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Light-duty-vehicle fuel consumption, cost and market penetration potential by 2020

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Abstract

The U.S. Department of Energy (DOE) Vehicle Technologies Program (VTP) is developing more energy-efficient and environmentally friendly highway transportation technologies that will enable America to use less petroleum. The 1993 Government Performance and Results Act (GPRA) holds federal agencies accountable for using resources wisely and achieving program results. GPRA requires agencies to develop plans for what they intend to accomplish, measure how well they are doing, make appropriate decisions on the basis of the information they have gathered, and communicate information about their performance to Congress and to the public. Owing to the large number of component and powertrain technologies considered, the benefits of the VTP R&D portfolio were simulated using Autonomie, Argonne National Laboratory's vehicle simulation tool. This paper evaluates major powertrain configurations (conventional, power-split, Extended Range Electric Vehicle (EREV) and battery electric drive) and fuels (gasoline, diesel, hydrogen and ethanol) for three different time frames (2010, 2015, and 2020). Uncertainties were also included for both performance and cost aspects by considering three cases (10%, 50% and 90% uncertainty) representing technology evolution aligned with original-equipment-manufacturer improvements based on regulations (10%) as well as aggressive technology advancement based on the VTP (90%). The paper will provide fuel consumption, vehicle cost, and market penetration potentials for each technology considered.

Keywords: HEV, PHEV, vehicle fuel consumption and cost, market penetration.

1 Introduction

The U.S. Department of Energy (DOE) Vehicle Technologies Program (VTP) is developing more energy-efficient and environmentally friendly highway transportation technologies and tools that will enable America to use less petroleum. The long-term aim is to develop "leapfrog" technologies that will provide Americans with greater freedom of mobility and energy security while lowering costs and reducing impacts on the environment. The DOE VTP examines pre-competitive, high-risk research needed to develop the following:

- Component and infrastructure technologies necessary to enable a full range of affordable cars and light trucks.
- Fuelling infrastructure to reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions without

sacrificing freedom of mobility and freedom of vehicle choice.

As part of this ambitious program, numerous technologies are addressed, including engines, energy storage systems, fuel-cell (FC) systems, hydrogen storage, electric machines, and materials, among others.

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Owing to the large number of component and powertrain technologies considered in the VTP, the benefits of each were simulated using Autonomie [2]. Argonne designed Autonomie to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process, from modeling to control. Autonomie, a forward-looking model developed using MathWorks tools, offers the ability to quickly compare powertrain configurations and component technologies from a performance and fuel-efficiency point of view. A detailed description of the software can be found in reference [3].

2 Methodology

To evaluate the fuel-efficiency benefits of advanced vehicles, each vehicle is designed from the ground up on the basis of assumptions about each component. Each vehicle is sized to meet the same vehicle technical specifications, such as performance and grade-ability. The fuel efficiency is then simulated using the Urban Dynamometer Driving Schedule (UDDS) and Highway Federal Emissions Test (HWFET) cycles. The vehicle costs are calculated from the components' characteristics (power, energy, weight, etc.). Both the cost and fuel efficiency values are then used to define the market penetration of each technology and finally to estimate the amount of fuel saved. The process is highlighted in Figure 1.

This paper will focus on the first phases of the project: fuel efficiency, cost and market penetration.

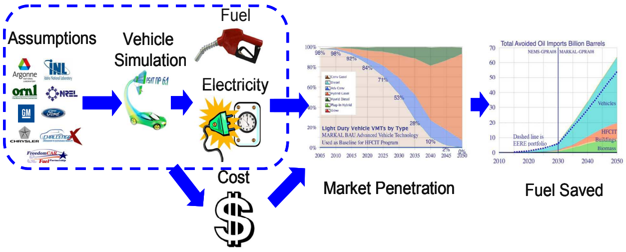

Figure 1: Process to evaluate vehicle fuel efficiency and cost of advanced technologies

To properly assess the benefits of future technologies, several options were considered, as shown in Figure 2:

- Three time frames: 2010, 2015, and 2020;
- Five powertrain configurations: conventional, Hybrid Electric Vehicle (HEV), power-split Plug-in Hybrid Electric Vehicle (PHEV), FC HEV, and Electric Vehicle (EV);
- Four fuels: gasoline, diesel, ethanol, and hydrogen; and
- Three risk levels: low, average, and high cases. These correspond, respectively, to 10% uncertainty (aligned with original equipment-manufacturer [OEM] improvements based on regulations), 50% uncertainty, and 90% uncertainty (aligned with aggressive technology advancement based on the DOE VTP). These levels are explained more fully below.

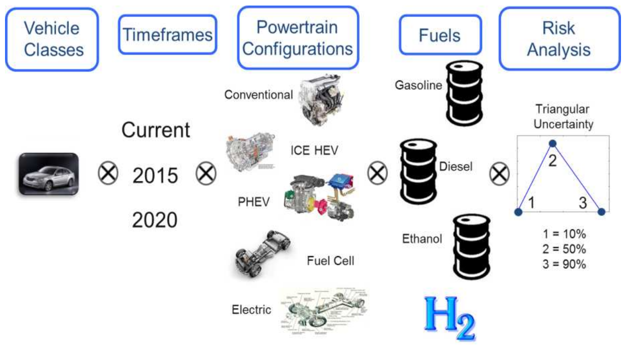

Figure 2: Vehicle classes, time frames, configurations, fuels, and risk levels considered

Overall, close to one thousand vehicles were defined and simulated in Autonomie. This paper does not address micro or mild hybrids and does not focus on emissions. Also, this paper will focus on a single vehicle class, i.e., midsize.

For each component, assumptions were made (i.e., efficiency, power density), and three separate values were defined to represent the 90th, 50th, and 10th percentile, respectively. A 90% probability means that the technology has a 90% chance of being available at the time considered. For each vehicle considered, the cost assumptions also follow a triangular uncertainty (Figure 3). Each set of assumptions, however, is used for each vehicle, and the most efficient components are not automatically the cheapest. As a result, for each vehicle considered, we simulated three options for fuel efficiency. Each of these three options also has three values representing the cost uncertainties [4]. Hereafter, this uncertainty will be represented in the figures with an error bar.

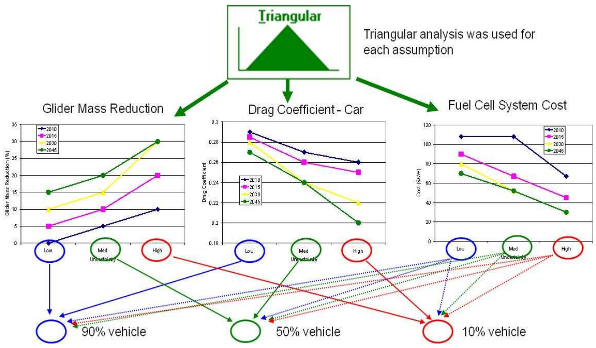

Figure 3: Uncertainty process description

3 Assumptions

3.1 Engine

Several state-of-the-art internal combustion engines (ICEs) were selected as the baseline for the fuels considered: gasoline (spark ignition or SI), diesel (compression ignition or CI), ethanol (E85), and hydrogen (H_2). The gasoline, diesel, and ethanol engines used for reference conventional vehicles were provided by automotive car manufacturers, while the port-injected hydrogen engine data were generated at Argonne [5]. The engines used for HEVs and PHEVs are based on Atkinson cycles, generated from test data collected at Argonne's dynamometer testing facility [6]. Table 1 shows the engines selected as a baseline for the study, and Figure 4 shows the peak efficiencies of the different fuels and technologies.

Table 1: Engines selected

Fuel	Source	Displace-ment (L)	Peak Power (kW)
SI (Conventional)	OEM	2.4	123
CI	OEM	1.9	110
H_2	Argonne	2.2	84
E85 (Conventional)	OEM	2.2	106
SI/E85 (HEV)	Argonne	1.5	57

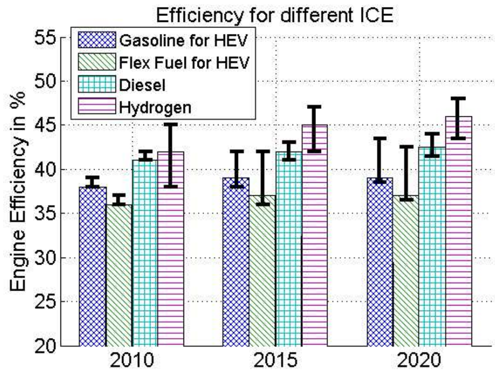

Figure 4: ICE peak efficiency for diesel, hydrogen, and gasoline

3.2 Fuel Cell System

Extensive research and development is being conducted on fuel cell (FC) vehicles because of their potential for high efficiency and low (even zero) emissions. Because FC vehicles remain expensive and demand for hydrogen is limited at present, very few fueling stations are being built. To try to accelerate the development of a hydrogen economy, some OEMs in the automotive industry have been working on a hydrogen-fueled ICE as an intermediate step.

Figure 5 shows the evolution of the FC system peak efficiencies. Currently, the peak FC efficiency is assumed to be at 55% and is projected to increase to 60% by 2015. A value of 60% has already been demonstrated in laboratories and is believed to be in some prototype vehicles. The peak efficiencies will remain constant in the future, as most research is expected to focus on reducing cost and increasing durability.

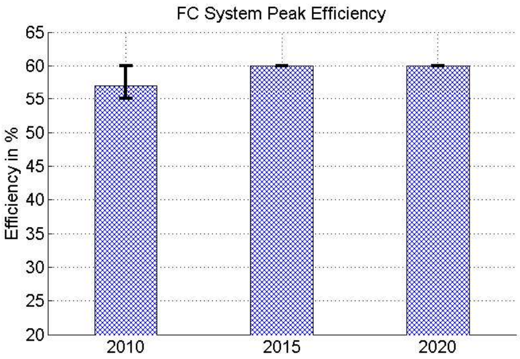

Figure 5: Fuel-cell system efficiency

3.3 Hydrogen Storage

The evolution of hydrogen storage systems is vital to the introduction of hydrogen-powered vehicles. As in the case of the FC systems, all of the assumptions used for hydrogen storage were based on values provided by DOE. Overall, the volumetric capacity dramatically increases between the reference case and 2020 (Figure 6).

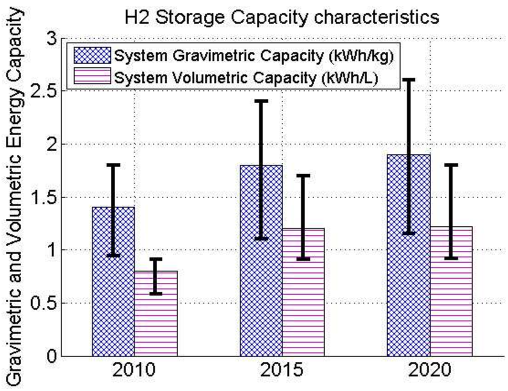

Figure 6: Hydrogen storage capacity in terms of hydrogen quantity

3.4 Electric machine

Two different electric machines will be used as references in the study:

- The power-split vehicles run with a permanent-magnet electric machine (similar to that used in the Toyota Camry [7]), which has a peak power of 105 kW and a peak efficiency of 95%.
- The series-configuration (FC) and electric vehicles use an induction electric machine with a peak power of 72 kW and a peak efficiency of 95%.

Figure 6 and Figure 7 respectively show the electric machine specific power and peak efficiencies.

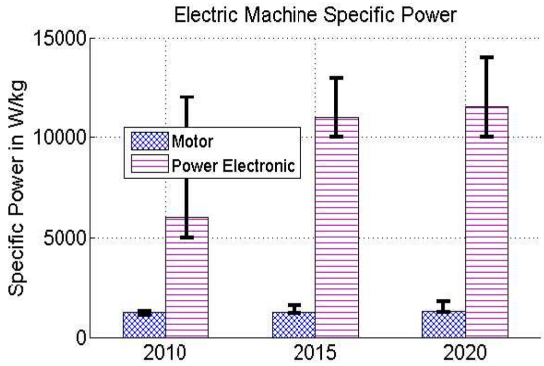

Figure 7: Motor power and peak efficiency values

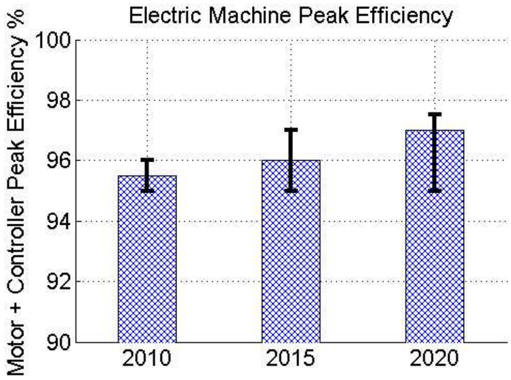

Figure 8: Motor peak efficiency

3.5 Energy System Storage

The battery used for the HEV reference case is a nickel metal hydride battery. It is assumed that this technology is the most likely to be used until 2015. The model used is similar to the one found in the Toyota Prius. For PHEV applications, all of the vehicles are run with a lithium-ion battery model from Argonne [8].

After a long period of time, batteries lose some of their power and energy capacity. To maintain the same performance at the end of life (EOL) compared to the beginning of life, an oversize factor is applied while sizing the batteries for both power and energy. These factors are supposed to represent the percentage of power and energy that will not be provided by the battery at the EOL as compared to the initial power and energy provided by the manufacturer. The oversize factor is reduced over time to reflect an improvement in the ability of batteries to deliver the same (uniform) performance throughout their life cycles.

Table 2: Battery Technologies

	Source	Technology	Reference Cell Capacity [Ah]
HEV	Idaho Nat lab Battery manufacturer	NiMH Li-ion	6.5 6
PHEV	Argonne Nat Lab	Li-ion	41

2010			2015			2020		
Ref/Low	avg	high	low	avg	high	low	avg	high
NiMH	NiMH	NiMH	NiMH	Li-ion			Li-ion	

Figure 9res 9 and 10 show battery cost. The battery cost for HEV applications will decrease over time for all cases, but the reduction is more aggressive for the high case between 2010 and 2015.

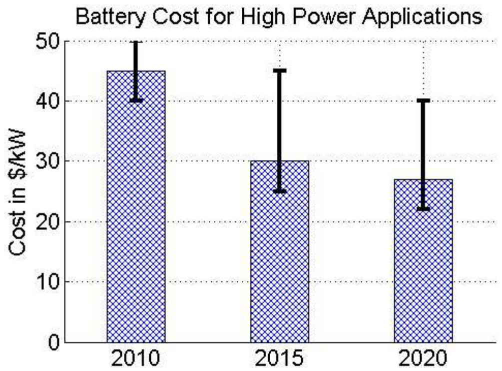

Figure 9: HEV battery cost

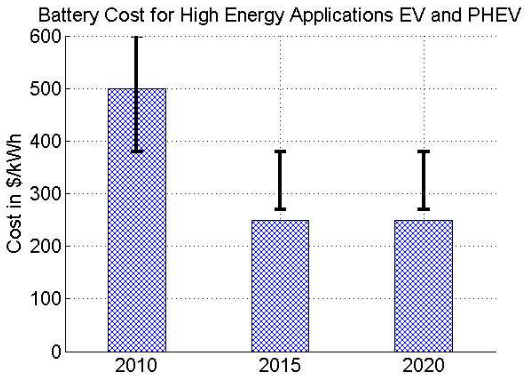

Figure 10: PHEV and EV battery cost

3.6 Vehicle

One of the main factors affecting fuel consumption is vehicle weight. Lowering the weight ("light-weighting") reduces the forces required to follow the vehicle speed trace. As a result, the components can be downsized, resulting in decreased fuel consumption. However, the impact of lightweighting is not the same for all of the powertrain configurations; studies have shown that the technology has greater influence in lowering fuel consumption in conventional vehicles than it does in their electric-drive counterparts [9] (Figure 11).

	Glider Mass (kg)	Frontal Area (m^2)	Tire	Wheel Radius (m)
Midsize	996	2.24	P195/65/R15	0.317

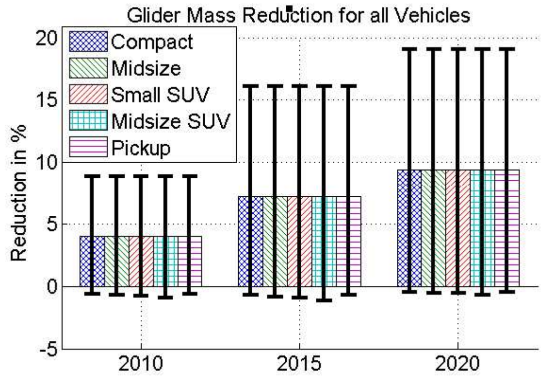

Figure 11: Glider mass reduction

Reductions in rolling resistance, frontal area, and drag coefficient also have the potential to improve fuel consumption significantly, as these factors also lead to a reduction in the force required at the wheels.

4 Vehicle Technical Specifications

All of the vehicles have been sized to meet the same requirements:

- Initial vehicle movement to 60 mi/h in 9 sec +/− 0.1 sec,
- Maximum grade of 6% at 65 mi/h at gross vehicle weight, and
- Maximum vehicle speed >100 mi/h.

These requirements are a good representation of the current American automotive market as well as American drivers' expectations.

Table 3 summarizes the travel distances with a full tank of fuel for the different powertrains. The vehicles using gasoline, diesel, or ethanol fuel have been sized for a distance of 500 miles on the combined driving cycle, based on unadjusted fuel consumption. All vehicles have a range of at least 320 miles except the battery electric vehicle (BEV) (100 miles) and the hydrogen vehicles.

Table 3: Travel distances in miles

		Time frame		
Vehicle Type	**Ref**	**2010**	**2015**	**2020**
Conv. H_2	320	320	320	320
HEV H_2, FC	320	320	320	320
PHEV H_2, FC	320 + AER[a]	320 + AER	320 + AER	320 + AER
BEV	100	100	100	100

[a] AER = all-electric range.

Input mode power-split configurations, similar to those used in the Toyota Camry, were selected for all HEV and PHEV applications using engines. The series FC configurations use a two-gear transmission to be able to achieve the maximum vehicle speed requirement. The vehicle-level control strategies employed for each configuration have been defined in previous publications [10-15].

5 Vehicle Sizing

Several automated sizing algorithms were developed to provide a fair comparison between technologies. These algorithms are specific to the powertrain (i.e., conventional, power-split, series, electric) and the application (i.e., HEV, PHEV). As shown in Figure 12, the engine power for all of the powertrains decreases over time. The power-split HEV powertrain shows the highest engine power reduction, ranging from 6% to 36%, whereas power for the conventional engine decreases by only 3% to 27%. The engine power is higher when the all-electric range increases because the power is sized on the basis of acceleration and grade and because the different PHEVs (for the same fuel) vary from one another only by having a successively larger battery (which results in a heavier car).

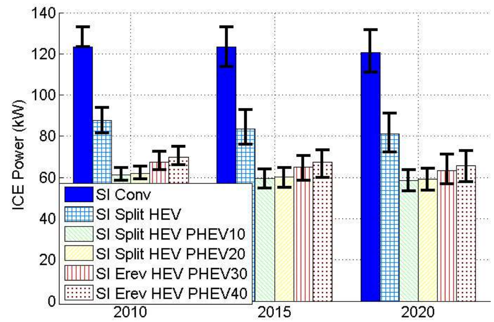

Figure 12: Engine power for gasoline-fueled cars

Figure 13 shows the electric machine power for the gasoline HEVs and PHEVs. The electric machines used for the PHEV10 and PHEV20 cases are sized to have the ability to follow the UDDS drive cycle in EV mode, while those used for the PHEV30 and PHEV40 cases allow the vehicles to follow the US06 drive cycle. It is important to note that the vehicles have the ability to drive the UDDS cycle in electric mode—the control strategy employed during fuel-efficiency simulation—which is based on blended operation. However, the power does not increase significantly compared to HEVs for the power-split configuration.

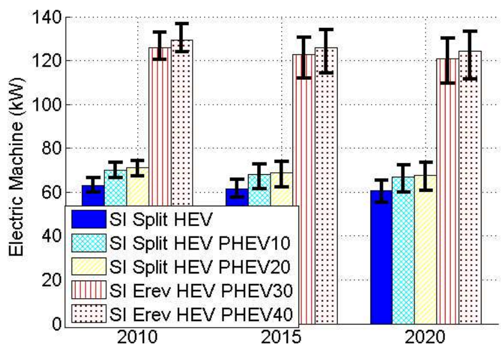

Figure 13: Motor power for hybrid cars

6 Vehicle Simulation Results

The vehicles were simulated on both the UDDS and HWFET drive cycles. The cold-start penalties shown in Table 4 were defined for each powertrain technology option on the basis of available data collected at Argonne's dynamometer facility and available in the literature. This percentage is the penalty applied after simulation to the fuel economy value, since all simulations run under hot conditions.

Table 4: Cold-start penalty values

Powertrain	2010	2015	2020
Conventional	12%		
Power-Split HEV	8%		
Power-Split PHEV	6%		
FC HEV	0%		
FC PHEV	0%		
Electric	5%		

Figure 14 shows fuel consumption results for a midsize car, focusing on different gasoline-fueled configurations.

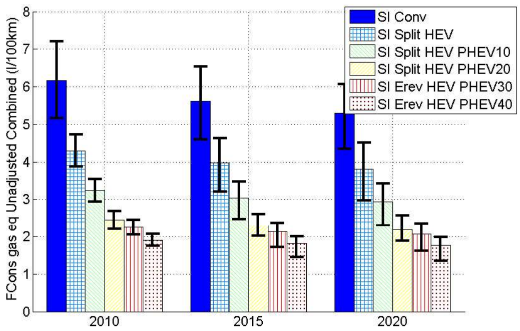

Figure 14: Fuel consumption for midsize cars with various gasoline-fueled configurations

As shown in Table 5 and Table 6, the comparisons between power-split HEVs and conventional gasoline engines show that the percentage improvement ranges around 15.9% for conventional, whereas it ranges from 4% to 23% for HEVs. This shows that HEV vehicles are more sensitive to the uncertainty. PHEVs range similarly to HEVs, with a large discrepancy shown (3%-29% for PHEV10, 3-20% for PHEV 30).

Table 5: Fuel consumption for vehicles with ICE (low uncertainty)

	Low uncertainty		
	2010	2020	Improvement
Conventional	5.16	4.34	15.9%
HEV	3.87	2.97	23.3%
Split PHEV10	3.24	2.29	29.3%
Split PHEV20	2.19	1.88	14.2%
EREV PHEV30	2.05	1.62	21.0%
EREV PHEV40	1.75	1.36	22.3%

Note that PHEV10 vehicles will benefit more from advances in the future for the low case scenario, whereas conventional vehicles show a 15% improvement in the high case scenario.

Table 6: Fuel consumption for vehicles with ICE (high uncertainty)

	High uncertainty		
	2010	2020	Improvement
Conventional	7.21	6.06	15.95%
HEV	4.72	4.5	4.7%
Split PHEV10	3.54	3.42	3.4%
Split PHEV20	2.68	2.57	4.1%
EREV PHEV30	2.44	2.35	3.7%
EREV PHEV40	2.07	1.98	4.3%

Figure 15 shows fuel consumption results for midsize cars, focusing on FC vehicles.

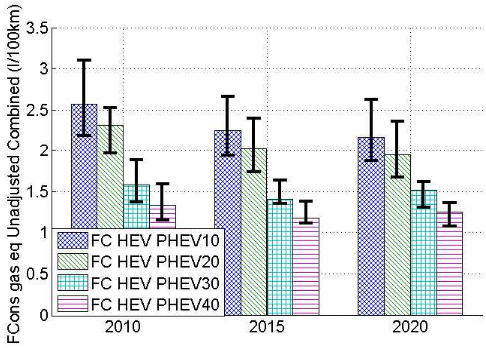

Figure 15: Fuel consumption for midsize fuel-cell cars

As shown in Table 7 and table 8, the fuel cell (FC) PHEV10 consumes around 15% less in 2020 for both low and high cases. Other FC vehicles shows fuel consumption improvements ranging from 5% to 14%

Table 7: Fuel consumption for fuel cell vehicles (low uncertainty)

	Low uncertainty		
	2010	2020	Improvement
FC PHEV10	2.18	1.87	14.2%
FC PHEV20	1.96	1.67	14.8%
FC PHEV30	1.37	1.3	5.1%
FC PHEV40	1.15	1.07	7.0%

Table 8: Fuel consumption for fuel cell vehicles (low uncertainty)

	High uncertainty		
	2010	2020	Improvement
FC PHEV10	3.1	2.62	15.5%
FC PHEV20	2.52	2.36	6.3%
FC PHEV30	1.88	1.61	14.4%
FC PHEV40	1.58	1.35	14.6%

Note that fuel cell vehicle technology will continue to provide less fuel efficiency improvement than the technologies for the gasoline HEVs as well as conventional gasoline engines.

Figure 16 shows the electric consumption for a BEV on the UDDS and HWFET cycles. No significant difference in electrical consumption is observed between the two cycles. The main reason is that the electric machine operates at high efficiency points at both low and high speeds. Nevertheless, electric consumption decreases slightly over time between 2010 and 2020. This decrease is due to the small improvement in the electric machine efficiency and lightweighting.

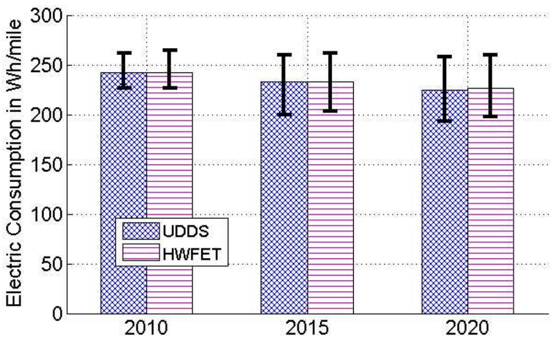

Figure 16: Electric consumption for midsize BEV

Figure 17 shows the incremental cost versus fuel consumption for gasoline vehicles. Incremental cost compares actual cost to the baseline (2010) conventional gasoline engine. Note that vehicles at the bottom right are the most cost-effective (low cost, low fuel consumption). It is hard to draw a conclusion, but it can be said that PHEV40 vehicles are significantly cheaper and more efficient in 2020 than in 2010, whereas conventional-vehicle cost remains constant over those years.

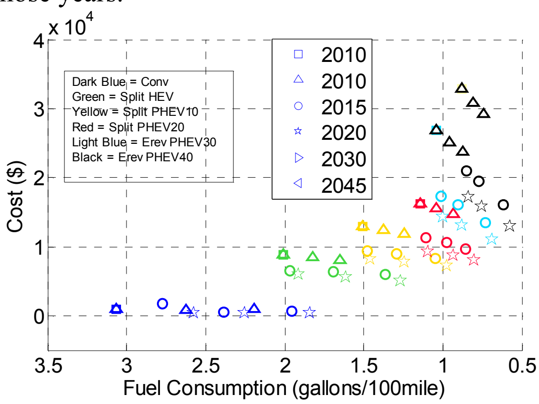

Figure 17: Incremental cost vs. fuel consumption for gasoline-fueled midsize cars.

Figure 18 shows the incremental cost versus fuel consumption for FC vehicles. The cost spread between 2010 and 2020 is higher for the FC PHEV40 than for the other FC vehicles; i.e., the FC PHEV40 is more likely to show improvement over those years. Note that in 2020 the cost differential among FC PHEV vehicles is small, especially for FC PHEV10 vs. FC PHEV20 and FC PHEV30 vs. FC PHEV40.

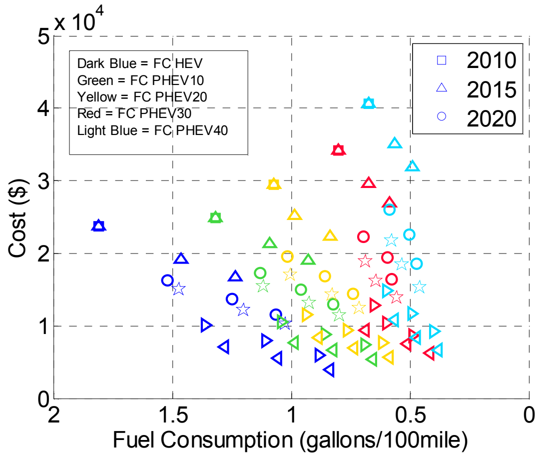

Figure 18: Incremental cost vs. fuel consumption for midsize fuel-cell cars

7 Market Penetration

Assessing the fuel displacement potential of specific technology platforms on a national scale requires an analysis of their market penetration potential. One approach to do so is to compare the lifecycle vehicle cost (the sum of initial vehicle cost plus the net present value of fuel costs over the vehicle's lifetime, expressed as cents/mile) across technology platforms to examine whether incremental costs for advanced technology vehicles are sufficiently counterbalanced by reduced operating costs such that the market is willing to accept those advanced vehicles. A prerequisite step to summing vehicle and fuel costs is a method for aligning the timing of payments: a vehicle purchase payment is assumed to be made only once at the beginning of a vehicle's life (note that financing the vehicle into a series of payments over time would change this calculation) but fuel purchases are made regularly over the life of the vehicle. This analysis uses a net present value of the sum of annual fuel expenditure (discounted at

7%) to estimate the value of the total expected expenditure on fuel at the point of vehicle purchase:

$$NPV = \frac{\$}{gal} \bullet \frac{VMT}{mpg} \bullet \sum_{t=1}^{15} \frac{1}{(1+d)^t} \quad (1)$$

The above equation calculates the net present value (NPV) of fuel as the product of the price of fuel ($/gal), the amount of fuel purchased annually (10,000 average vehicle miles travelled per year, VMT, divided by fuel economy, mpg, which is a function of the vehicle architecture modelled in Autonomie), and a coefficient to reflect the discounted (at d = 7%) cash flow over a vehicle lifetime of 15 years. For each powertrain modelled, the net present value of fuel is added directly to the estimated vehicle purchase price to arrive at vehicle lifecycle costs, which are presented for all advanced powertrains as a percentage of the lifecycle cost of the Reference SI vehicle described in the preceding modelling sections in Figure 19. Specifically, Figure 19 compares the lifecycle costs for advanced powertrains in the Low- and High-Tech scenarios in 2010 and 2020 to illustrate how lifecycle costs for advanced vehicles are expected to decline over time, and, to draw attention to the extent to which a High-Tech case, in which advanced technologies achieve higher performances and lower costs, can lower the lifecycle cost of advanced technology vehicles to a level below that of a conventional Reference vehicle by 2020. Note that in the High-Tech scenario, all advanced powertrains cost less than 100% of the Reference SI vehicle's lifecycle cost by 2020. In the Low-Tech scenario, advanced powertrains still require performance advances and/or cost reductions to achieve Reference SI-comparable lifecycle costs.

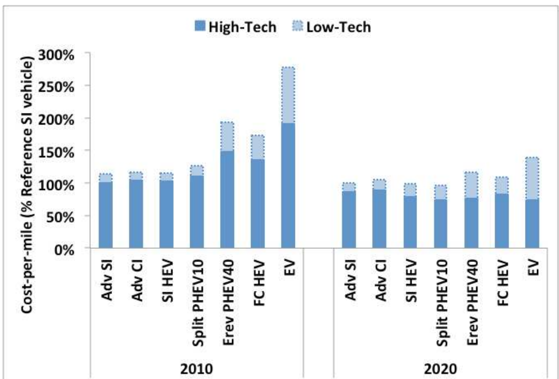

Figure 19 - Lifecycle cost comparison in 2010 and 2020 in High- and Low-tech scenarios

An advanced vehicle achieving a vehicle lifecycle cost less than that of a Reference SI vehicle is not sufficiency to guarantee the market update of that vehicle. The ratio of incremental vehicle cost and annual fuel savings is a critical factor in determining the period over which an advanced technology vehicle's fuel savings will offset initial incremental price. Figure 20 depicts lifecycle costs at the 50% level (with the 10% and 90% shown as lower and upper bounds, respectively) decomposed into vehicle component capital costs and fuel costs to facilitates an examination of how advanced component technologies (which contribute to initial vehicle cost) and overall vehicle efficiency (which reduce fuel cost) contribute to total cost of ownership. Note that higher levels of electrification are associated with higher initial vehicle costs, lower fuel cost, and higher technology uncertainty (the range of possible lifecycle costs for each technology platform). Note that, for example, the advanced SI vehicle in 2010 costs slightly more than the Reference vehicle, suggesting that the decrease in fuel expenditure achieved by that powertrain does not fully offset the incremental price of the vehicle, and likewise for other advanced powertrains. The PHEV40 and EV architectures stand out as especially expensive, despite very low fuel costs, which is not surprising given the high present-day costs associated with relatively large batteries these powertrains incur. By 2020, all initial vehicle costs decline as a result of expected technology improvement (as noted in preceding modelling discussions). Fuel costs, conversely, increase, despite an increase in efficiency for all powertrains (also noted in preceding modelling discussions), as a result of an increase in fuel prices over time [16]. The very high efficiency of electric-drive vehicles combined with a smaller increase in electricity prices relative to the increase in petroleum-product prices, results in a far smaller change in fuel cost for the PHEV40 and EV. The fuel cell vehicle fuel costs decrease as a result of an assumption that DOE H2 fuel cost goals are met by 2020 [17]. Note that Figure 20 is consistent with Figure 19 with respect to which powertrains achieve Reference SI-comparable lifecycle costs by 2020 at the 10% levels (indicated by the lower bound of the uncertainty bands).

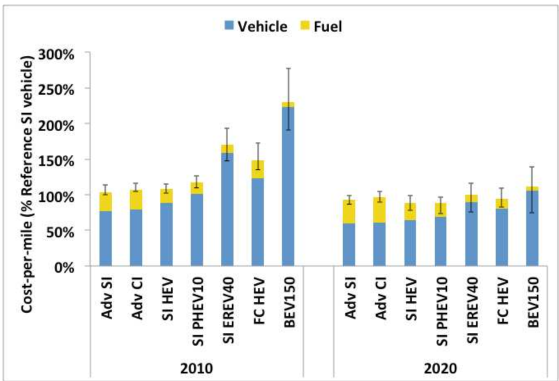

Figure 20 - Lifecycle cost comparison in 2010 and 2020 comparing initial vehicle purchase and the net present value of lifetime fuel expenditure

The incremental vehicle prices and annual fuel savings displayed Figure 20 can be used to calculate the period over which the advanced technology powertrains pay for themselves; that is to say, the time at which the discounted net present value of annual fuel savings over time exactly offsets the incremental price of the advanced vehicle. The equation to calculate that payback period is found by setting equation (1) equal to incremental vehicle price, P, and solving for time period, t, as follows:

$$t = \frac{\ln\left(\frac{a}{a - P*(1+d)}\right)}{\ln(1+d)} \quad (2)$$

Note that for simplicity' sake, the annual fuel savings, which is the product of the price of fuel and the annual VMT divided by fuel economy, is denoted simply as 'a'. Solving equation (2) using the parameters for each powertrain in the 10% and 90% scenarios yields the full spectrum of potential payback periods possible given Autonomie-generated performance and cost assumptions (discussed in the modelling sections above). Figure 21 shows these payback periods are displayed for 2015 and 2020 (2010 is not shown, as no advanced vehicle achieves payback based on characteristics estimated for 2010). The average consumer typically expects payback periods of less than three years before considering a more expensive vehicle that offers savings over time [18]. In 2015, no powertrain achieves a payback period of less than 3 years; though, the advanced SI and HEV powertrains come close. It's possible, then, that some consumers—those willing to accept a slightly longer payback period than the average consumer—will consider these vehicles. By 2020, many advanced powertrain vehicles satisfy the 3-year payback requirement: the payback calculations shown in Figure 21 suggest that in a high-tech scenario all advanced powertrains except for PHEV40s, FC HEVs, and EVs can achieve wide market appeal (at least economically speaking). Even these vehicles with a relatively high payback period are approaching the three-year threshold, so it is likely that some consumers will consider purchasing them. It is important to recognize that no advanced powertrain achieves a payback period less than 10 years in the low-tech scenario.

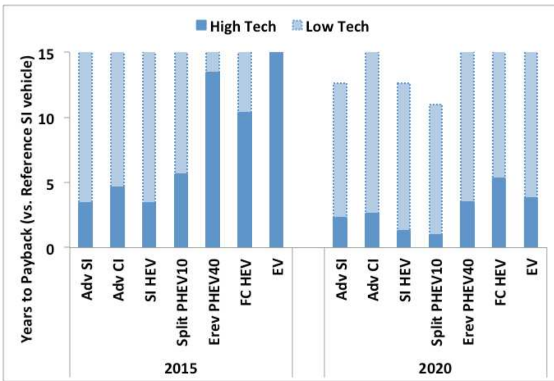

Figure 21 - Lifecycle cost and payback periods for advanced powertrains in low- and high-tech scenarios

8 Conclusion

The vehicle modelling, simulation, and economic analysis contained in this paper indicate that technology progress is critical to achieving a high-efficiency (and therefore, implicitly, low-carbon) advanced vehicle technology future. A comparison of possible vehicle technology futures in a relatively optimistic, high-technology scenario and a relatively pessimistic, low-technology scenario suggests that two very different vehicle market outcomes could result as a function of the difference between those two scenarios, which, in this paper, was accelerating vehicle technology improvement.

The combination of the technology improvements leads to significant fuel consumption and cost reduction across light duty vehicle applications. Due to the uncertainty of the evolution of the technologies considered, research should continue to be conducted in the different area showing high fuel displacement potential. Due to expected improvements, advanced technologies are expected to have significant market penetration over the next decades. In the short term, both engine HEVs and PHEVs allow for significant fuel displacement with acceptable additional cost. While electric vehicles do provide a promising solution, they are likely to remain expensive and range limited in the near future.

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