the different electrified powertrains for different performance categories.

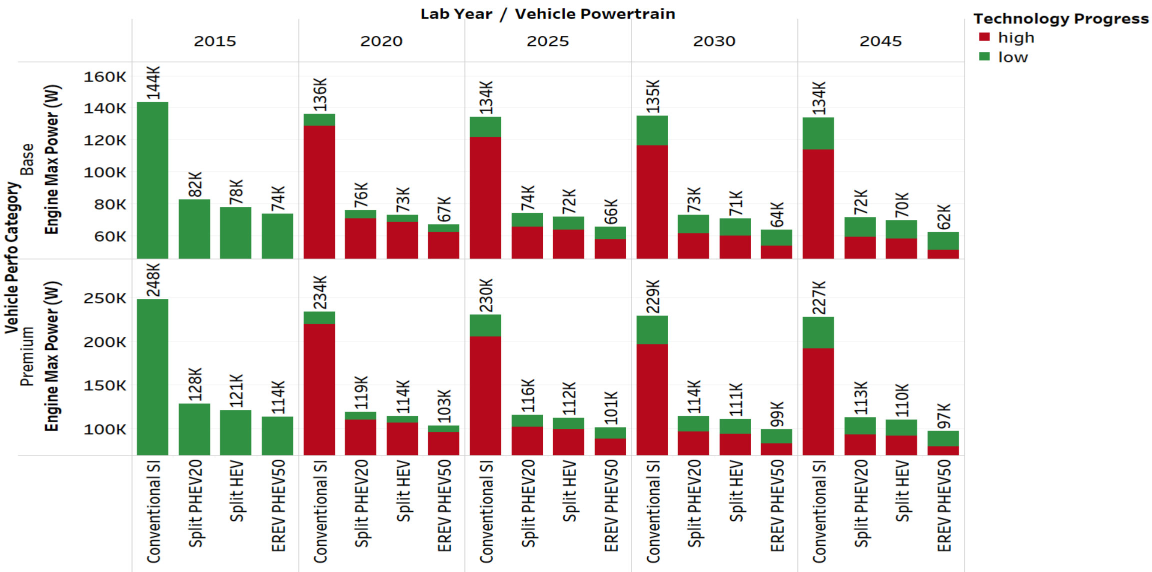


Figure 1: Engine Peak Power for Midsize vehicles

It can be observed that over time, the engine peak power decreases across the different powertrains. The effects of vehicle lightweighting with time primarily explains the trend observed. The more aggressive performance targets set for the premium category can explain the difference observed between the base and premium categories.

Motor Power Figure 2 shows the motor peak power for midsize vehicles across the different electrified powertrains for different performance category.

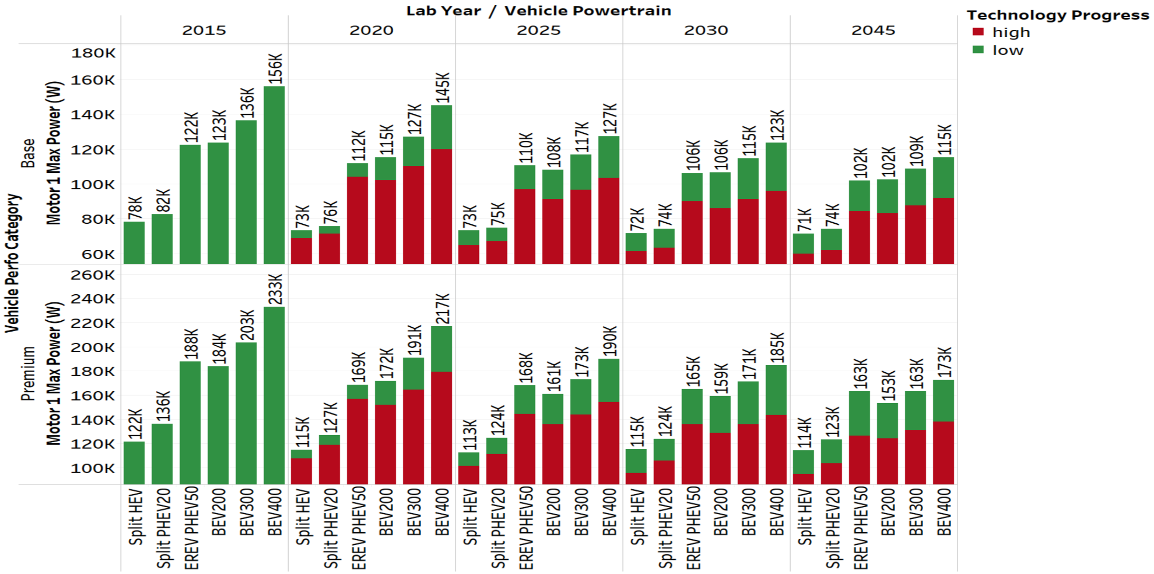


Figure 2: Motor Peak Power (W) for Midsize vehicles

Similar to what is observed for the engine power, the motor power also decreases across the different powertrains in the future years. Vehicle lightweighting along with other aggressive targets for different components weights (electric machine, battery, etc.) significantly contribute to the motor downsizing.

Battery Power Figure 4 shows the battery peak power for midsize vehicles across the different electrified powertrains for different performance category.

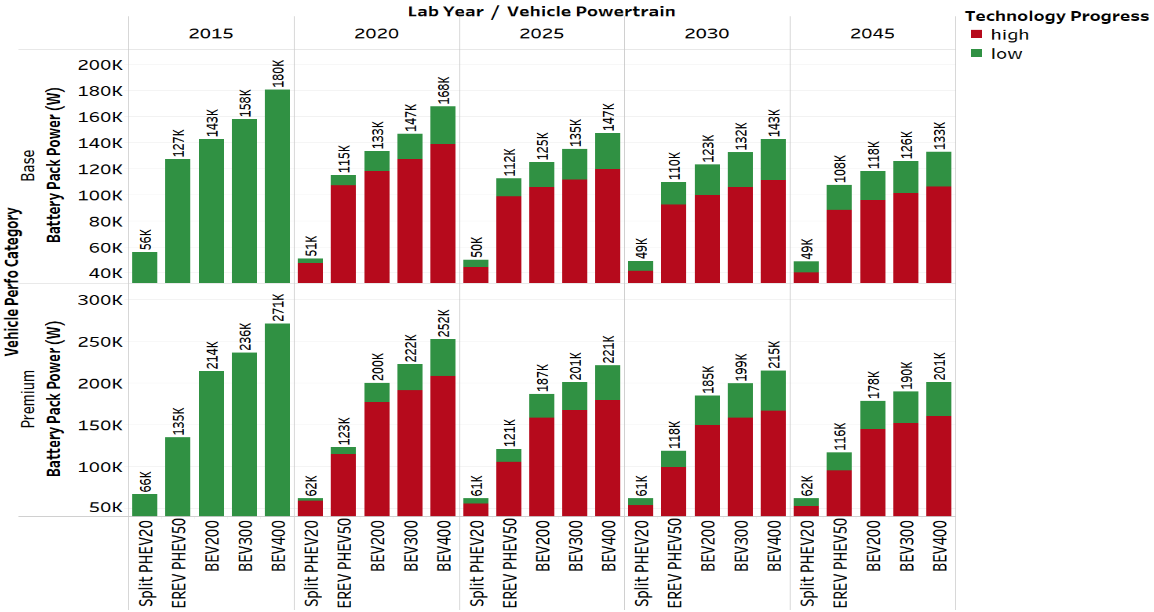


Figure 3: Battery Peak Power (W) for Midsize vehicles

The battery total power requirement decreases overtime across the different powertrains. The battery power also increases with increasing AERs. The significant difference in battery power from 20AER to 50AER (and beyond) is explained by the more aggressive US06 cycle that 50AER (and beyond) is sized on in EV mode compared to UDDS for 20AER.

Battery Total Energy Figure 4 shows the battery total energy for midsize vehicles across the different electrified powertrains for different performance category.

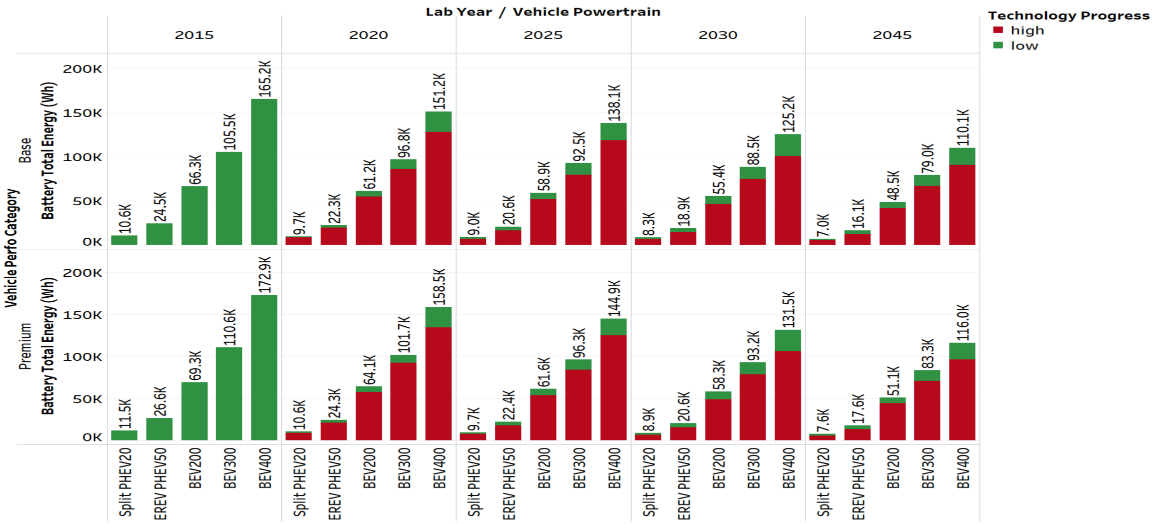


Figure 4: Battery total energy for midsize vehicles

4.2 Energy Consumption

Figure 5 shows the unadjusted fuel economy of midsize vehicles across the different powertrains of different performance categories.

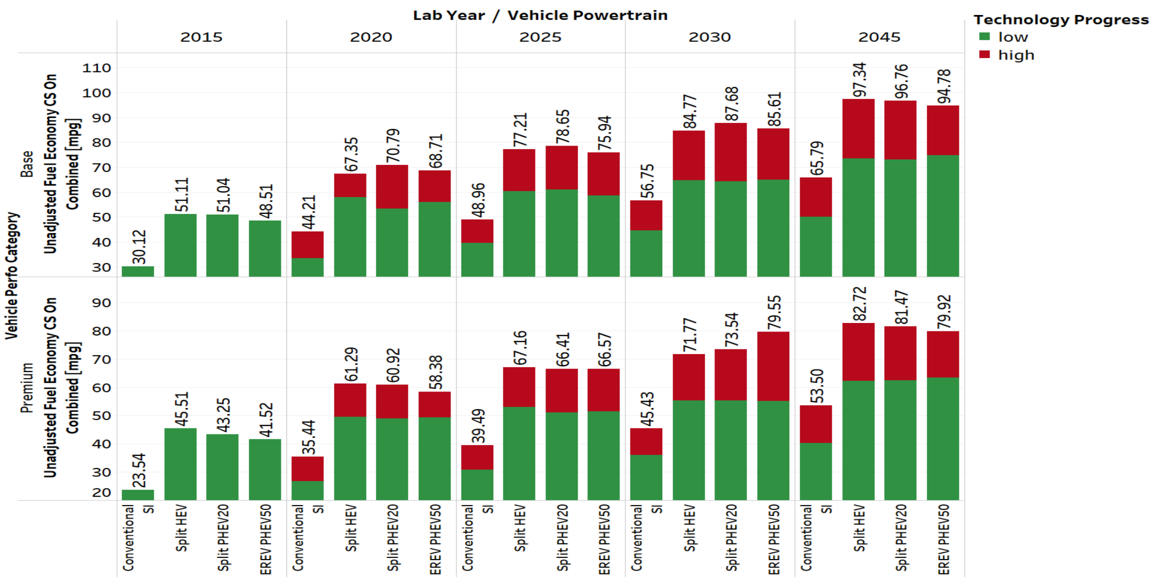


Figure 5: Unadjusted fuel economy on combined for midsize vehicles

The fuel economy of the different powertrains increases over time. The effect of the increments varies across the different electrified powertrains, owing to the varying component efficiency targets. The higher vehicle weight contributed from the higher components weights explains difference in the fuel economy observed for the premium category compared to the base category. Figure 6 shows the unadjusted electrical energy consumption (utility-weighted for PHEVs) of midsize electrified vehicles for different performance category.

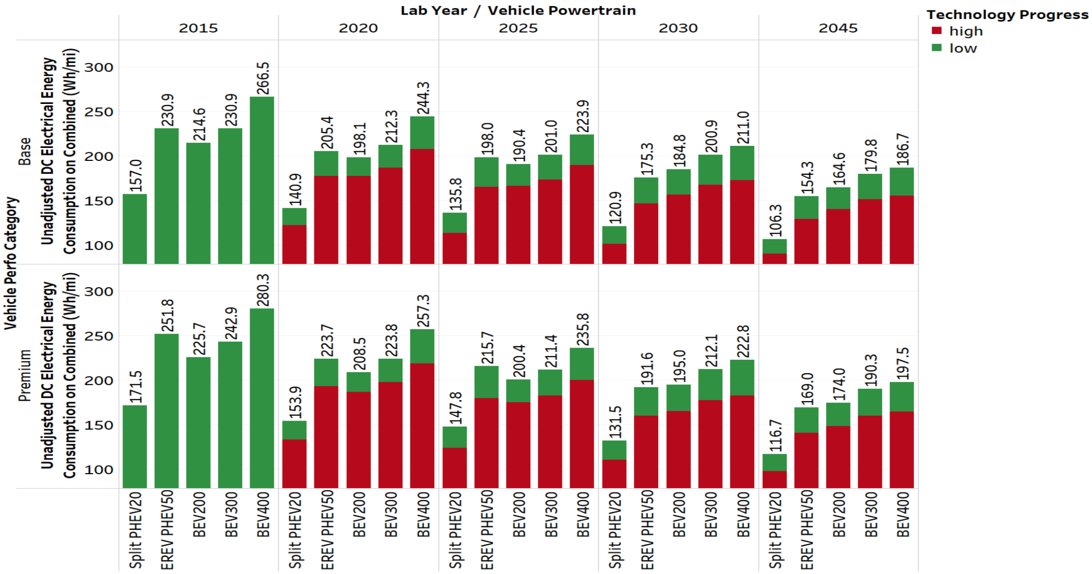


Figure 6: Unadjusted DC Electrical Energy Consumption on Combined (Wh/mile) for midsize vehicles

Over time, the electrical energy consumption decreases for the different electrified powertrains. The range of reduction varies for the different AERs as well as the different performance categories.

5 Cost Analysis

5.1 Component Cost

Figure 7 shows the motor cost for electrified powertrains for midsize vehicles across the different performance categories.

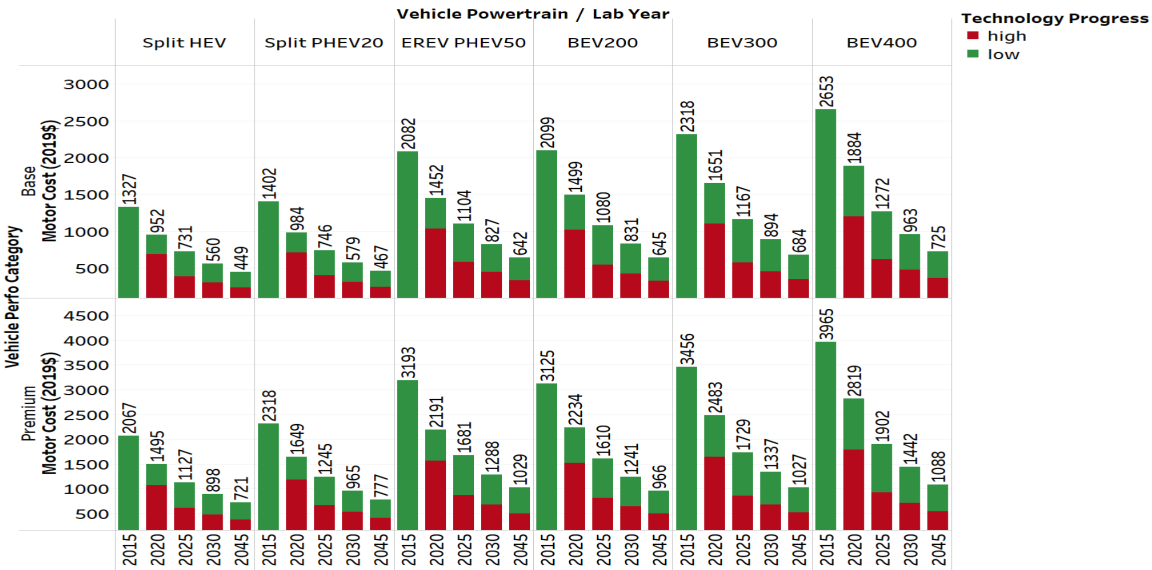


Figure 7: Motor cost of Midsize vehicles

Figure 8 shows the battery cost for electrified powertrains for midsize vehicles across the different performance categories.

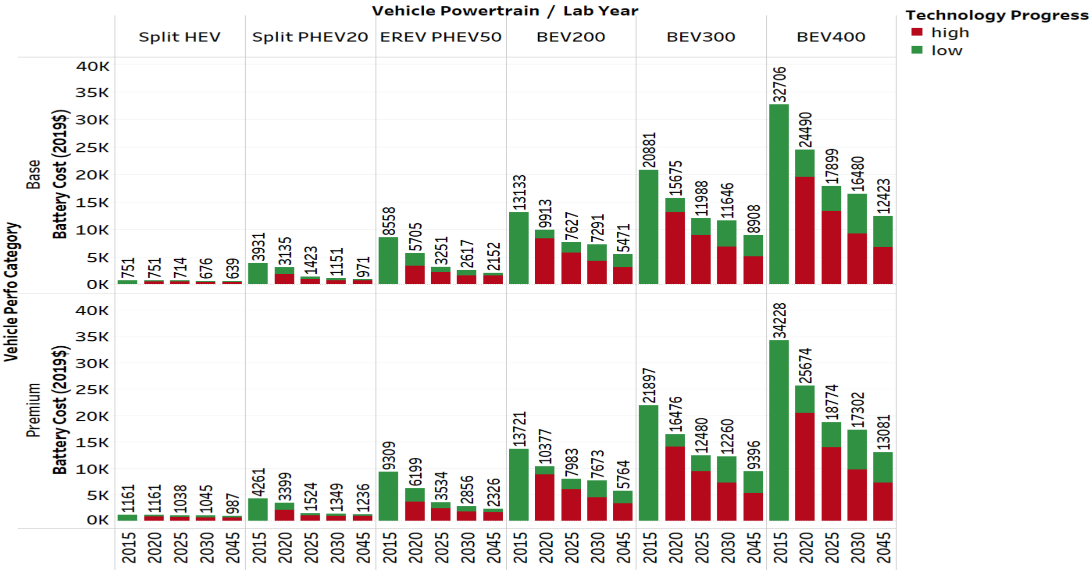


Figure 8: Battery cost of Midsize vehicles

5.2 Manufacturing Cost

Figure 9 illustrates the manufacturing costs for the different powertrains considered in this analysis for midsize vehicle class. The illustration further reflects the effect in manufacturing cost across the two performance categories considered.

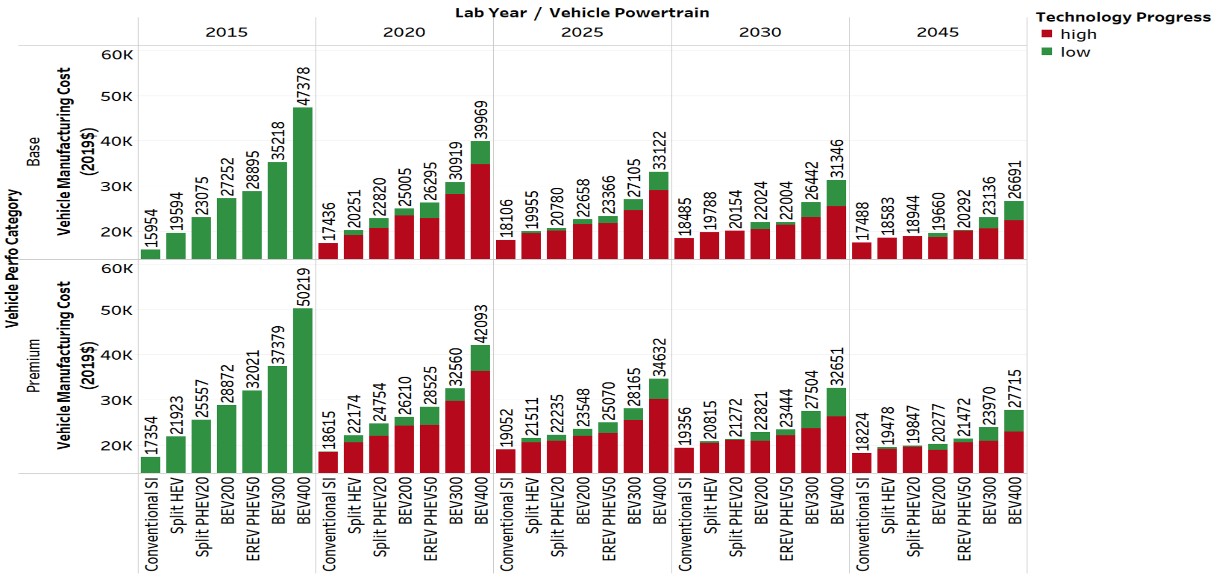


Figure 9: Manufacturing cost of midsize vehicles

6 Energy Consumption vs. Vehicle Manufacturing Cost

This section discusses the evolution of fuel consumption (due to linearity) with respect to vehicle manufacturing cost for the different vehicle powertrains modeled across the 5 vehicle classes.

Conventional Figure 10 illustrates the comparison of vehicle manufacturing cost vs. fuel consumption for the covnentional vehicles across multiple vehicle classes. The different colored lines represent the trend lines of vehicle manufacturing cost vs. fuel consumption for different vehicle classes.

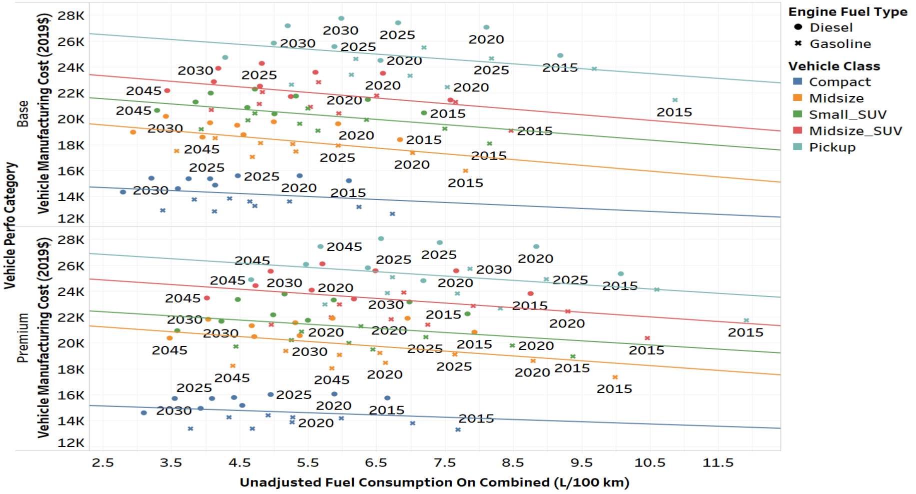


Figure 10: Manufacturing cost vs. fuel consumption of conventional vehicles

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

Split HEV Figure 11 illustrates the comparison of vehicle manufacturing cost vs. fuel consumption for the split HEVs across multiple vehicle classes.

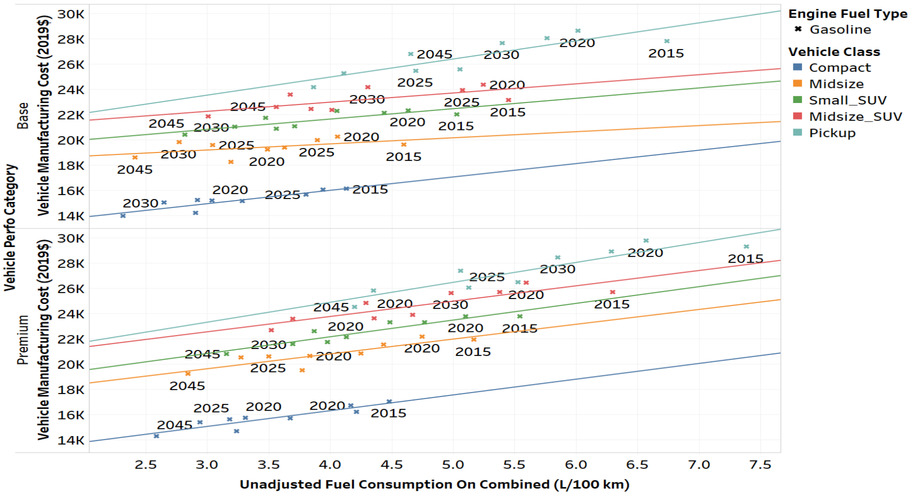


Figure 11: Manufacturing cost vs. fuel consumption of split HEVs

The figure 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.

Split/EREV PHEV Figure 12 illustrates the comparison of vehicle manufacturing cost vs. fuel consumption for the PHEVs across multiple vehicle classes.

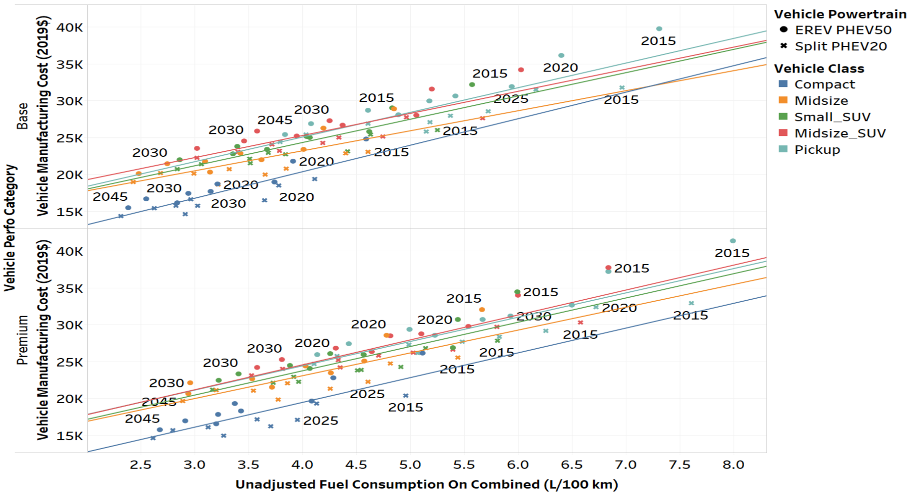


Figure 12: Manufacturing cost vs. fuel consumption of PHEVs

The different colored lines represent the trend lines of vehicle-manufacturing cost versus fuel consumption for different types of PHEVs. 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 fall in manufacturing costs with respect to improved fuel consumption for PHEVs with higher AERs. This cost decrease can be explained by the improvement in component specifications followed by the decrease in battery costs over time.

BEV Figure 13 illustrates the comparison of vehicle manufacturing cost vs. electrical energy consumption for the BEVs across multiple vehicle classes.

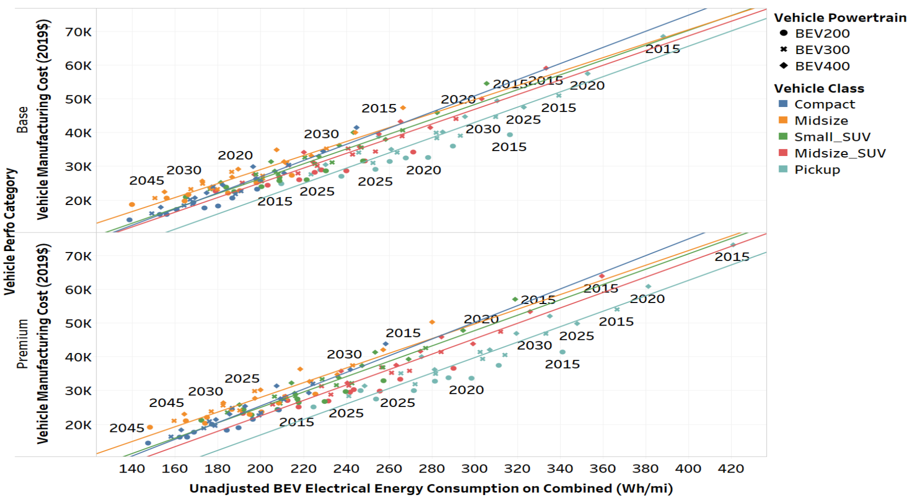
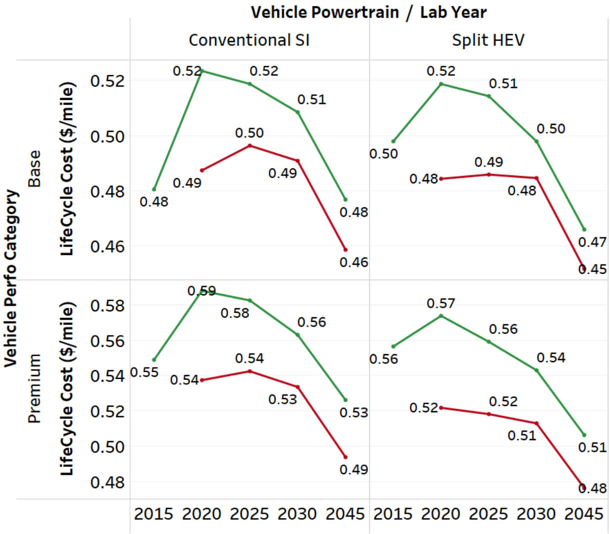


Figure 13: Manufacturing cost vs. electrical energy consumption of BEVs

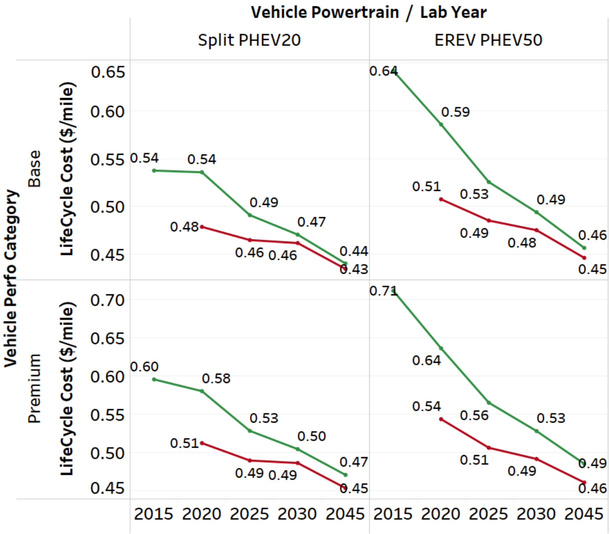
It can be observed that as AER increases, manufacturing cost increases (owing to bigger battery sizes) and fuel consumption decreases. The effect of technological improvements over the years can be seen in the reduction in fuel consumption and manufacturing cost from laboratory year 2015 to 2045. Furthermore, 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.

7 Levelized Cost of Driving

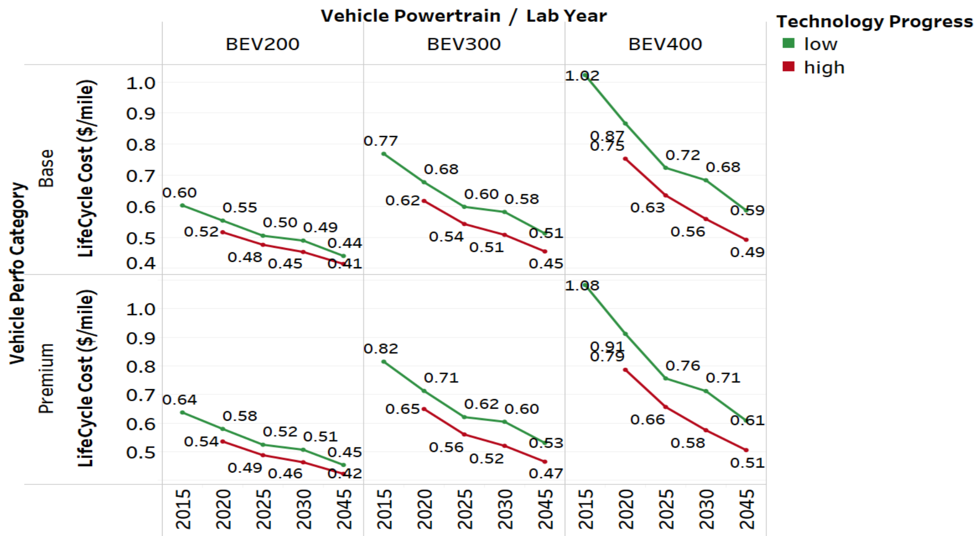
Figure 14 illustrates the levelized cost of driving ($/mile) for the different powertrains considered in this analysis for midsize vehicle class. The illustration further reflects the effect in life-cycle cost across the two performance categories considered.



(a) Lifecycle cost for Conventional SI. vs. Split HEV



(b) Lifecycle cost for PHEVs



(c) Lifecycle cost for BEVs

Figure 14: Levelized cost of driving cost comparisons across different powertrains

From figure 14, it can be seen the incremental glider costs play a significant impact to determine the Levelized cost of driving cost until Lab year 2025. From lab year 2025, the advancements in the cost assumptions for other components play a bigger impact to drive down the Levelized cost of driving cost. Comparatively, for PHEVs & BEVs, the advancements in battery cost assumptions drive the levelized cost of driving cost decrements across time. It can be further observed that the higher the all-electric ranges (with bigger batteries), the greater the cost drop observed.

8 Summary and Conclusion

The paper presents a large scale simulation process used to evaluate the potential benefits of vehicle electrification over a period of time, along with a comparison of HEVs & PHEVs to conventional vehicles. The metric for the comparison is limited to fuel consumption and cost for simplicity. The following conclusions can be drawn from the study:

- In terms of engine, electric machine and battery sizes, the requirements decrease with time from 2015 to 2045 lab year, due to higher component efficiencies, lightweighted vehicles, and the combined effect of advancements in other technologies. Moving from 2015 to 2045 lab year, the engine max power reduces by 7% to 21% for conventional vehicles, and 10% to 25% for power-split HEV vehicles. The decrease is about 11% to 27% for PHEV20 AER, and 13% to 29% for PHEV50 AER vehicles. The battery and motor peak power is expected to decrease over time to meet current vehicle performance. The powers are expected to decrease up to 22% for gasoline-engine HEVs, 28% - 31% for PHEVs and 17% - 41% for BEVs. Battery total energy will decrease significantly owing to other component improvements, as well as a wider usable SOC range. The reduction in energy required for PHEVs could range from 34%- 51% and the reduction for BEVs could range from 25% to 45% by 2045 lab year.
- For fuel consumption comparison of conventional and power-split HEV vehicles, a slow decreasing ratio trend-line can be observed. The power-split midsize vehicle consumes about 41% less fuel compared to conventional vehicles in 2015 lab year. This drop ranges to about 32% in 2045 lab year. For midsize PHEVs with 20 mi of AER (PHEV20s), the reduction in fuel consumption compared to that for conventional gasoline vehicles improves over time from 41% in 2015 lab year to between 59% and 69% in 2045. For midsize PHEVs with 50 mi of AER (PHEV50s), the reduction in fuel consumption improves over time from 38% in 2015 lab year to between about 60% and 68% in 2045. The electrical energy consumption reductions by 2045 for high-energy vehicles ranges between 34% and 43% across the different AERs. The higher degrees of reductions is observed for increasing AERs due to the observed benefits from advanced component targets.
- In terms of manufacturing costs comparison, a higher drop rate in hybridized vehicles are observed, compared to conventional vehicles. The drop is higher for higher degrees of hybridizations. This is due to the greater influence of the lower battery and electric machine costs. The reductions in energy consumptions are related to advanced lightweighting and highly efficient vehicle components in the future.

Acknowledgments

The authors would like to acknowledge the financial support of Dr. Jacob Ward (Vehicle Technologies Office, U.S. Department of Energy) to conduct this work. The submitted manuscript has been created by the UChicago Argonne, LLC, Operator of Argonne National Laboratory (Argonne). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357.

References

[1] U.S. DOE Vehicle Technologies Office. Transportation Fact of the Week. *Fact 943: September 19, 2016 Fuel Economy Being Chosen as the Most Important Vehicle Attribute is Related to the Price of Gasoline*. Accessed from: https://energy.gov/eere/vehicles/fact-943-september-19-2016-fuel-economy-being-chosen-most-important-vehicle-attribute (April, 2020)

[2] A. Moawad, P. Balaprakash, A. Rousseau, S. Wild, *Novel Large Scale Simulation Process To Support DOT's CAFE Modeling System*, EVS28, May 2015.

[3] Islam, E., Kim, N., Moawad, A., Rouseau, A. *An Extensive Study on Sizing, Energy Consumption, and Cost of Advanced Vehicle Technologies, Contract ANL/ESD-17/17, October 2018.*

[4] Islam, E., Kim, N., Moawad, A., Rouseau, A. *Energy Consumption And Cost Reduction Of Future Light-Duty Vehicles Through Advanced Vehicle Technologies: A Modeling Simulation Study Through 2050, Contract ANL/ESD-19/10, (forthcoming).*

[5] *Autonomie*, Available at http://www.autonomie.net

Presenter Biography

Ehsan Sabri Islam completed his M. Sc. in Interdisciplinary Engineering from Purdue University, USA in 2019 and B.A.Sc in Mechatronics Engineering from University of Waterloo, Canada in 2016. His skills set and interests focus on applying Mechatronics principles to innovate systems and processes in advanced vehicle technologies and controls systems. At Argonne, he focuses his research on vehicle energy consumption analyses and inputs for U.S. DOE-VTO and NHTSA/EPA/U.S. DOT CAFE and CO_2 standards using innovative large scale simulation processes and applications of AI.