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Impact of U.S. DOE Vehicle Technologies Progress In Technoeconomic Feasibility of Future Electrified Vehicles

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Executive Summary

The U.S. Department of Energy Vehicle Technologies Office (U.S. DOE-VTO) has been developing more energy-efficient and environmentally friendly highway transportation technologies to enable the United States to burn less petroleum on the road. System simulation is an accepted way to evaluate the fuel economy potential of advanced (future) technology targets. U.S. DOE-VTO defines the targets for advancements in powertrain technologies (e.g., engine efficiency, battery energy density, lightweighting, etc.), and vehicle system simulation models based on these targets have been generated in Autonomie, to reflect the different EPA classifications of vehicles for five different timeframes- 2020, 2030, 2035, and 2050-as part of the technology assessment analysis.

This paper will present an approach based on a large-scale simulation process, in which simulations are performed over standard regulatory driving cycles for the small SUV vehicle class over a range of timeframes by implementing the technology advancement targets set by the U.S. DOE-VTO. This approach further evaluates the evolution of vehicle electrification compared to conventional powertrain options and its impact on fuel economy and costs.

1 Introduction

The impact of advances in powertrain technology - engine, battery, vehicle electrification and material (lightweighting) - is evaluated using a fuel consumption (or fuel economy or CO_2 g/mile) metric on standard regulatory drive cycles [1]. System simulation of vehicle models incorporating technology advancements is an accepted approach to evaluating their fuel economy potential [2].

The U.S. Department of Energy Vehicle Technologies Office, (U.S. DOE-VTO) 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 [4] 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 these simulation include conventional, hybrid (HEV), plug-in hybrid (PHEV) and battery-electric vehicles (BEVs) of different all-electric ranges (AERs). The technology advancements are evaluated for fuel economy and cost impact over standard regulatory driving cycles [5] [6] [7] [8].

2 Procedure

The different vehicle technology targets set by 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 the 2020, 2025, 2030, 2035, and 2050 model years.

The following subsections represent the breakdown involved during the vehicle simulation. The latest report from Argonne [8] 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 attributes 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/Premium	9/7	2.3	0.31	0.006
Midsize	Base/Premium	8/6	2.35	0.3	0.006
Small SUV	Base/Premium	8/6	2.65	0.36	0.006
Midsize SUV	Base/Premium	9/7	2.85	0.38	0.006
Pickup	Base/Premium	7/7	3.25	0.42	0.006

Table 2 below summarizes the main target assumptions associated with the different technologies over time. The vehicle simulations (and results to follow) represent the model years 2020, 2025, 2030, 2035, and 2050, but the assumption values from years 2020, 2025, 2035 and 2050 have been provided in the table for simplicity.

Table 2: Technology Assumptions

	2020	2025		2035		2050	
	Low	Low	High	Low	High	Low	High
Conventional Engine Peak Efficiency (%)	36	38	43	42	45	44	47
Hybrid Engine Efficiency (%)	40	40	46	41	48	43	50
Electric Machine Cost ($/kW)	12	9	6	4.8	3.2	2.25	1.5
Specific Power @ 70% SOC - HEVs (W/kg)	2750	3000	4000	4500	5500	5000	6000
Battery Pack Energy Density - PHEV (Wh/kg)	100	136	140	147	165	144	189
Battery Pack Energy Density - BEV (Wh/kg)	189	189	244	255	308	298	337
Battery Pack Cost - HEVs ($/W)	20	20	16	18	14	17	13
Battery Pack Cost - PHEV ($/kWh)	200	150	110	90	75	70	60
Battery Pack Cost - BEV ($/kWh)	140	128	95	90	70	70	60

4 Results & Observations

4.1 Component Sizes

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

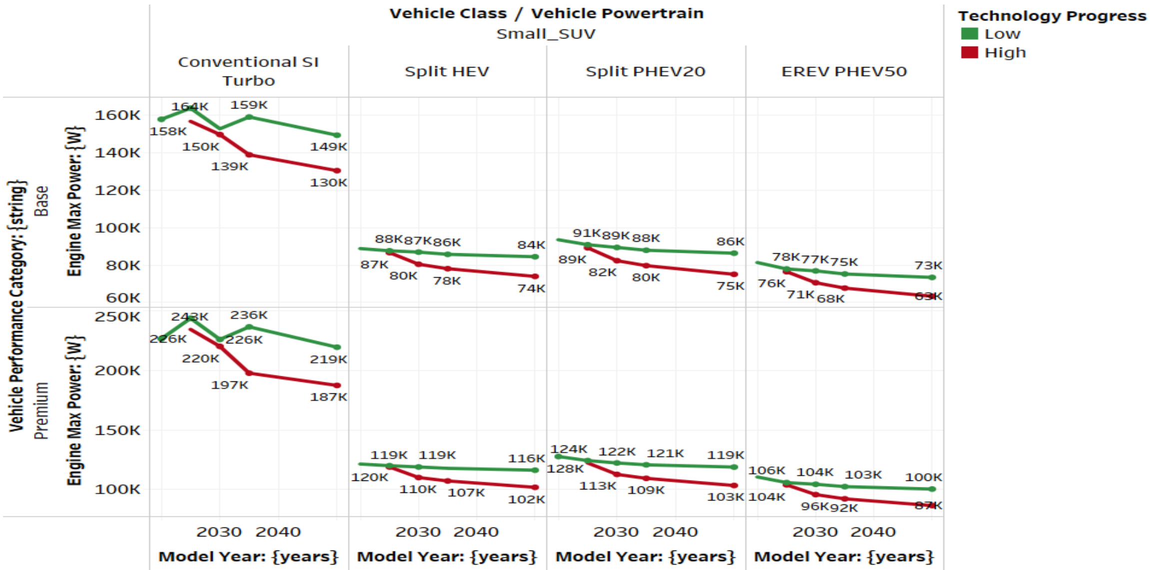


Figure 1: Engine peak power for small SUVs across performance categories

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

Motor Power Figure 2 shows the motor peak power for small SUVs across the different electrified powertrains for different performance categories.

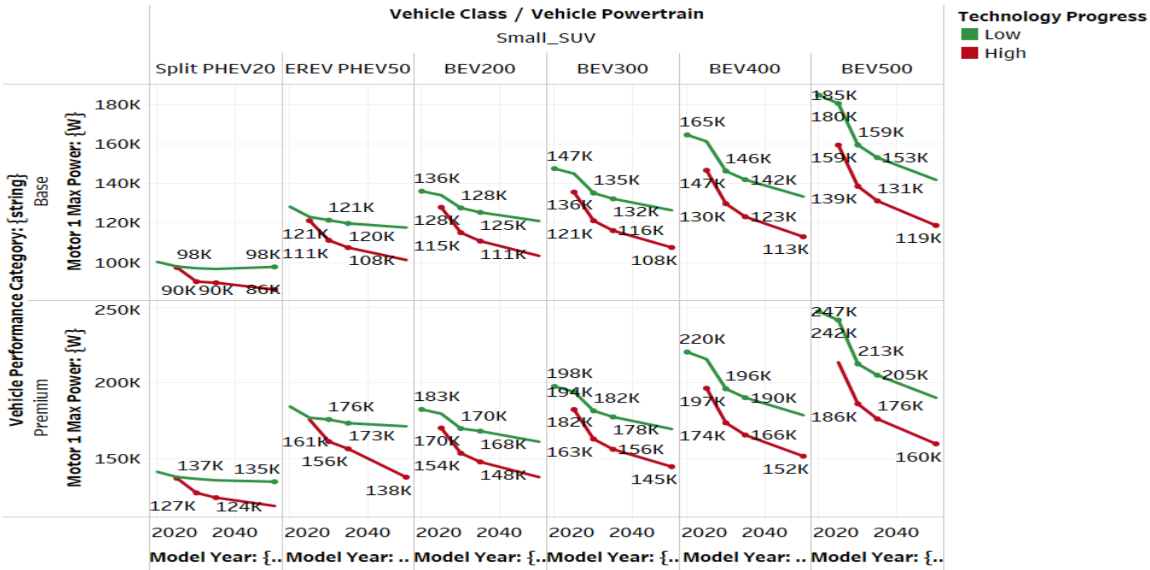


Figure 2: Motor peak power (W) for small SUVs across performance categories

Like engine power, motor power also decreases across the different powertrains in future years. Vehicle lightweighting along with other aggressive targets for different component weights (electric machine, battery, etc.), significantly contributes to the motor downsizing.

Battery Total Energy Figure 3 shows the battery total energy for small SUVs across the different electrified powertrains for different performance categories.

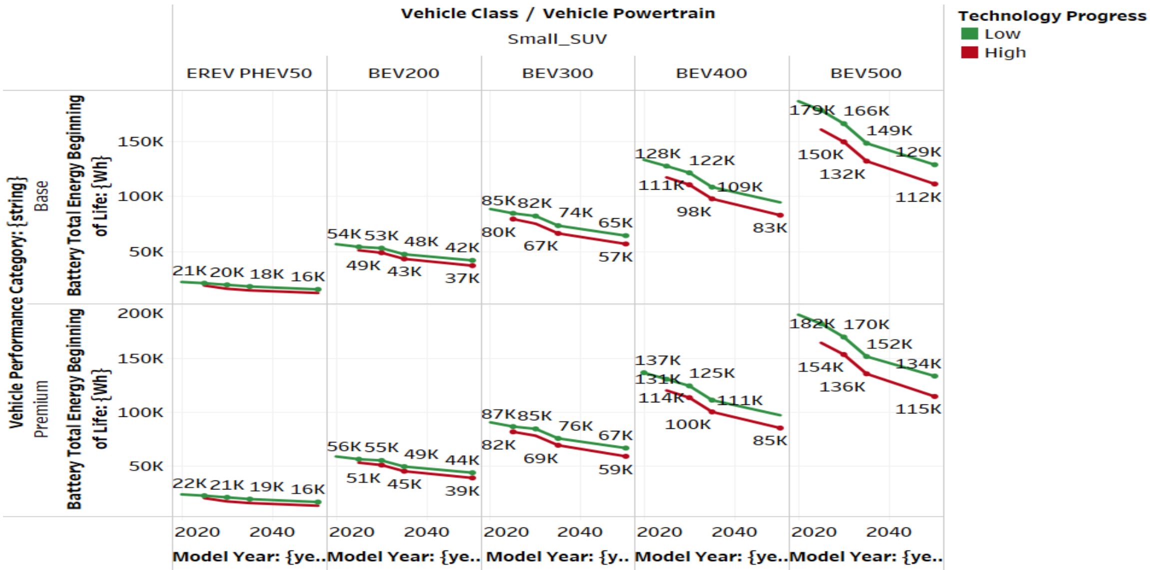


Figure 3: Battery total energy for small SUVs across performance categories

Following the trend line observed for motor power sizes, the battery total energy requirement also decreases similarly over time. For the BEV200, the battery pack total energy decreases by 35% for 2050 high technology progress case compared with 2020 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.

4.2 Energy Consumption

Figure 4 shows the adjusted fuel economy (utility-weighted for PHEVs) based on the EPA combined label for small SUVs across the different powertrains of different performance categories.

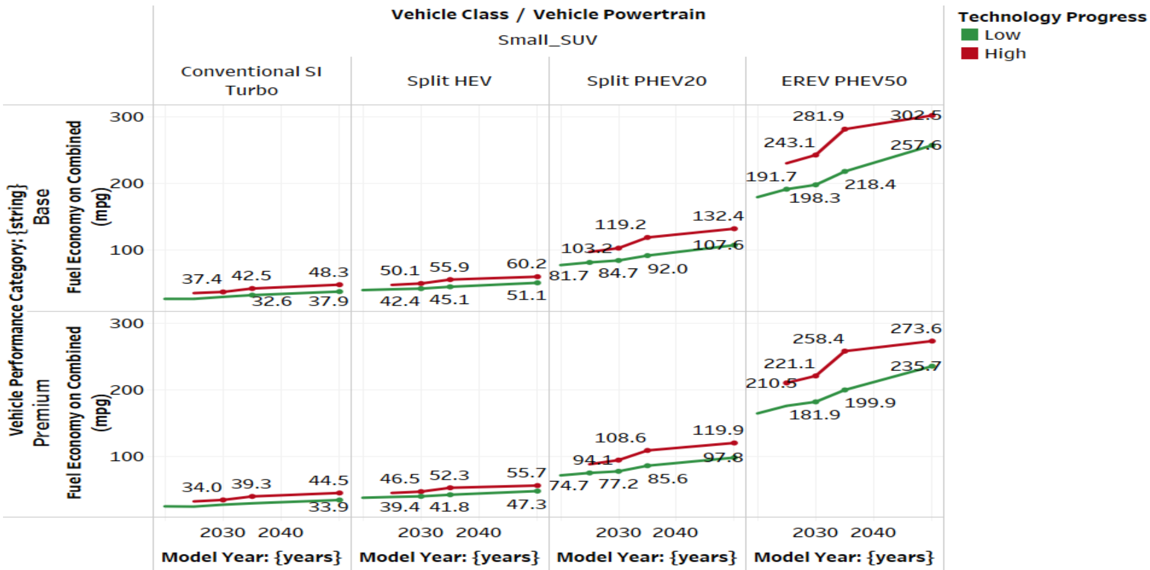


Figure 4: Adjusted fuel economy on combined label for small SUVs

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 by higher component weights explains the difference between the fuel economies observed of the premium category and the base category. Figure 5 shows the adjusted electrical energy consumption (utility-weighted for PHEVs) of small SUV electrified vehicles for different performance category.

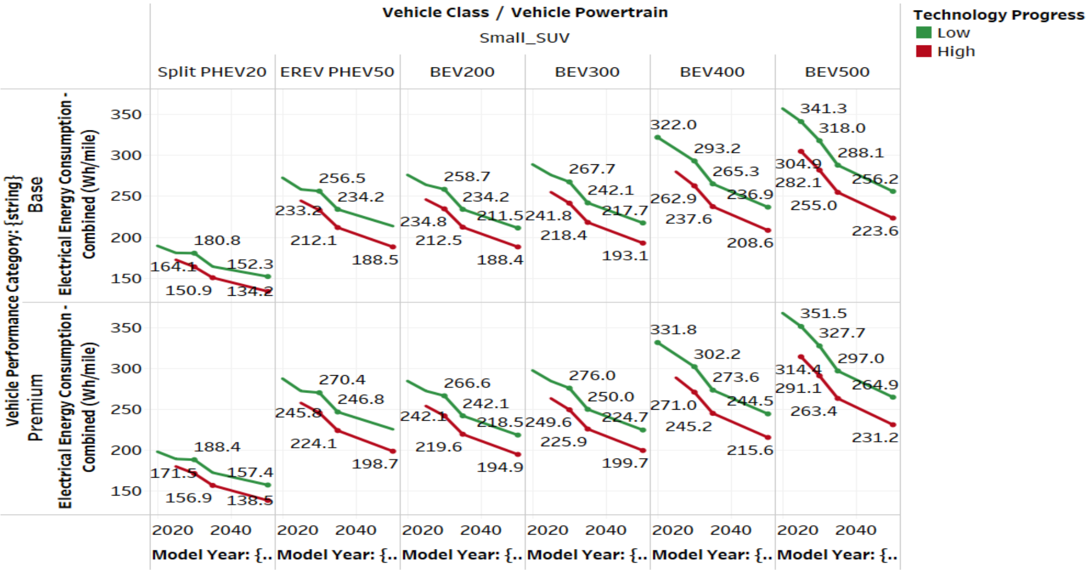


Figure 5: Adjusted DC electrical energy consumption on combined label (Wh/mile) for small SUVs

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

5 Cost Analysis

5.1 Component Cost

Figure 6 shows the motor cost for electrified powertrains for small SUVs across the different performance categories.

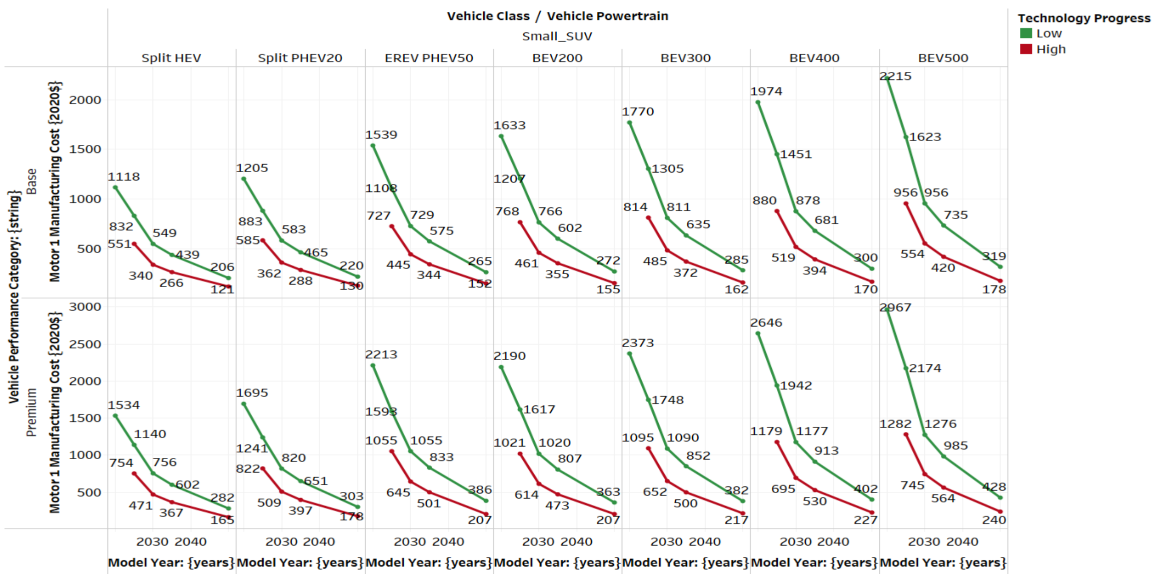


Figure 6: Motor cost of small SUVs

The reduction in motor manufacturing costs ranges from 75% to 82% across the various electrified powertrains and performance categories.

Figure 7 shows the battery cost for small SUVs electrified powertrains across the different performance categories.

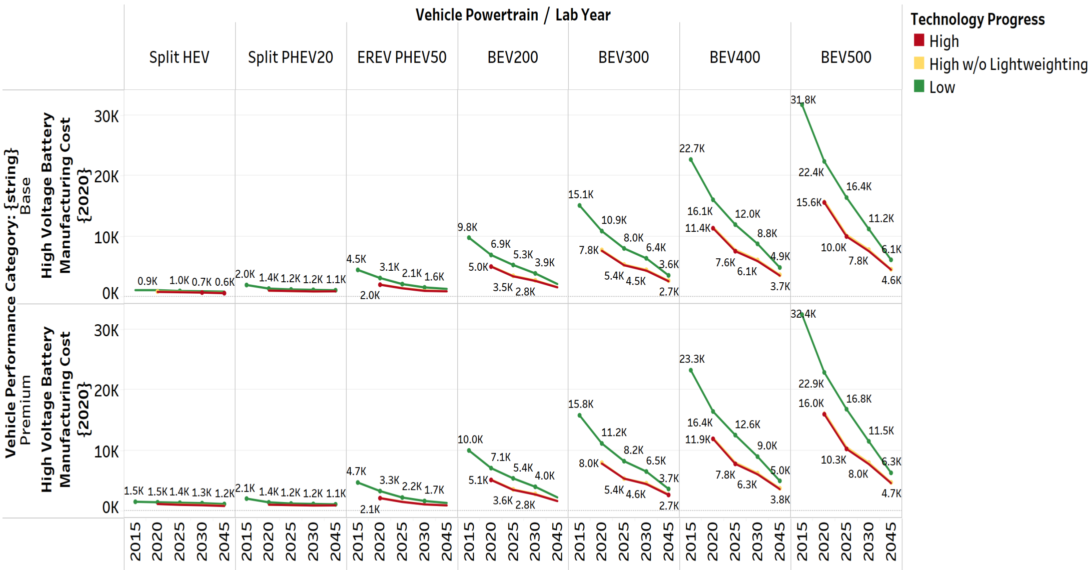


Figure 7: Battery cost for small SUVs

High-voltage battery costs decline by 21%-44% for HEVs, 44%-79% for PHEVs and 76%-87% for BEVs. Lightweighting has an effect on battery sizes: it decreases battery costs in future years. Battery size in turn affects the major manufacturing cost of BEVs. Higher-range BEVs have a great impact on manufacturing costs in future years

5.2 Vehicle Manufacturer Suggested Retail Price (MSRP)

Figure 8 shows the vehicle MSRP for the different powertrains considered in this analysis for the small SUV class, reflecting the effects of technology progress on manufacturing cost across the two performance categories considered.

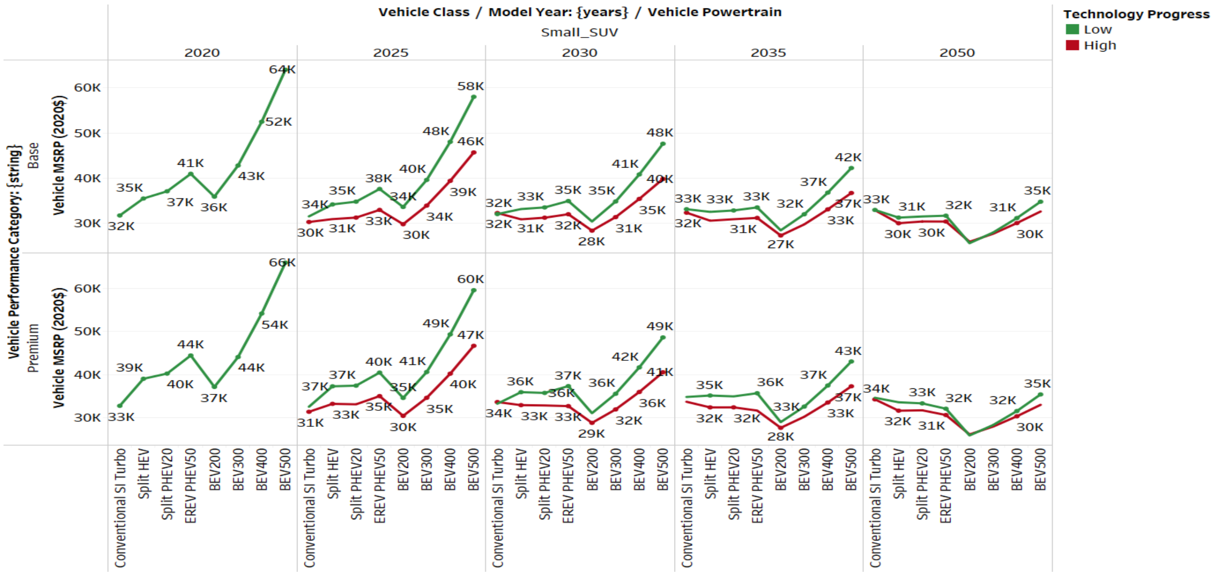


Figure 8: Vehicle MSRP of small SUVs

It can be seen that the manufacturing price of hybridized vehicles in comparison to conventional spark ignition (SI) Turbo vehicles evolves significantly over time. For example, the vehicle manufacturing cost of BEVs is about 50%-150% higher than for conventional SI Turbo vehicles in 2020 but declines to 10-20% less than conventional SI vehicles by 2050.

6 Energy Consumption vs. Vehicle Manufacturing Cost

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

Conventional Figure 9 illustrates vehicle manufacturing cost vs. fuel consumption for conventional vehicles across multiple vehicle classes. The different colored lines represent the trend lines of vehicle manufacturing cost vs. fuel consumption for different vehicle classes.

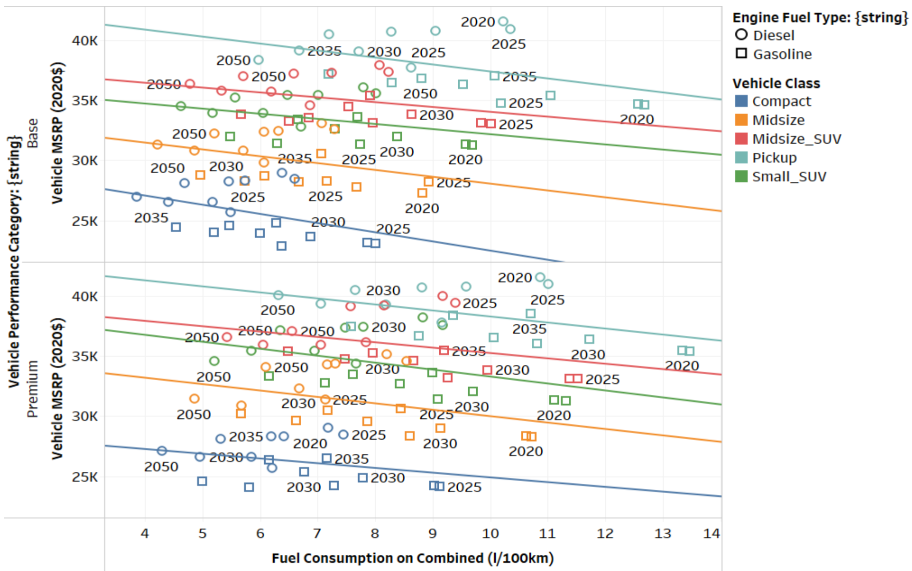


Figure 9: Manufacturing cost vs. fuel consumption of conventional vehicles

It is important to note that diesel vehicles have higher manufacturing costs than gasoline vehicles. The figure also shows the relative positions of the different vehicle classes in terms of fuel consumption and manufacturing costs: Midsize vehicles, small SUVs, and midsize SUVs cluster closely together, while compact and pickup classes lie on the two extremes. The trend lines in the plot also confirm this observation.

Split HEV Figure 10 illustrates vehicle manufacturing cost vs. fuel consumption for split HEVs across multiple vehicle classes.

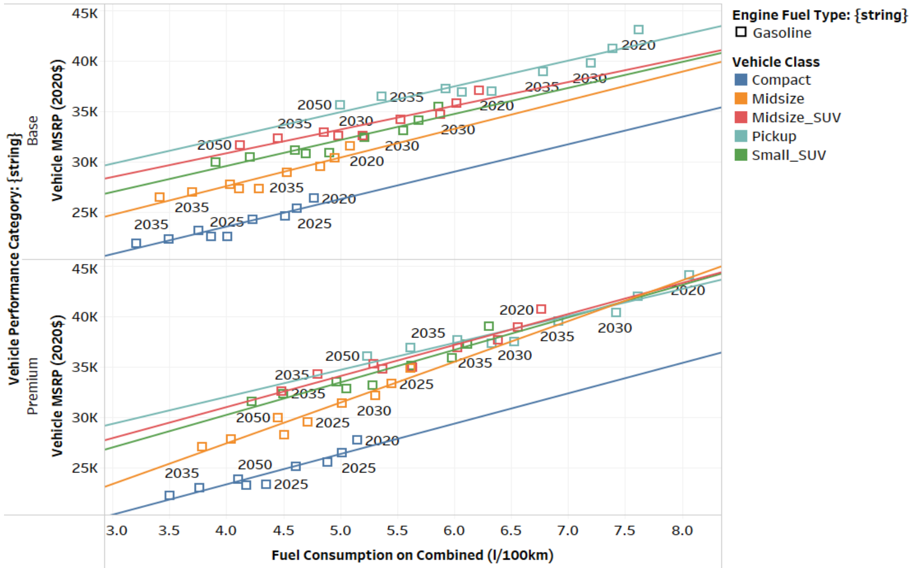


Figure 10: Manufacturing cost vs. fuel consumption of split HEVs

The figure shows how fuel consumption and manufacturing costs progress across the different model 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 confirms the clustering.

Split/EREV PHEV Figure 11 illustrates PHEV manufacturing cost vs. fuel consumption across multiple vehicle classes.

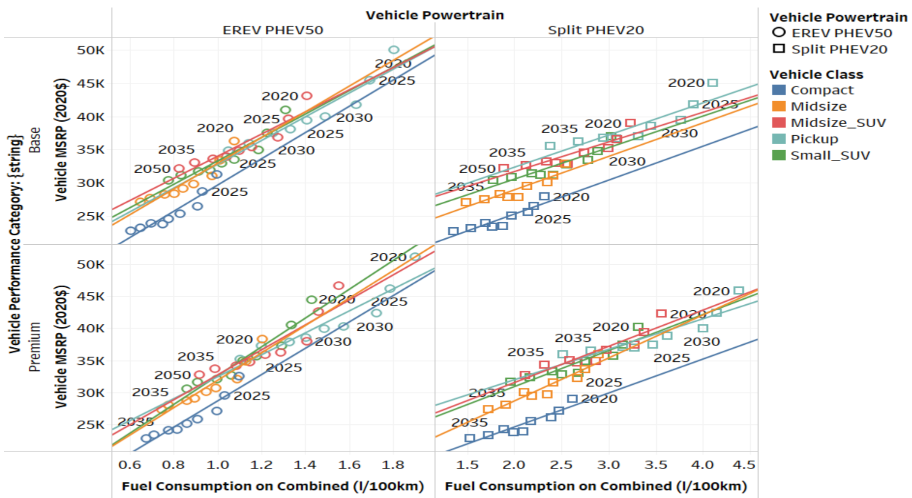


Figure 11: Manufacturing cost vs. fuel consumption of PHEVs

The different colored lines are trend lines for different types of PHEVs. The different vehicle classes follow trends similar to those previously discussed. As AER increases, manufacturing costs increase (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 costs from model year 2020 to 2050. The trend lines also show an aggressive drop 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 12 illustrates manufacturing cost vs. electrical energy consumption for BEVs across multiple vehicle classes.

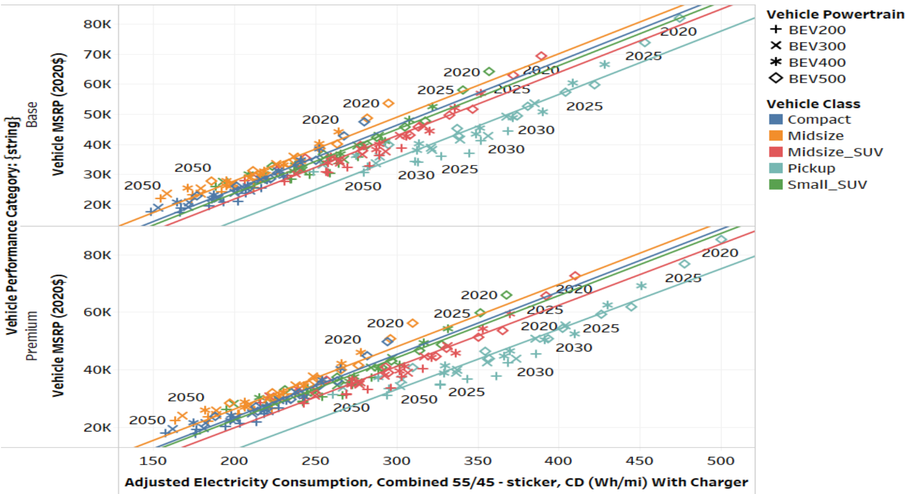
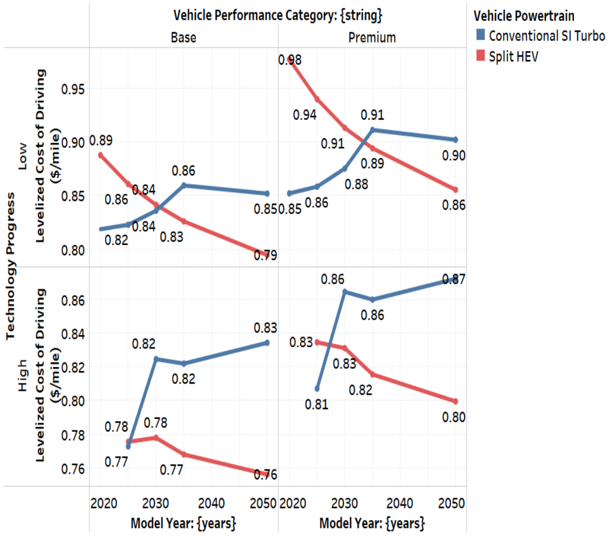


Figure 12: BEV manufacturing cost vs. electrical energy consumption

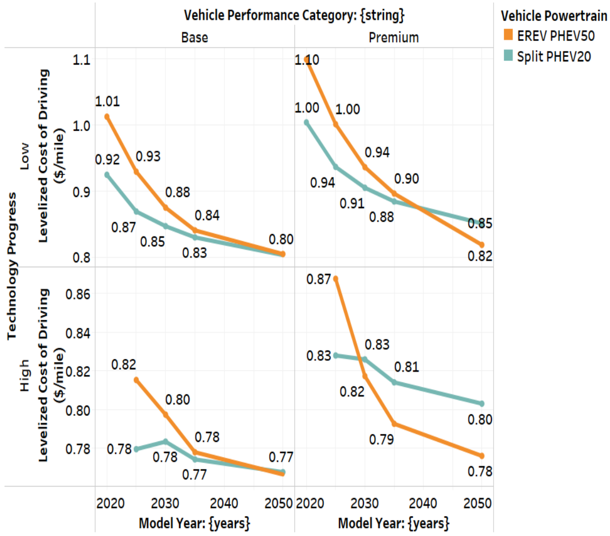
It can be observed that as AER increases, manufacturing cost increases (owing to bigger batteries) and fuel consumption decreases. The effect of technological improvements over the years can be seen in the reduction in fuel consumption and manufacturing cost from model year 2020 to 2050. The trend lines also 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

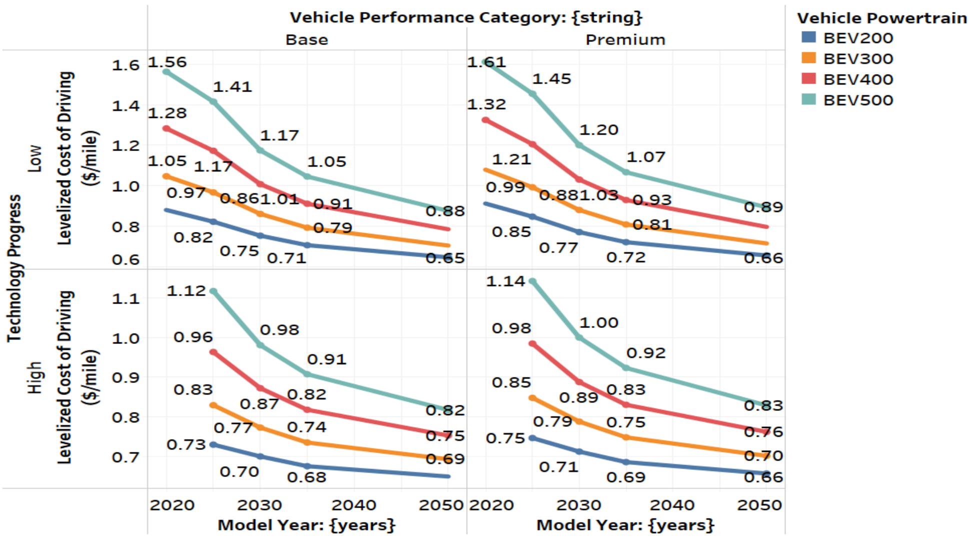
Figure 13 illustrates the levelized cost of driving ($/mile) for the different powertrains considered in this analysis in the small SUV vehicle class. The illustration shows the effect on life-cycle cost over time for the two performance categories considered.



(a) Cost of driving for conventional SI. vs. split HEV



(b) Cost of driving for PHEVs



(c) Cost of driving for BEVs

Figure 13: Levelized cost of driving cost comparisons across different powertrains

From Figure 13, it can be seen that incremental glider costs play a significant role in determining the levelized cost of driving until model year 2030. From 20030 on, the cost assumptions for other components play a bigger role into driving down the levelized cost of driving. Comparatively, for PHEVs and BEVs, battery cost assumptions drive the levelized cost of driving down over time. It can be clearly seen that the higher the all-electric ranges (with bigger batteries), the greater the cost drop.

It can be further seen that over time, the fuel consumption of conventional vehicles improves due to technological advances, as indicated by the technologies accelerated through future VTO targets; however, manufacturing costs increase due to increasing lightweighting costs, as observed earlier. The latter costs cause the levelized cost of driving to increase in future periods, with the highest costs occurring in the near-to-mid-term. Overall, the optimal technology progress case is the high-technology progress case without lightweighting effects.

8 Comparison Cost Analysis

Figure 14 illustrates the total cost of ownership comparison across different range of electrified powertrains.

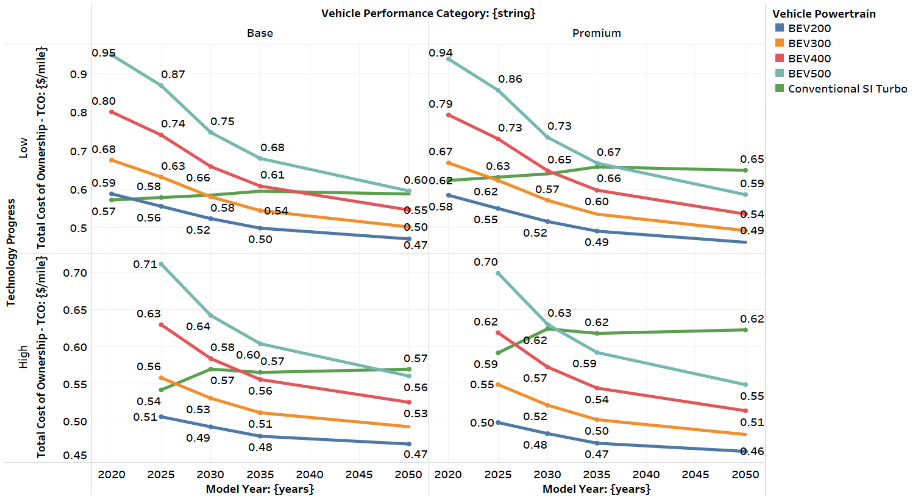


Figure 14: Total cost of ownership comparison across powertrains for small SUVs

The figure shows the cost parity of BEVs for passenger cars (small sport utility vehicle [SUV] class). The BEV cost is compared with that of a conventional spark-ignition (SI) turbocharged vehicle of the corresponding analysis year. For small SUVs, considering current technology progress trends (low technology scenario), BEVs will become cost competitive with conventional powertrains between the 2025 (BEV 200 miles) and 2040 (BEV 500 miles) model years. Under the high technology scenario, BEVs become cost competitive an average of 5 years earlier, significantly accelerating their market adoption

9 Summary and Conclusion

The paper presents a large-scale simulation evaluating the potential benefits of vehicle electrification over a period of time, along with a comparison of HEVs and PHEVs to conventional vehicles. For simplicity, the metrics for the comparison are limited to fuel consumption and manufacturing cost. The following conclusions can be drawn from the study:

- Engine, electric machine and battery sizes decrease from model year 2020 to 2050, due to higher component efficiencies, lightweighted vehicles, and the combined effects of advancements in other technologies. From model year 2020 to 2050, the engine maximum power decreases by 14% to 23% for conventional vehicles and by 15% to 21% for power-split HEV vehicles. The decrease is about 16% to 24% for PHEV20 AER and 17% to 26% for PHEV50 AER vehicles. The battery and motor peak power are expected to decrease over time to meet current vehicle performance, up to 22% for gasoline-engine HEVs, 11% to 25% for PHEVs, and 20% to 39% for BEVs. Battery total energy will decrease significantly owing to other component improvements, as well as a wider usable SOC range. The reduction in required energy for PHEVs could range from 31% to 41% and the reduction for BEVs from 26% to 40% by 2050.

- A comparison of fuel consumption by conventional and power-split HEV vehicles shows a slowly declining trend-line. A power-split small SUV consumes about 33% less fuel than a conventional vehicle in lab year 2015, and this drops to about 22% in lab year 2045. For small SUV PHEVs with 20 miles of AER (PHEV20s), the reduction in fuel consumption compared to that for conventional gasoline vehicles improves over time, from 65% in 2020 to between 62% and 64% in 2050. For small SUV PHEVs with 50 miles of AER (PHEV50s), the reduction in fuel consumption improves from 38% in model year 2020 to between 60% and 68% in 2050. The electrical energy consumption of high-energy vehicles declines between 31% and 44% across the different AERs by 2050. The higher degree of reduction for increasing AERs is due to the benefits of advanced component targets.

- Manufacturing costs for hybridized vehicles decrease more than that of conventional vehicles. The higher the degree of hybridization, the higher the drop is in manufacturing costs due to lower battery and electric machine costs. Reductions in energy consumption are related to advanced lightweighting and highly efficient vehicle components in the future.

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Presenter Biography

Ehsan Sabri Islam completed his MSc in Interdisciplinary Engineering from Purdue University, USA in 2019 and BASc 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.