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Detailed Assessment of Fuel Cell Vehicles Through 2050 Based on U.S. DOE Research and Innovation

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Executive Summary

The U.S. Department of Energy's (DOE) Hydrogen & Fuel Cell Technologies Office (HFTO) 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, both HFTO and the Vehicle Technologies Office (VTO) has developed specific targets for a wide range of powertrain technologies (e.g., fuel cell system, hydrogen storage, engine, battery, electric machine, lightweighting, etc.).

The objective of the paper is to quantify the impact of HFTO R&D on vehicle energy consumption and cost compared to expected historical improvements across vehicle classes, powertrains, component technologies and timeframes with specific focus on fuel cell vehicles. 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 HFTO R&D targets compared to historical predicted trends.

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] [2]. 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 [3].

Hydrogen & Fuel Cell Technologies Office (HFTO), U.S. Department of Energy (U.S. DOE) generates the advancements in technology associated with fuel cell technologies[4], including vehicle electrification, hydrogen tank assumptions, light weighting, etc. over a given time frame [5]. The Vehicle System Simulation tool Autonomie [6] 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 vehicles, power-split hybrid electric vehicles and fuel cell hybrid. The advancements in technologies are generally evaluated over standard regulatory driving cycles, for fuel economy and cost impact [7].

2 Procedure

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

To implement uncertainties in the assumptions, two different set of targets have been implemented for all years - low technology progress (business as usual), and high technology progress (U.S. DOE goals). The following subsections represent the breakdown involved during the vehicle simulation. The latest report from Argonne [8] details the vehicle level assumptions and procedure involved behind the vehicle modeling and simulation efforts.

2.1 Fuel Cell Configuration

For the purpose of this study, series configurations are considered for the different fuel cell powertrains. Figure 1 describes the configuration of the FC HEV powertrain. It includes a gearbox in addition to the final drive, as well as DC/DC converter for the high-voltage battery and the 12-V accessories.

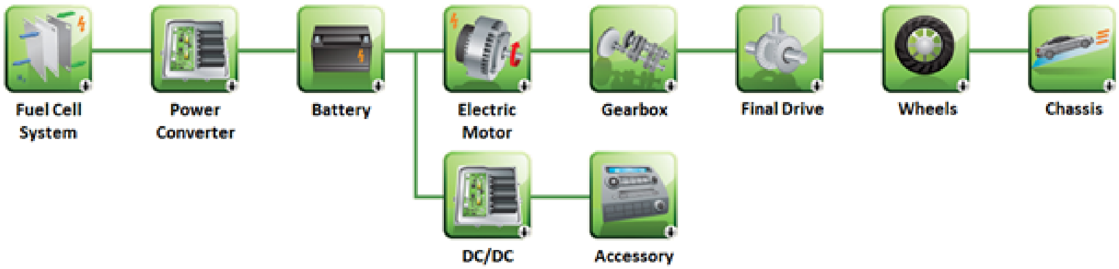

Figure 1: Fuel Cell HEV configuration

Due to the higher efficiencies in fuel cell system, the battery is not used as the primary power source. The vehicle-level control strategies have been implemented for the core functionality of the battery to store the regenerative braking energy from the wheel and return it to the system when the vehicle operates at low speed. The battery also provides power during the transient operation when the fuel cell is unable to meet the demand. The state-of-charge (SOC) of the battery is monitored and regulated to ensure that the battery remains within the defined operating ranges.

3 Technology Target Assumptions

The technology target assumptions received from HFTO has been assigned accordingly over the pre-defined timeframe for the different vehicle classes. Table 1 below illustrates a sample of the assumptions associated with the fuel cell system technologies over time. The vehicle simulations (and results to follow) represent the ”lab years” 2015, 2020, 2025, 2030, and 2045.

Table 1: Fuel Cell System & Hydrogen Tank Assumptions

Lab Year	2015	2020		2025		2030		2045	
Technology Progress	Low	Low	High	Low	High	Low	High	Low	High
Conventional Engine Peak Efficiency (%)	36	38	43	40	43	42	45	44	47
Power-split HEV Engine Efficiency (%)	40	40	46	41	46	41	48	43	50
FC System - Specific Power (W/kg)	650	860	860	860	900	860	900	860	1000
FC System Peak Efficiency ($\%$)	61	64	64	64	65	64	67	64	68
FC System - Specific Cost ($\$/kW$)	165	111	111	77	66	64	52	40	30.0
H_2 Tank Weight (kg tank / kg H_2)	21	22.7	22.7	22.7	22.7	22.7	22.7	22.7	22.7

The hydrogen storage tank costs are evaluated using the equation:

$$HydrogenStorageCost = A + B \times FuelMass(kg) \quad (1)$$

The values for the coefficients A, B across the timeframes are defined in table 2. The assumptions have been given for the lab years 2015 - 2045 to evaluate the acceleration of cost assumptions.

Table 2: H_2 Storage Tank Cost Assumptions (2015$)

Lab Year	2015	2020		2025		2030		2045	
Technology Progress	Low	Low	High	Low	High	Low	High	Low	High
A	1946	1946	1946	1946	1849	1946	981	1946	679
B	352	352	352	352	236	352	191	352	145

The FuelMass is determined through sizing the fuel-cell vehicles to run for 300 and 400 miles (Fuel Cell 300 and Fuel Cell 400) on the combined procedure (EPA adjusted label). 100% of the available hydrogen in the storage tank is assumed as usable hydrogen.

Table 3 details the different vehicle classifications defined for various performance times (0-60 mph time) in seconds as well as corresponding vehicle attributes.

Table 3: 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

4 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 as 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 [3]. 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 review of the EPA test car data. 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 EPA procedure.

5 Results & Analysis

The results and analysis of the vehicle simulations would comply with the full range of timeframes as mentioned earlier.

5.1 Vehicle Components Size

5.1.1 Fuel Cell Power

Fuel-cell systems show a decrease in peak power over time, due to vehicle lightweighting and improved fuel cell system efficiencies. Figure 2 illustrates the fuel cell peak power for the different fuel-cell vehicles across different performance categories.

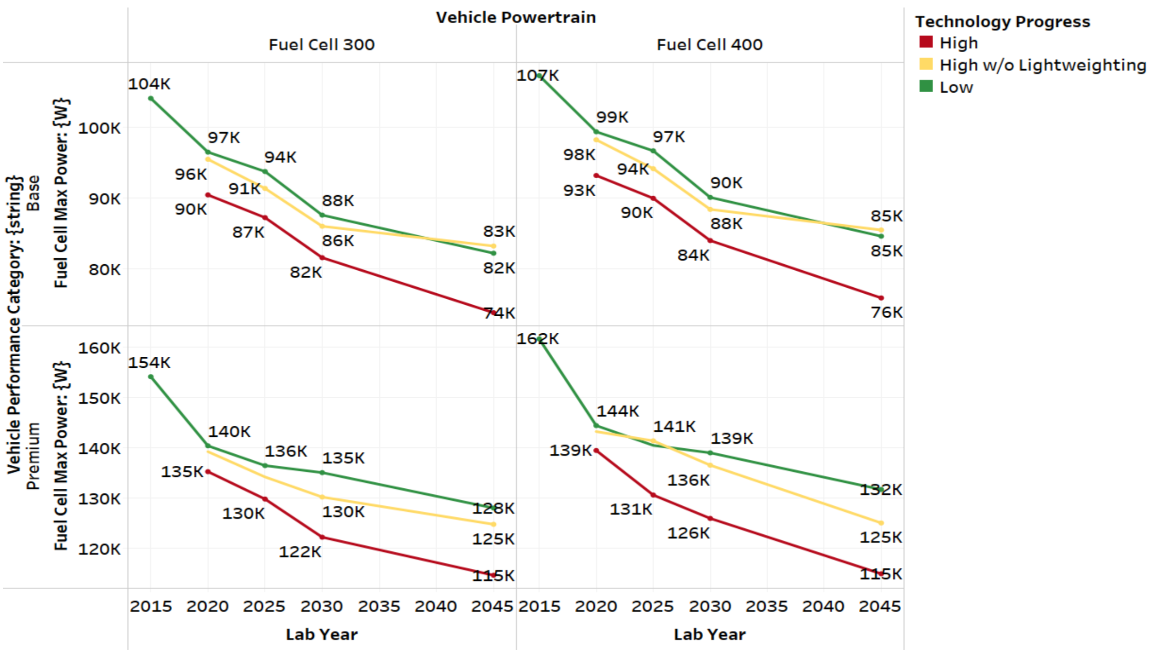

Figure 2: Fuel-cell system power of different fuel cell vehicles for small SUV across different performance categories

The reduction in fuel cell power requirement going from lab year 2015 to 2045 ranges from 21% to 29% across different ranges.

5.1.2 H_2 Fuel Mass

Figure 3 shows the evolution in hydrogen fuel mass for fuel cell vehicles for small SUVs across performance categories, across the specified timeframes.

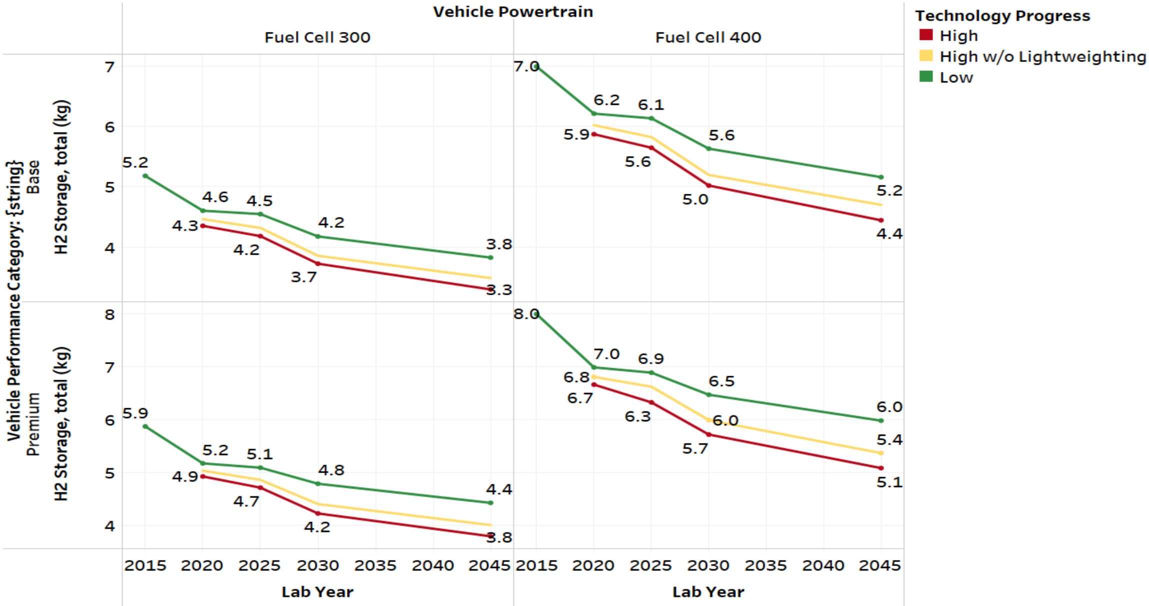

Figure 3: H_2 Fuel Mass (kg) fuel-cell vehicles of small SUVs across different performance categories

The hydrogen fuel mass represents the amount of hydrogen present in the tank and is used by the fuel cell vehicle during the simulations since 100% of the available hydrogen is considered as usable.

Advancements in vehicle lightweighting and aggressive fuel cell component targets result in reduced hydrogen mass requirements. From lab year 2015 to 2045, the hydrogen fuel mass reduces by 27% to 37% across the different technology progress and performance categories for small SUVs.

5.1.3 H_2 Storage Mass

Figure 4 shows the evolution in hydrogen storage mass for small SUV fuel cell vehicles for across performance categories, across the specified timeframes.

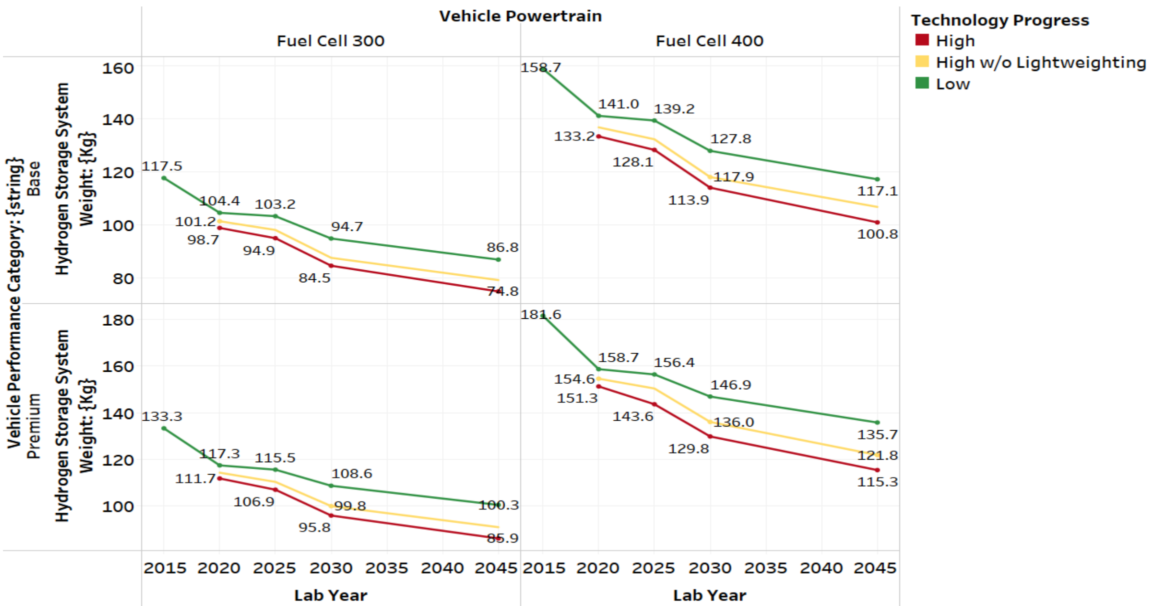

Figure 4: H_2 Storage Mass (kg) for fuel-cell vehicles across different performance categories

The reduction in hydrogen storage mass reflects the storage weight assumptions across the different timeframes. It is a combined effect of the reduction in the coefficient values used in the formula, along with the reduced h_2 fuel mass. From lab year 2015 to 2045, the hydrogen storage mass reduces by 26% to 36% for small SUVs across the different technology progresses and performance categories. This range reflects the trend-line observed across vehicle classes. It can be seen that with increasing vehicle weight, the rate of reduction in the hydrogen storage mass is higher.

5.2 Evolution of Fuel Displacement

Figure 5 illustrates the fuel consumption evolution of small SUV fuel cell vehicles across the defined time frames of lab years 2015 - 2045. The metric used for illustration is the gasoline equivalent fuel economy for the combined drive cycles using the EPA adjusted values.

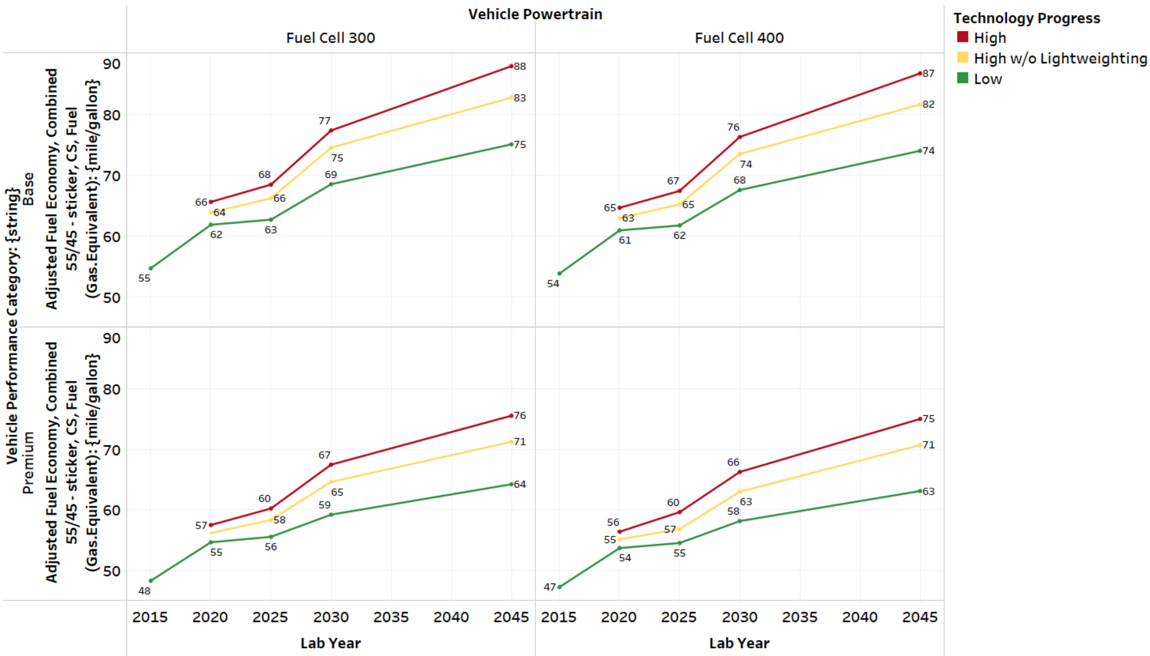

Figure 5: Gasoline-equivalent fuel economy for small SUV fuel cell vehicles

The figure illustrates that the fuel cell vehicles consume about 26% - 38% less fuel by lab year 2045, when compared to the reference lab year 2015.

5.2.1 Fuel Cell vs. Conventional/Split HEV Powertrains

Figure 6 shows the evolution in the comparison of EPA adjusted fuel economy on combined procedure for fuel cell HEV vehicles, along with conventional and power-split HEVs of small SUV vehicle class.

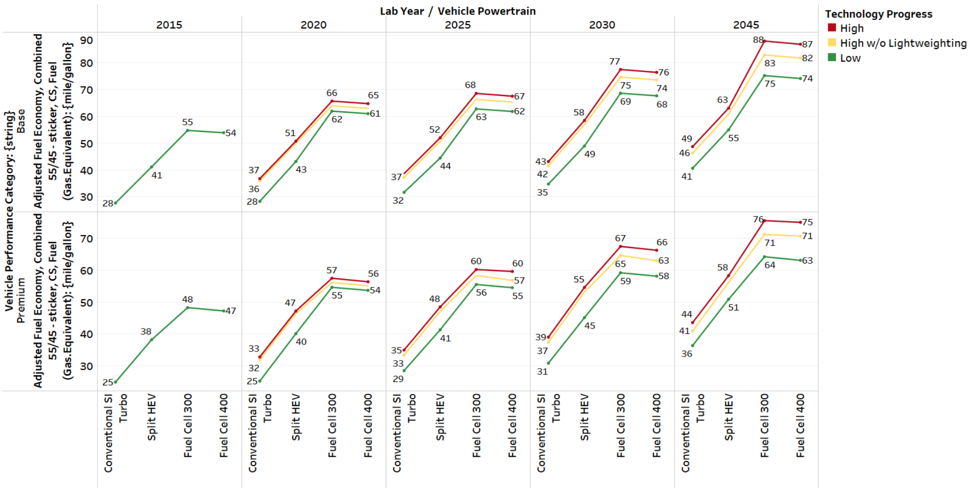

Figure 6: Gasoline-equivalent fuel economy across powertrains for small SUVs

The comparison between the gasoline conventional turbo, Split HEV and the fuel-cell small SUV vehicles can be further evolved in terms of improvements in fuel economy between the fuel-cell vehicles, Split HEVs and the gasoline conventional turbo vehicles for small SUV vehicle class as seen in figure 7.

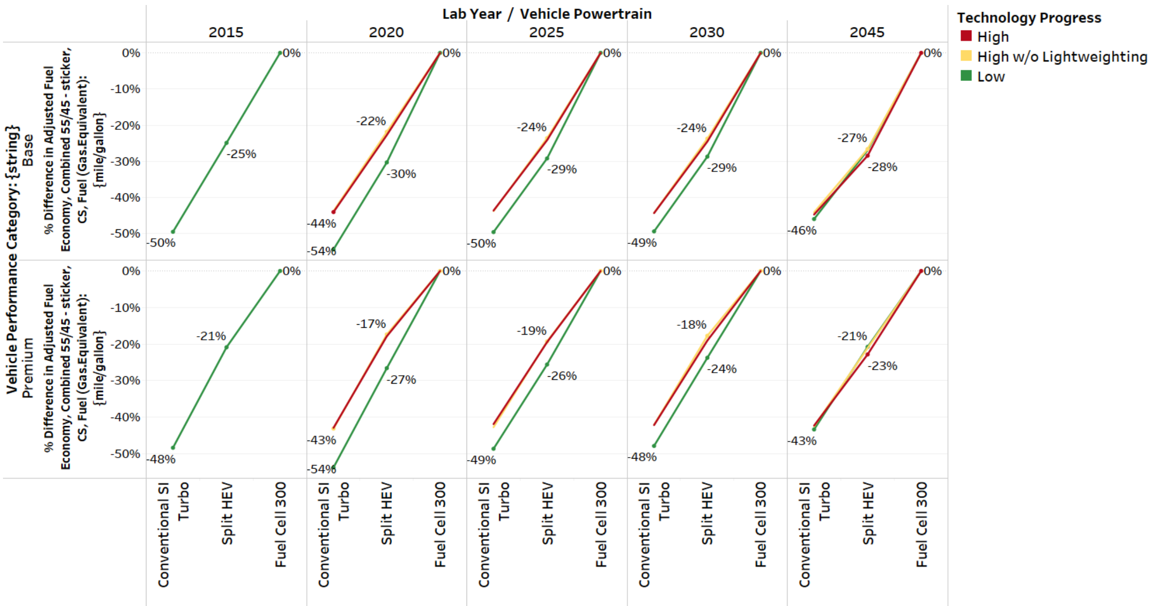

Figure 7: % Diff. in unadjusted fuel economy for midsize gasoline conventional, Split HEVs vs. fuel cell HEVs

The effects of technology improvements in the evolution of conventional vehicles can be observed from the graph. It can be seen that in the reference year (2015 lab year), the gasoline-equivalent fuel economy of fuel-cell vehicles is about 48% - 50% higher compared to the gasoline conventional vehicle and 21% to 25% higher compared to Split HEV. However this improvement decreases to about 43% to 46% for the high case in lab year 2045 for gasoline conventional vehicles but remains steady at 21% to 27% for Split HEVs. This shows the fuel-cell vehicles respond to a less aggressive advancement in technologies that result in lesser fuel consumption compared to gasoline conventional vehicles and Split HEVs.

5.3 Cost Feasibility

5.3.1 Fuel Cell System Cost

Figure 8 shows the evolution in the costs of fuel cell systems from lab years 2015 to 2045 for the small SUV fuel cell vehicles.

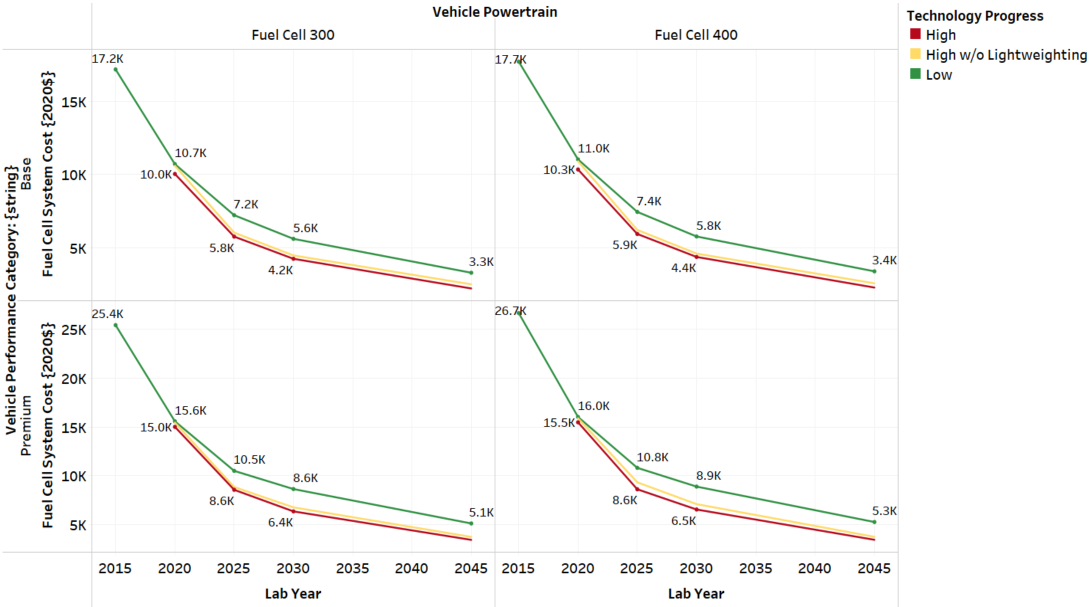

Figure 8: Fuel cell system costs for small SUV vehicle class

The evolution in fuel cell system costs represent the effects of accelerated cost targets from HFTO. It is further impacted by the reduction in fuel cell power over the period due to the advancement in fuel cell technology targets. Over the years, it can be seen that the fuel cell system cost reduces by 80% to 87% by lab year 2045 across the different performance categories.

5.3.2 H_2 Storage Cost

Figure 9 shows the evolution in the hydrogen storage tank costs over the defined timeframe from lab years 2015 to 2045 for the small SUV fuel-cell vehicles.

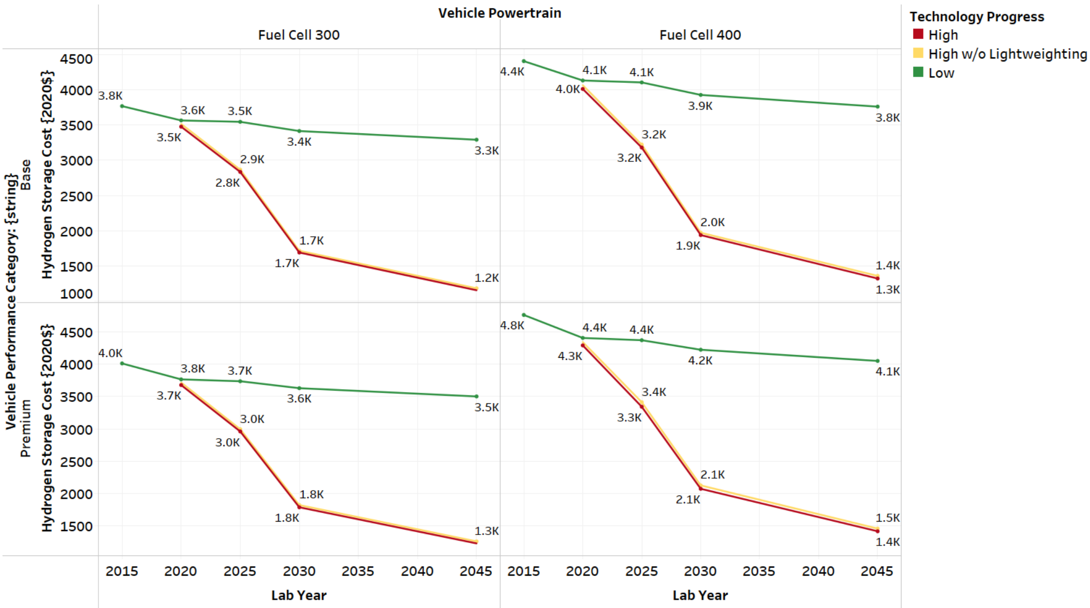

Figure 9: Hydrogen storage system costs for small SUV vehicle class

It can be seen that over the years, the cost reduces by 13% to 14% for low technology progress category and 68% to 72% for high technology progress, across the different performance categories.

5.3.3 Vehicle Manufacturing Cost

Figure 10 shows the evolution in the manufacturing costs of small SUV fuel cell vehicles. These values represent the manufacturing costs and do not account for retail price factors.

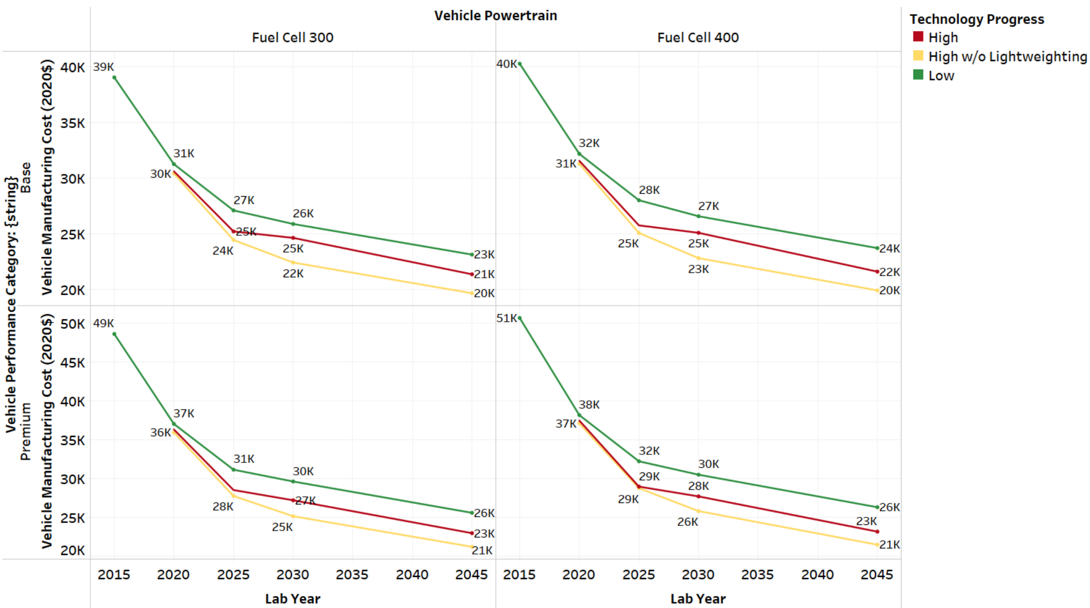

Figure 10: Fuel cell vehicle manufacturing costs for small SUV vehicle class

It can be seen here that the decreasing fuel cell system costs and hydrogen storage costs influences the reduction in vehicle manufacturing costs. From lab year 2015 to 2045, the cost reduces by 37% to 46% for low technology progress and 44% to 54% for high technology progress, across the different performance categories. Furthermore, it can be seen that the high technology progress case without lightweighting application results in the most significant reduction as the additional cost of lightweighting is not being associated.

5.4 Vehicle Manufacturing Cost vs. Fuel Economy

Figure 11 shows the trendlines in unadjusted fuel economy vs vehicle manufacturing costs for the different electrified powertrains, for all vehicle classes.

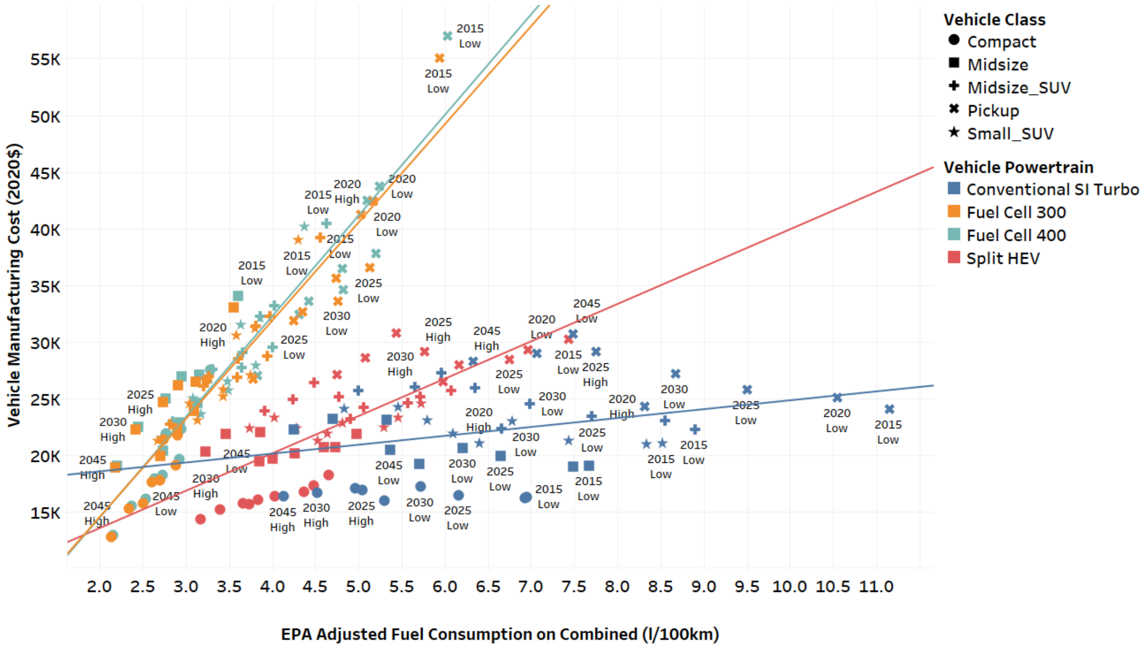

Figure 11: EPA adjusted fuel consumption vs. manufacturing cost of different electrified powertrains across vehicle classes

Looking at the evolution of manufacturing costs with respect to fuel economy across the different vehicle powertrains, a rapid evolution in fuel cell vehicles can be observed. Moving from 2015 to 2045 lab years, it can be seen the fuel economy increases while the manufacturing cost decreases. The rate of this decrease with respect to the fuel efficiency improvement can be observed from the slope of the trendline for the different vehicle powertrains. The fuel cell vehicles consume far less fuel in 2045 lab year compared to 2015 lab year, while the reduction manufacturing costs affect to a far greater extent. This is due to the acceleration of fuel cell cost targets, compared to the technology assumptions. Compared to the other electrified vehicle powertrains, the fuel cell vehicles has a far more aggressive slope with respect to manufacturing cost reductions.

5.4.1 Levelized Cost of Driving

Figure 12 shows the levelized cost of driving of small SUV fuel cell vehicles. The detailed assumptions for cost of driving and ownership is provided in the full report.

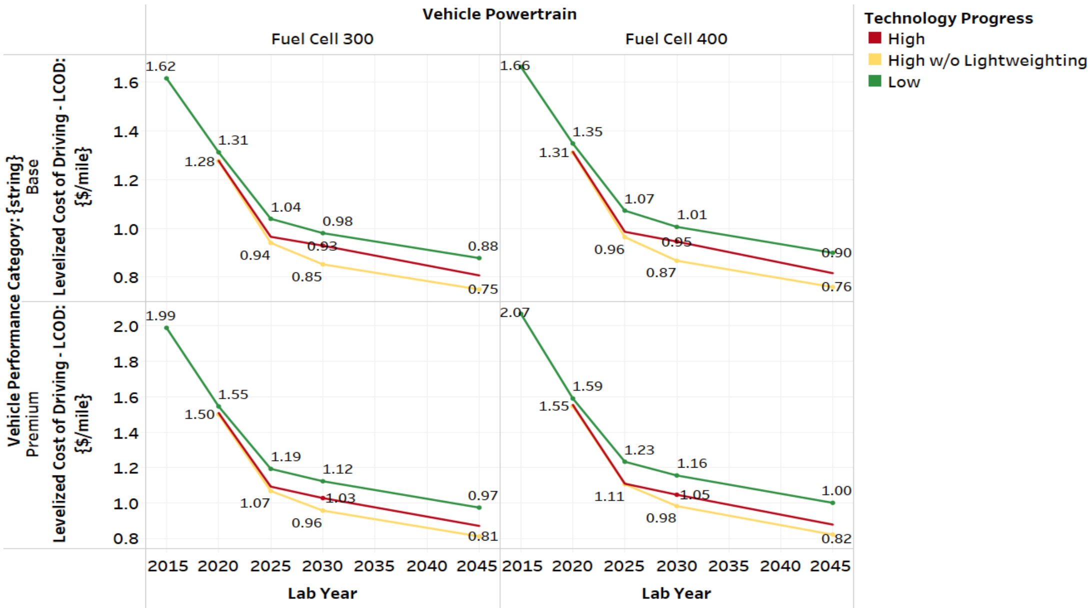

Figure 12: Fuel cell vehicle cost of driving for small SUV vehicle class

It can be seen here that the decreasing fuel cell system costs and hydrogen storage costs influences the reduction in fuel cell vehicle cost of driving. Along with the decreasing component costs, the reduction in hydrogen fuel prices also influences the accelerated reduction in cost of driving. From lab year 2015 to 2045, the cost reduces by 46% for low technology progress and 54% for high technology progress, across the different performance categories.

6 Summary and Conclusion

The paper presents a large scale simulation process used to evaluate the fuel displacement and cost impacts of fuel cell vehicles over a period of time, along with a comparison of fuel cell vehicles to conventional vehicles with respect to fuel economy.

The following conclusions can be drawn from the study:

- In terms of fuel cell power, the requirement decrease with time from 2015 to 2045 lab year, due to higher efficiencies, light weighted vehicles and the combined effect of advancements in other technologies. From 2015 to 2045 lab year, the fuel cell power decreases by 11% to 22% for compact, 13% to 31% for midsize, 19% to 28% for small SUV, 21% to 29% for midsize SUV, and 21% to 29% for pickup vehicle classes. The same is seen across the two performance categories.
- In terms of amount of hydrogen used during the EPA combined procedure runs, the amount decreases over time for the different fuel cell vehicles. From 2015 to 2045 lab year, the hydrogen fuel mass reduces by 36.3% for compact, 41.2% for midsize, 40% for Small SUV, 41% for Midsize SUV and 40% for Pickups. Similar range is also observed across the different performance categories.
- The improvement in fuel economy compared to that for conventional gasoline vehicles decreases over time across the different vehicle classes. It decreases from 63-66% in 2015 lab year to between 55% and 57% in 2045 lab year for midsize class. A similar trend is also seen across different vehicle classes.

- In terms of vehicle manufacturing costs, the value reduces by at most 54% across the different vehicle performance categories. This is due to the accelerated influence of lower fuel cell system and hydrogen storage costs.

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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.