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Prediction of Electrified Vehicles' Energy Consumption and Cost Based On U.S. Department of Energy Targets

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Abstract

The U.S. Department of Energy, Vehicle Technologies Office (U.S. DOE-VTO) is developing more energy-efficient and environmentally friendly highway transportation technologies that would enable the United States to burn less petroleum on the road. System simulation is an accepted approach 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.) Vehicle system simulation models based on these targets have been generated in Autonomie, to reflect the different EPA classifications of vehicles for six different timeframes: 2010, 2015, 2020, 2025, 2030, and 2045 as part of the DOE Benefits and Scenario Analysis (BaSce).

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

Keywords: energy consumption, EREV (extended range electric vehicle), EV (electric vehicle), BEV (battery 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].

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, lightweighting, etc., over a given timeframe [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-VTO. 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 2010, 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.

To implement uncertainties in the assumptions, a triangular distribution approach is implemented that states the low, medium, and high uncertainty cases [5]. These uncertainties have been assigned to each component assumption (e.g., engine efficiency, power density, costs, etc.) and values have been assigned accordingly to represent the 90th percentile, 50th percentile, and 10th percentile. A 90% probability would mean that the technology has a 90% chance of being available in the market during the designated timeframe. The terms "low," "medium," and "high" are used to represent the 90th percentile, 50th percentile, and 10th percentile, respectively.

The following subsections represent the breakdown involved during the vehicle simulation.

2.1 Technology Target Assumptions

The technology target assumptions received from U.S. DOE-VTO have been assigned accordingly over the pre-defined timeframe for the different vehicle classes. A subset of the assumptions received for the midsize vehicle class are outlined in Table 1.

Table 1: Vehicle Assumptions (Midsize Class)

	2010	2015	2025			2045		
	Low	Low	Low	Medium	High	Low	Medium	High
Frontal Area (m^2)	2.372	2.372	2.341	2.295	2.26	2.332	2.288	2.244
Glider Mass (*kg*)	1105	1028	1019	972	925	979.472	867.87	756.26
Drag Coefficient	0.311	0.311	0.298	0.2835	0.2715	0.28	0.25	0.22

Table 2 summarizes the main target assumptions associated with the different technologies over time. The vehicle simulations (and results to follow) represent the "lab years" 2010, 2015, 2020, 2025, 2030, and 2045, but the assumption values from years 2010, 2015, 2025 and 2045 are provided in the table for simplicity.

Table 2: Technology Assumptions

	2010	2015	2025			2045		
	Low	Low	Low	Medium	High	Low	Medium	High
Conventional Engine Efficiency (Gasoline) (%)	36	36	38	40	43	43	47	50
Hybrid Engine Efficiency (Gasoline) (%)	39	40	40	43	46	42	47	52
Engine Efficiency (Diesel) (%)	42	42	44	47	50	48	50	52
Electric Machine Efficiency (%)	91	92	93	95	96	95	96	97
Specific Power @ 70% SOC - HEVs (*W/kg*)	2750	3750	400	4500	5000	5000	5500	6000
Specific Power @ 70% SOC - PHEVs (*W/kg*)	375	375	1000	1250	1500	1000	1250	1500
Energy Density - PHEV (*Wh/kg*)	50	60	105	115	125	115	145	170
Energy Density - BEV (*Wh/kg*)	150	170	230	270	310	280	300	320

2.2 Approach

Autonomie is used for simulation of the vehicles over the defined timeframe. The vehicles are sized for the given timeframe according to the component assumptions stated earlier. A large-scale simulation approach is undertaken to evaluate the high volume of vehicle uncertainties. It uses a distributed computing method that accelerates and facilitates the simulation runs [2]. The vehicles are assessed using the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) drive cycle. The vehicle component sizing procedure is used to calculate the costs associated with the components.

The simulations are performed under hot conditions. The cold-start penalties associated are assessed accordingly after the simulations, on the basis of test data collected at Argonne's Advanced Powertrain Research Facility (APRF) and literature search. A two-cycle test procedure is implemented that is based on the UDDS and HWFET drive cycle (55% UDDS + 45% HWFET). The calculations are consistent with the latest U.S. Environmental Protection Agency (EPA) procedure [3].

3 Results & Analysis

The results and analysis of the vehicle simulations would comply with the full range of timeframes as mentioned earlier. To isolate the technology benefits, the results represent the midsize vehicle class only, unless otherwise stated.

3.1 Evolution of Electrified and Conventional Vehicles

3.1.1 Vehicle Components Size

Engine Power

Figure 1 illustrates the evolution in engine peak power of midsize conventional and split HEV vehicles.

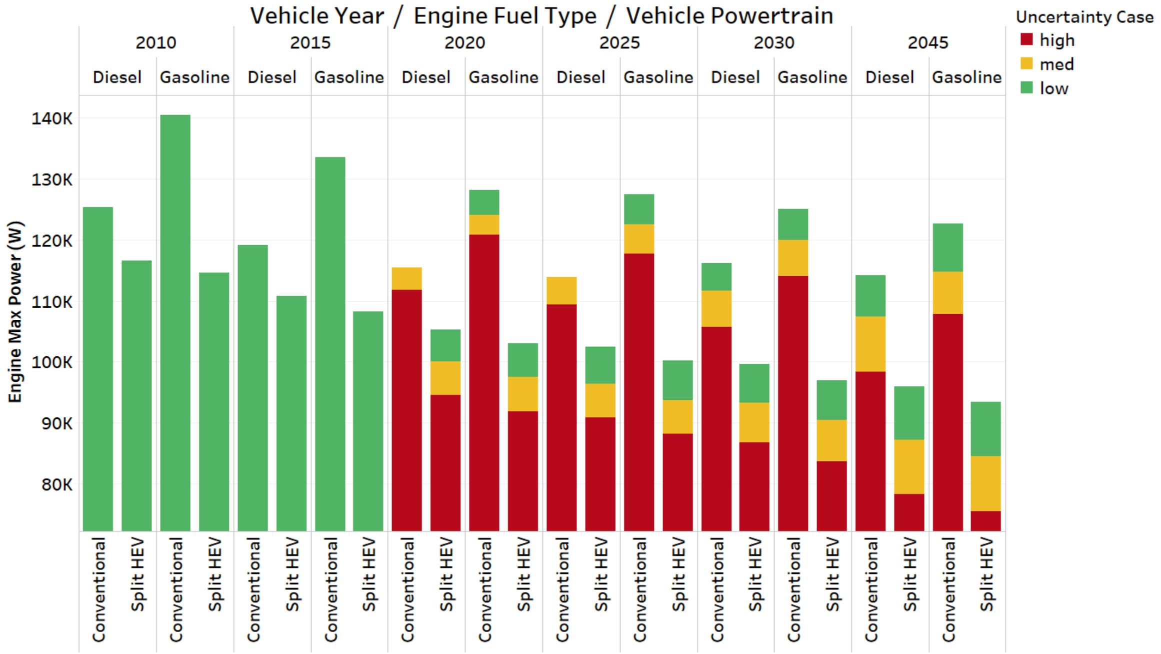

Figure 1: Engine peak power for midsize conventional and HEV engines

It can be seen that over time, the engine peak power decreases. This trend can be explained by the effects of lightweighting with time. The engine power for HEVs is determined by both the performance and grade requirements. While performance is the primary factor for current technologies, future lightweighting makes gradeability requirements critical for some cases.

Figure 2 shows the engine peak power for the various midsize PHEV (of different AERs) vehicles and timeframes. Due to the presence of electric machines, the engines are all sized to provide acceptable gradeability.

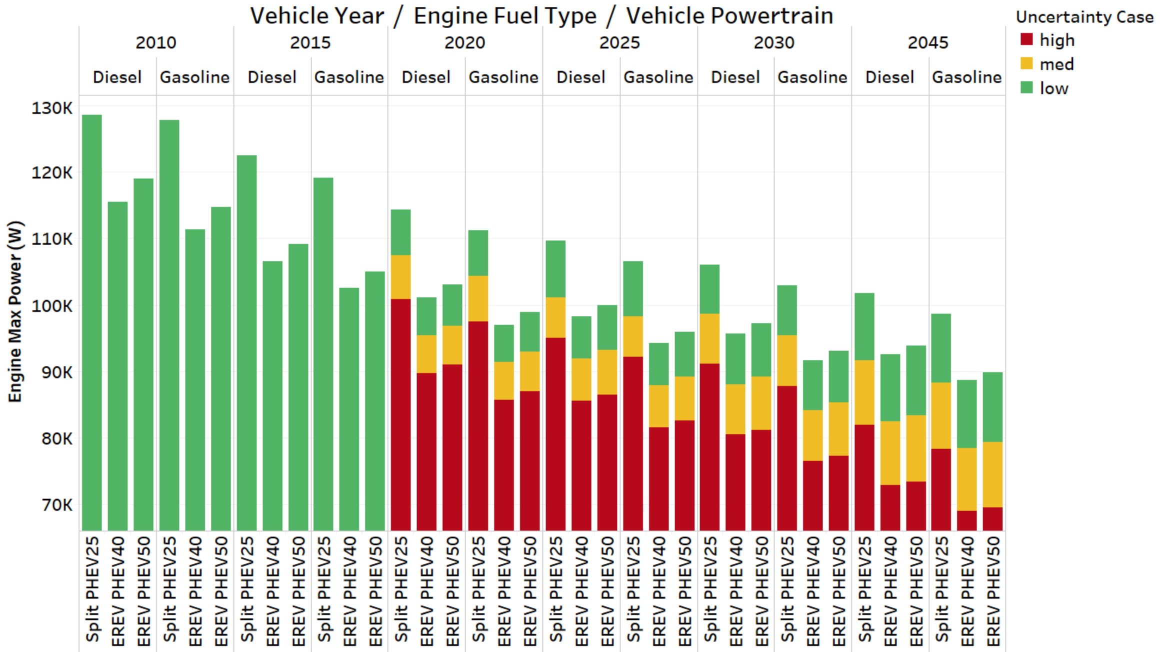

Figure 2: Engine peak power for midsize PHEV powertrains across range classifications

Electric Machine Power

Figure 3 illustrates the peak power of the different electric machines for the midsize BEV vehicles with different AERs.

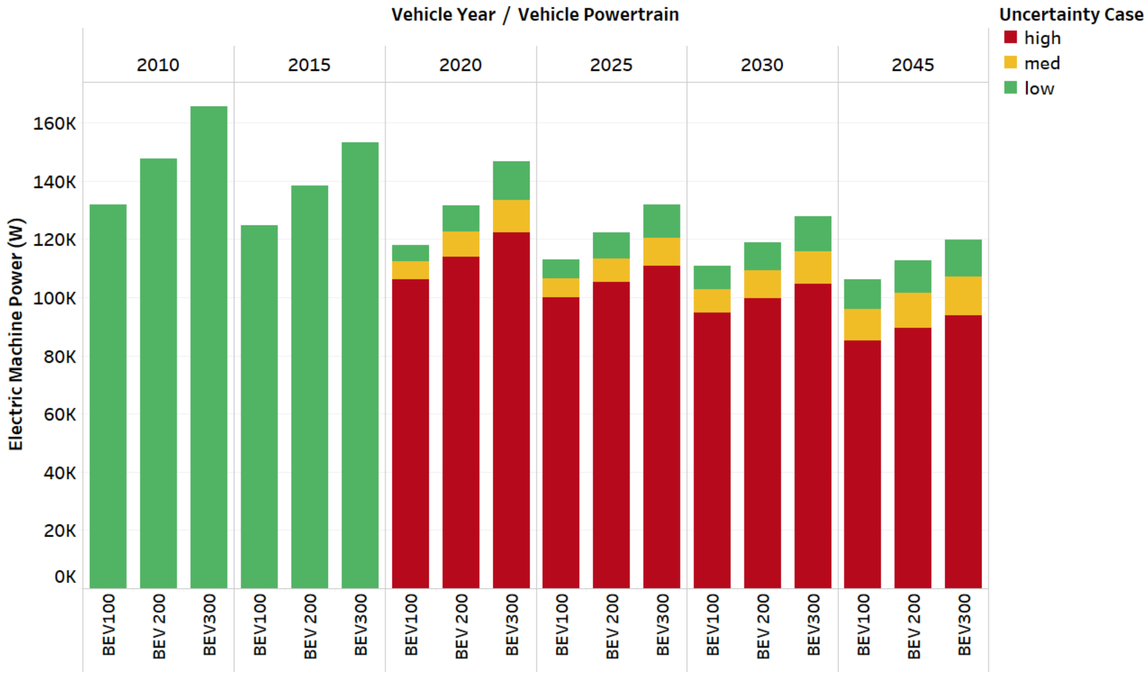

Figure 3: Electric machine peak power for midsize BEV vehicles for various AERs

It can be observed that the technology evolution leads to various power reduction levels for different powertrain configurations.

Battery Power

Figure 4 illustrates the battery pack power for the midsize split HEV and different PHEV powertrains across the specified timeframes.

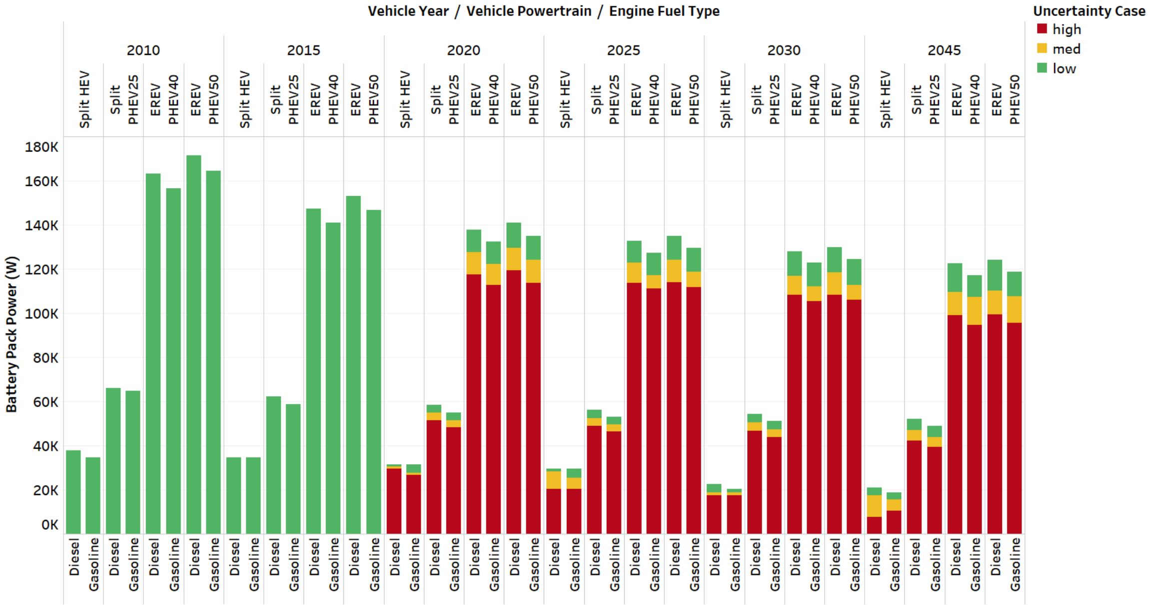

Figure 4: Battery pack power for midsize HEV and PHEV powertrains across range classifications

It can be concluded that the battery pack power for PHEV25 AER decreases by 26% over time, and for PHEV40 AER and PHEV50 AER, it decreases by nearly 30%. From one AER to the next, the battery power increases by an average of 3% for EREV powertrains.

Figure 5 illustrates the battery pack power for the midsize BEV vehicles across the specified timeframes.

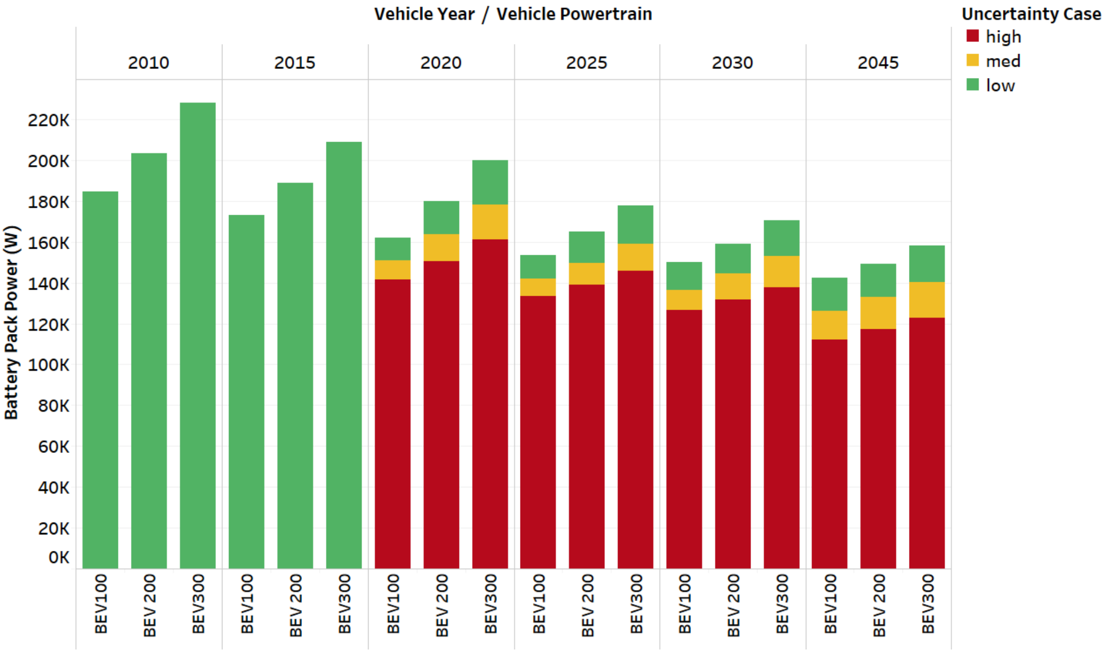

Figure 5: Battery pack power for midsize BEV vehicles with various AERs

The battery pack power decreases by about 40% for BEV100 AER, 42% for BEV200 AER, and about 46% for BEV300 AER, moving from 2010 to 2045 lab years.

3.1.2 Energy Consumption

Figure 6 illustrates the fuel consumption evolution of midsize split HEV and conventional vehicles over the timeframes of 2010–2045 “lab year”.

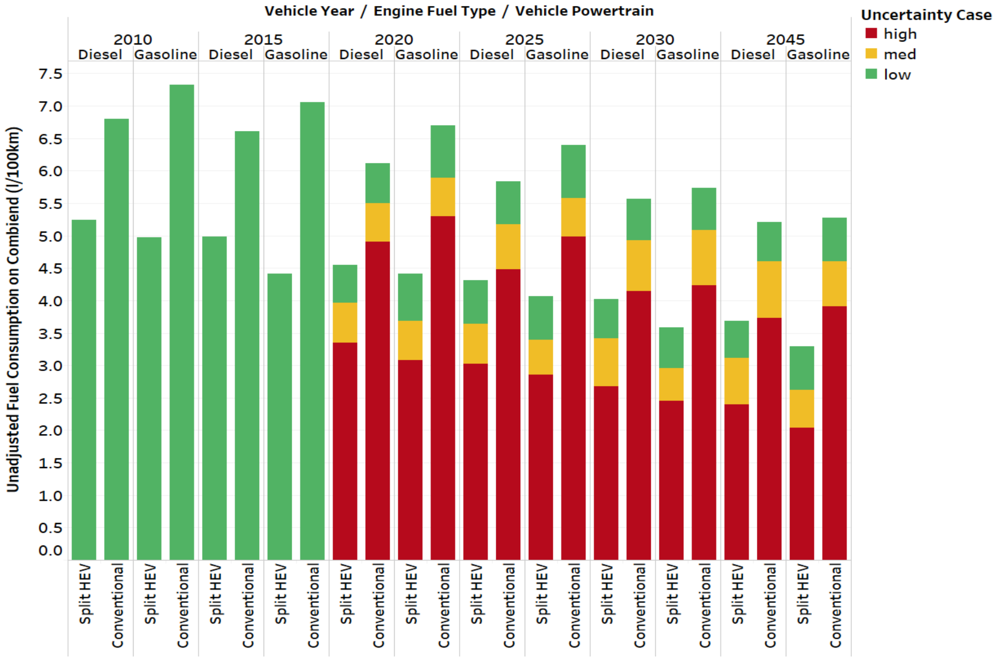

Figure 6: Midsize conventional vs. split HEV fuel consumption on combined cycle

This comparison can be further evolved in terms of fuel consumption ratios between the midsize power-split HEV and conventional vehicles as shown in Figure 7.

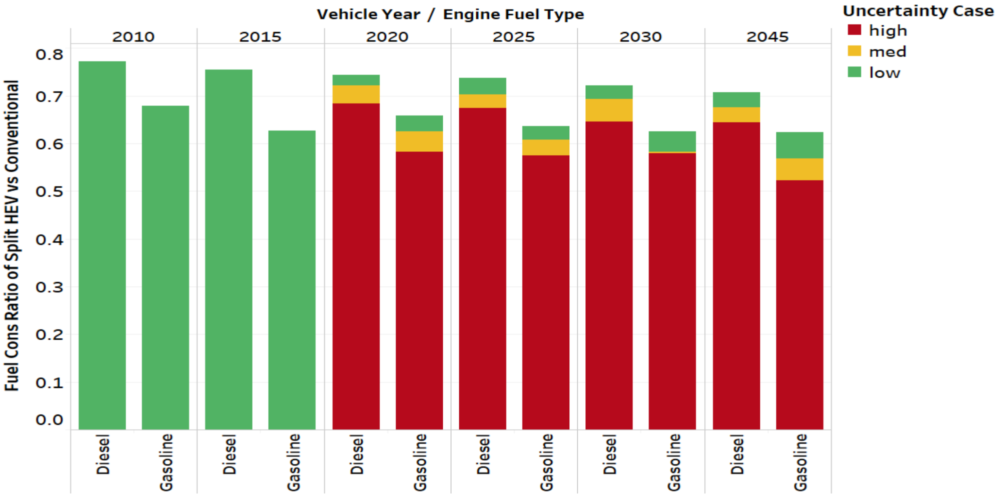

Figure 7: Ratio on fuel consumption of midsize split HEV vs. conventional for same year/same case

The fuel consumption evolution for midsize power-split PHEVs is similar to that of the power-split HEVs.

As observed in Figure 8, the fuel economy improves with higher AER for the same fuel. This can be explained with the fact that the bigger the battery (for higher AER PHEVs), the less fuel is consumed. However, a trend line between the battery size and the specific fuel consumption improvement cannot be deduced. For instance, between 2010 and 2045 lab years, the fuel-consumption improvement of gasoline engines is about 39% for split PHEV 25 AER, 33% for EREV 40 AER, and 34% for EREV PHEV 50 AER. These variations do not show a trend related to battery size and improvements over the years.

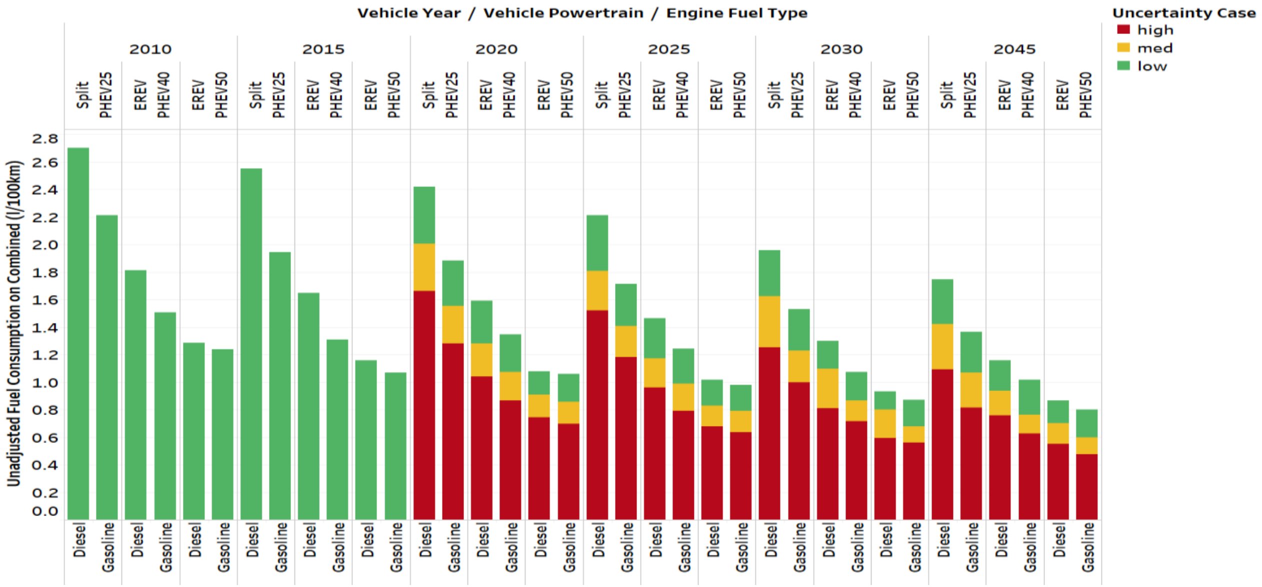

Figure 8: Gasoline-equivalent fuel consumption for midsize PHEV cars (CD + CS)

For BEVs, the results are evaluated in terms of electrical consumption for the EPA combined procedure. Lightweighting and component sizing improvements in future years leads to a significant decrease in electrical consumption over time. Figure 9 illustrates the electrical consumption for midsize BEV vehicles with various AERs. The values, expressed in Wh/mile, represent the average energy provided by the battery to drive the vehicle for one mile.

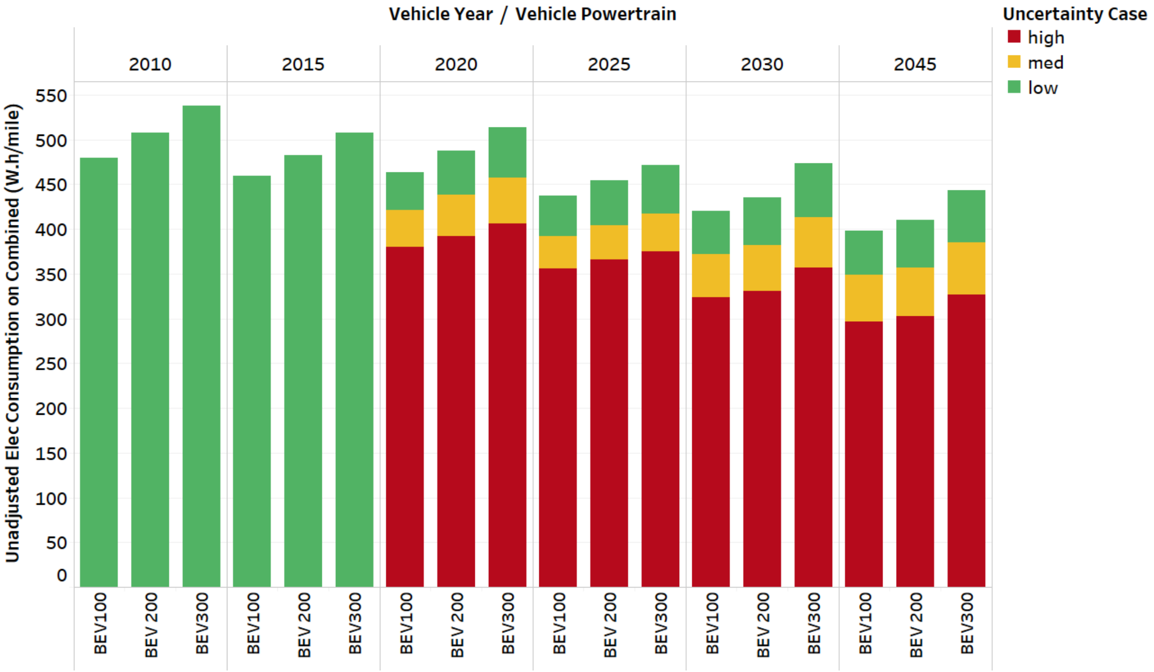

Figure 9: Electrical energy consumption by midsize BEVs on combined procedure

3.1.3 Vehicle Manufacturing Costs

All the costs reported in this section are in terms of 2015 USD.

Figure 10 illustrates the manufacturing costs for midsize conventional and split HEV vehicles.

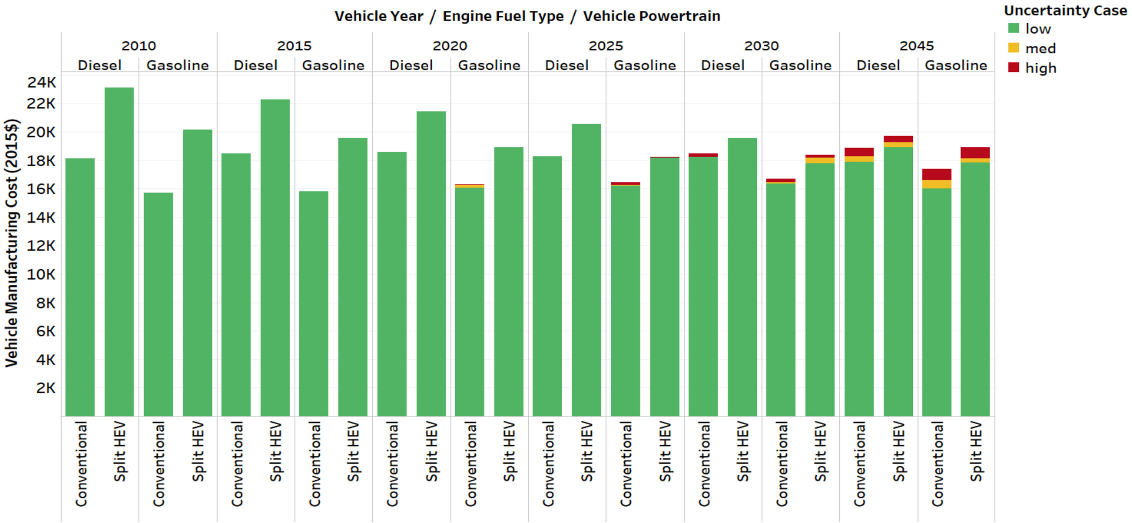

Figure 10: Manufacturing cost of midsize conventional and split HEV vehicles

As can be observed from the illustration, the vehicle prices increase slightly (almost negligible) from lab year 2010 to 2045 for conventional vehicles. The increase in costs can be explained due to several factors, including lightweighting (decrease in vehicle weight is accompanied by material cost increases, due to increase in the use of aluminum or carbon fiber) and advanced component technologies. The impact of this increments in cost is however not observed for split HEV vehicles due to the greater influence of battery cost reductions in the future due to smaller power requirements. It can also be observed that the gasoline vehicles are cheaper than the corresponding diesel configurations.

Figure 11 illustrates the vehicle manufacturing cost evolution for the midsize PHEV vehicles with different AERs.

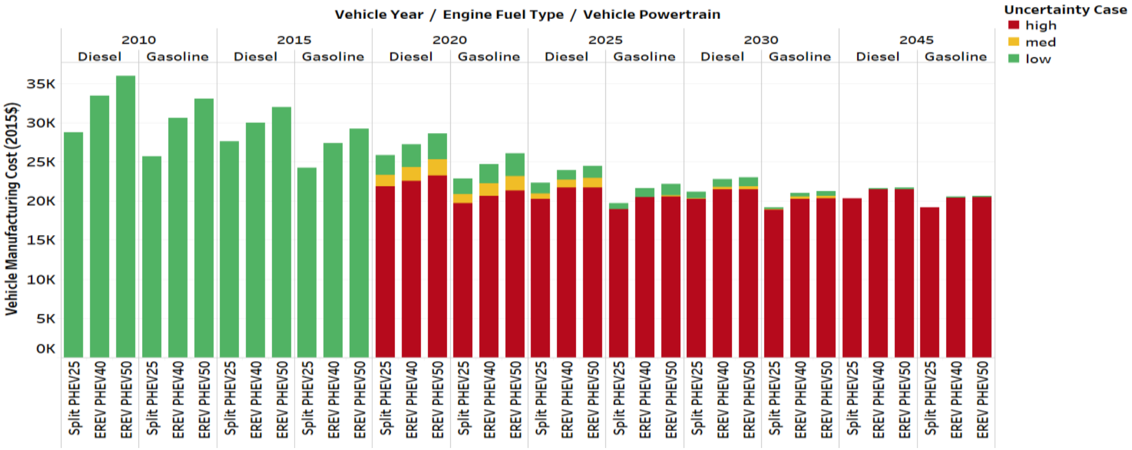

Figure 11: Manufacturing cost of midsize PHEV vehicles

The overall cost follows similar trend lines across the different fuels. Within each case, increasing AER increases the manufacturing cost due to bigger batteries. However, with time, the battery cost decreases, which results in decreased vehicle manufacturing costs. This effect is further fueled by the battery sizes in the future as can be observed by the differences across different AERs.

Figure 12 illustrates the evolution of electric vehicles in terms of manufacturing cost.

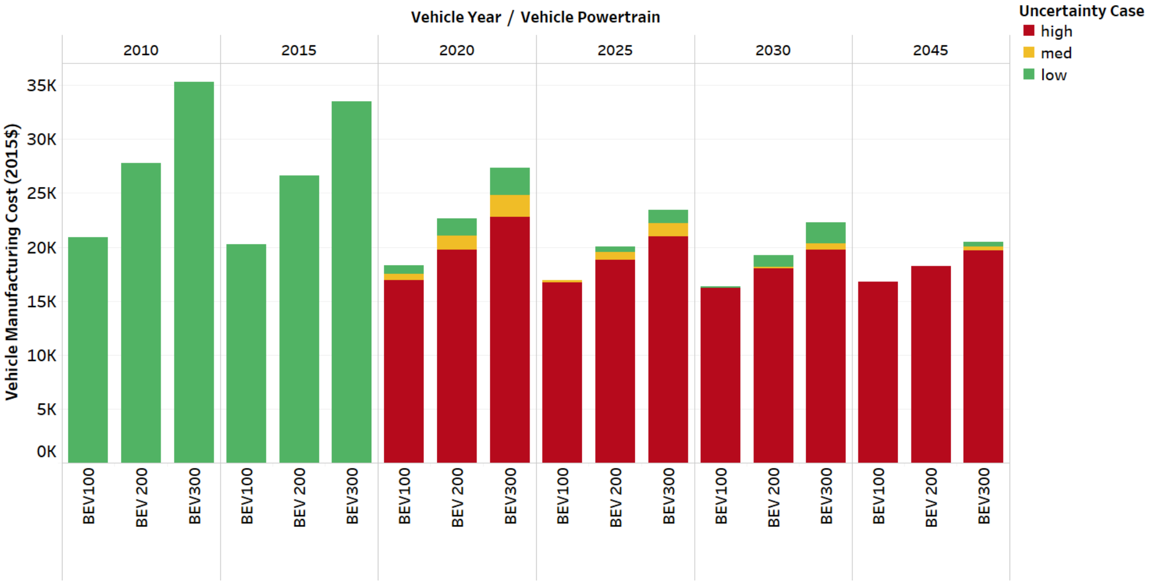

Figure 12: Manufacturing cost of midsize BEV vehicles across various AERs

Lightweighting has an effect on battery sizes, and hence, affects the battery costs in future years. This, in turn, greatly influences the fall in the overall manufacturing costs of the vehicles. It can be seen that the higher-range BEVs take a greater impact on the manufacturing costs in future years.

3.1.4 Vehicle Fuel Consumption vs. Manufacturing Cost

Figure 13 illustrates the comparison of vehicle manufacturing cost vs. fuel consumption for conventional vehicles across multiple vehicle classes.

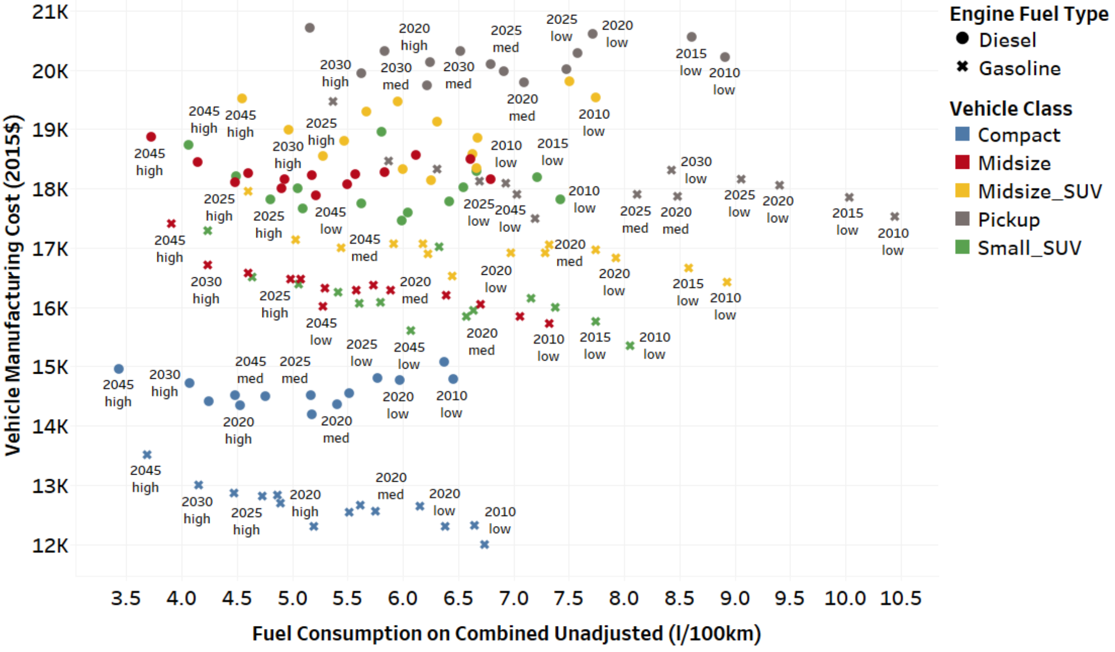

Figure 13: Vehicle manufacturing cost vs. fuel consumption for conventional vehicles

One key observation is that the diesel vehicles have relatively higher manufacturing costs compared to gasoline vehicles. Also, it shows a trend of how the different vehicle classes line up in the spread in terms of fuel consumption and manufacturing costs. Midsize, Small SUVs, and Midsize SUVs cluster closely to each other in terms of fuel consumption and costs, while Compact and Pickup classes lie on the two extremes.

Figure 14 shows the comparison of vehicle manufacturing cost vs. fuel consumption for split HEV vehicles across multiple vehicle classes.

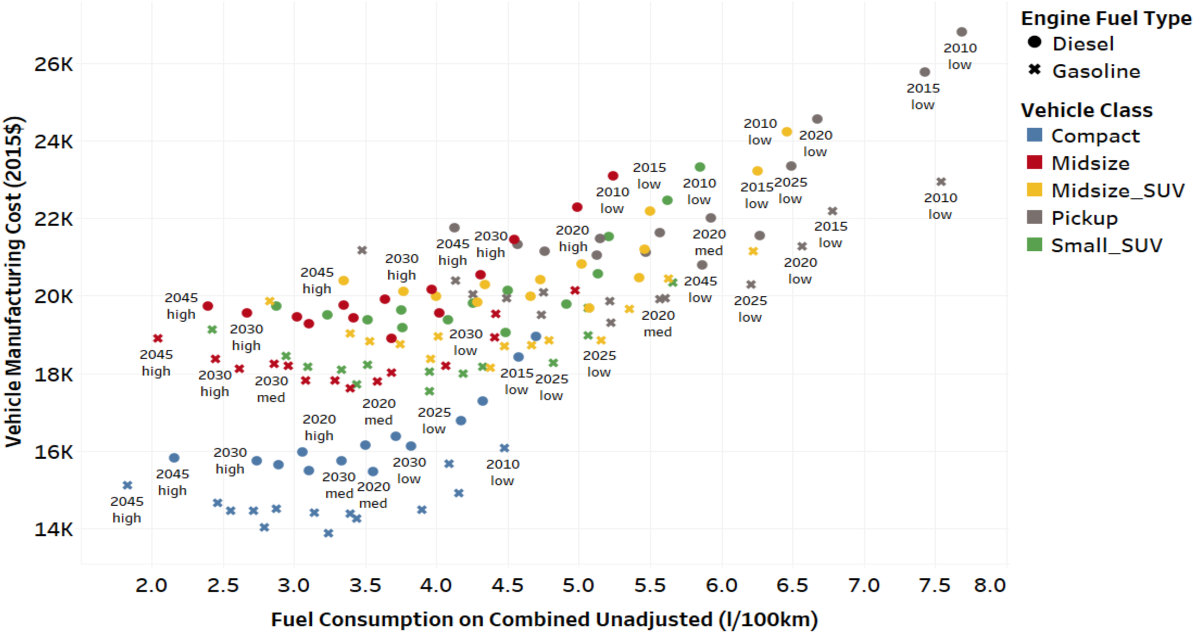

Figure 14: Vehicle manufacturing cost vs. fuel consumption for power-split HEV vehicles

As observed earlier, the diesel vehicles tend to be more expensive when compared to the gasoline vehicles. The effect of the different vehicle classes on fuel consumption and manufacturing costs is similar to that observed earlier. The plot further shows how the manufacturing cost and fuel consumption progresses across the different lab years.

Figure 15 shows the comparison of vehicle manufacturing cost vs. fuel consumption for PHEV vehicles across multiple vehicle classes. For simplicity and to illustrate the focus on the different AERs, only gasoline vehicles are evaluated.

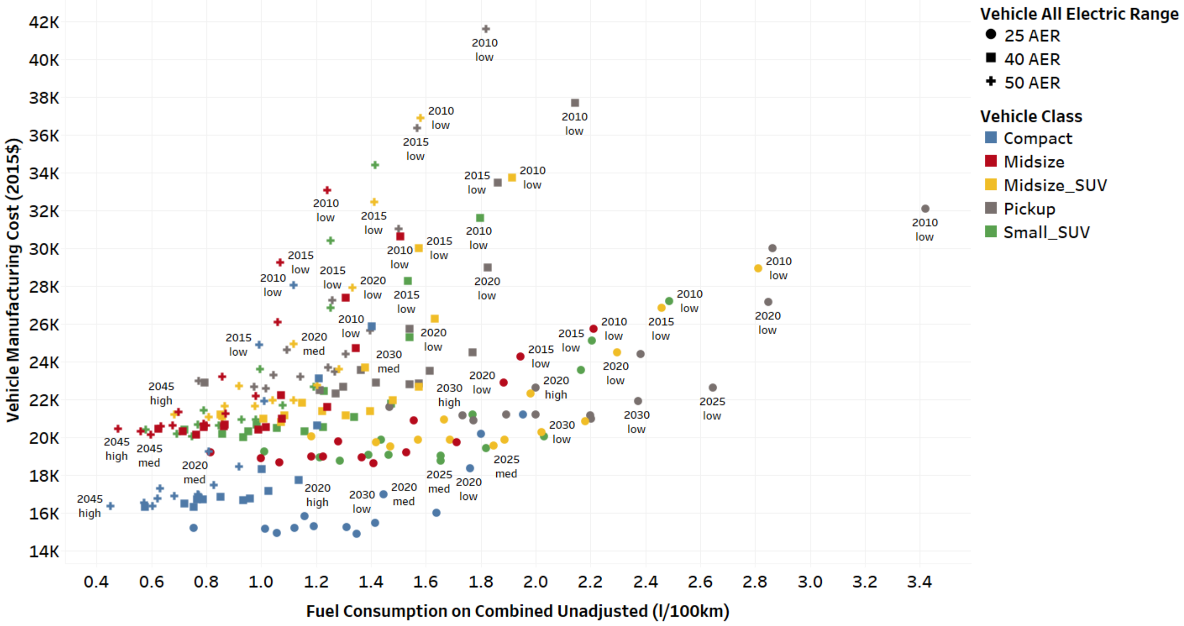

Figure 15: Vehicle manufacturing cost vs. fuel consumption for PHEV vehicles across different AERs

The different vehicle classes follow similar trends as before. It also can be observed that with increasing AERs, the manufacturing cost increases (due to bigger battery sizes) and fuel consumption decreases. The effect of technological improvements over the years can also be seen in terms of reduced fuel consumption and manufacturing costs, moving from lab year 2010 to 2045.

4 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 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 powers, the requirements decrease with time from 2010 to 2045 lab year, due to higher efficiencies, lightweighted vehicles, and the combined effect of advancements in other technologies. Moving from 2010 to 2045 lab year, the engine max power reduces by 3% to 15% for conventional vehicles, and 20% to 35% for power-split HEV vehicles. The decrease is about 22% to 39% for PHEV25 AER, 20% to 38% for PHEV40 AER and 21% to 39.4% for PHEV50 AER vehicles.
- For fuel consumption comparison of conventional and power-split HEV vehicles, a slowly decreasing ratio trend line can be observed. The power-split Midsize vehicle consumes between 24% to 40% less fuel compared to conventional vehicles until 2015 lab year. This drop ranges to about 50% in 2045 lab year on the EPA combined driving procedure.
- In terms of manufacturing costs, a higher drop rate in split HEV vehicles are observed, compared to Conventional vehicles. This is due to the greater influence of the lower battery and electric machine costs, lightweighting, and highly efficient vehicle components. From 2010 to 2045 lab year, the manufacturing cost for split HEV decreases by 6% to 10%. The decrease observed for PHEV25 is about 25%, 33% for PHEV40, and about 38% for PHEV50.

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