Electric Vehicle Transportation Center

Fuel Cells as Electric Vehicle Range Extenders

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Abstract

Fuel cells were modeled as range extenders for electric vehicles. In this application, the fuel cell would supplement a medium sized (16kWh) battery in order to increase the range of the electric vehicle. The fuel cell range extender is compared to an internal combustion engine (ICE) based range extender in terms of vehicle fuel economy and cost per mile driven. Since the fuel cell is about 40% more efficient than the ICE, the fuel economy of a fuel cell range extender was estimated to be 68 miles per gallon gasoline equivalent (MPGe), while the economy of an ICE range extender was estimated as 42 MPGe. The use of a fuel cell also increased the fuel economy during battery-only operation by 4%, since the fuel cell range extender is slightly lighter than the ICE. The cost per mile driven of a range extended electric vehicle changes with trip length, and energy source costs. However, at $4/kg hydrogen, the fuel cell range extended vehicle cost per mile is about 30% lower than that of the ICE-based range extended vehicle at $2.90/gal regular-grade gasoline.

Introduction

Fully battery electric vehicles (BEVs) have recently been introduced to the mass market, with the front-runners being Nissan's Leaf and Tesla's Model S and Model X. These vehicles carry several advantages over conventional vehicles (CVs) in that they emit no pollution at the tailpipe, and wells-to-wheel green-house gas (GHG) emissions are significantly lower. Furthermore, BEVs are much more efficient, near 100 mile/gallon gasoline equivalent (MPGe), vs. 30 mpg CV efficiency. These characteristics provide substantial motivation for a transition to BEVs to improve our "green-ness" within the transportation sector.

However, with the exception of the Tesla, most BEVs have ranges less than 80 miles, due to the high cost of the batteries. This limited range presents several problems for BEVs: 1) charging infrastructure must be considered for long trips; 2) the time for charging must be included for long trips; 3) the energy used for proper temperature control of the battery further limits cold-weather range. The charging infrastructure is critical to BEV adoption, as consumers will be less-likely to purchase a BEV if there are limited places to charge it. Charging stations are classified by their power output, as defined in the SAE J1772 standard. BEVs may be charged at home using AC Level 1 (1-2 kW) or 2 (3-20 kW) chargers, however this can take from 4 hours (level 2) to as long as 20 hours (level 1), depending on battery size. Alternatives to at-home charging methods include public AC Level 2 and DC Level 1 and 2 fast charging (16-100 kW) stations, the latter of which can reduce charging times to 30 minutes. This is in contrast to the 3 minute fill-time for CVs. However, in order to make the most of these stations, they need to be strategically placed, and optimizing their location for widespread BEV adoption is challenging. As battery range increases, the number of charging stations that will be needed will decrease, rendering it more difficult to identify charging station sites today that will still be relevant in the future. Another difficulty that BEVs must overcome is that in cold weather, the BEV range will decrease. This is due to both the sluggish transport of ions within the cell, as well energy used to warm the passenger cabin and keep the battery at an optimal operating temperature. If the battery is too cold, significant degradation will occur and the lifetime will be shortened dramatically.[1]

One approach that could address the range and charging problem of BEVs is to focus on a hybrid vehicle that employs an additional generator to provide an extended range. This vehicle employs a medium-sized battery (16kWh) with an internal combustion engine (ICE) that powers an electric generator. The electric generator can then be used to recharge the battery for extended range. The battery was sized such that it has a range of about 40 miles, which covers the vast majority of trips, allowing it to be charged at home each night. However, if a longer trip was needed, the ICE could supply the energy once the battery's energy was exhausted. This type of vehicle is referred to as a plug-in hybrid electric vehicle (PHEV), or as a range extended vehicle. Several car companies offer range extended electric vehicles, such as BMW, Ford, Honda, and others, but one of the more well-known models is the Chevy Volt.

In Figure 1, the fuel economies of four different vehicles are compared, with each vehicle representing a different technology: battery electric vehicle (BEV), PHEV, CV and hybrid. The hybrid curve represents a vehicle with a small battery that cannot be plugged in, such as the Prius-C. For the BEV, CV and Hybrid curves, the fuel economies are independent of trip length since these vehicles operate on a single energy source: electricity for the BEV and gasoline for the Hybrid and CV. However, for the PHEV, the contribution of the ICE to the vehicle's fuel economy will depend on the length of the trip. For example, a trip of 25 miles would be entirely electric, and would have an economy of 98 MPGe. A 50 mile trip would consist of 40 miles electric and 10 miles with ICE, resulting in an economy of 70 MPGe. For longer trips, the ICE's contribution to the fuel economy increases, resulting in lower MPGe.

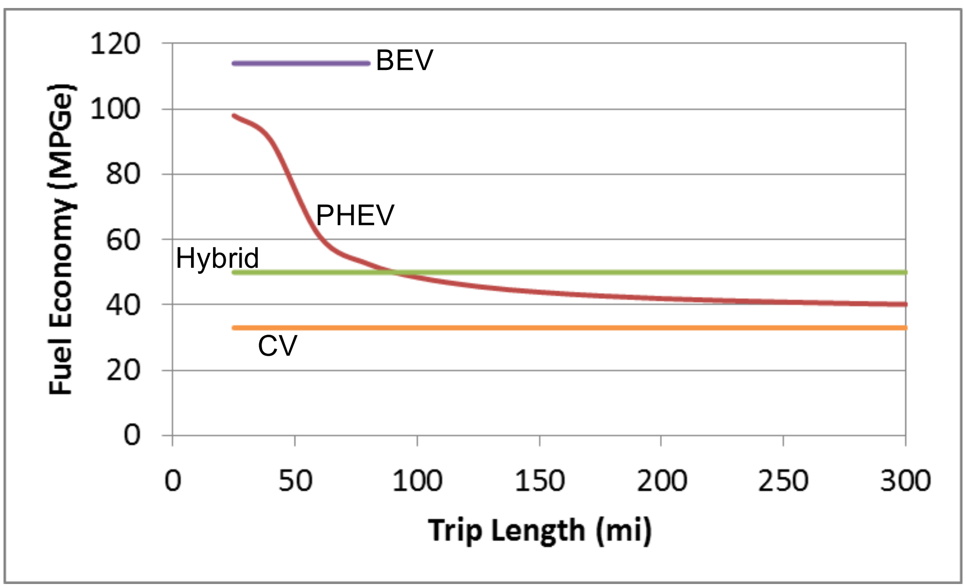

Figure 1. Fuel economy vs. trip length for three vehicles

During cold weather, BEV range will decrease as energy is diverted to keep the passenger cabin and battery warm. A benefit of a PHEV is that the heat from the ICE generator may be used to keep the battery and passenger compartments warm. Additionally, the widespread availability of gasoline stations provides unlimited range for the PHEV with little to no impact on the consumer. However, the low efficiency of the ICE (30%) renders this approach less "green" than the BEV. An alternative to the ICE is needed that has improved efficiency and lower GHG emissions. That alternative is a fuel cell.

Fuel cells are electrochemical devices that convert hydrogen and oxygen into heat, electricity and water, at an efficiency that is roughly twice that of an optimized ICE. If a fuel cell is used as the only power source, the result is a fuel cell electric vehicle (FCEV) that could have fuel economies around 60 MPGe. Recently, Hyundai began offering a fuel cell-powered Santa Fe in a limited lease option in California. Toyota recently announced their plans to offer a fuel cell powered car in the fall of 2015, while a Honda and GM partnership will follow suit in 2016. These vehicles will emit no pollution at the tailpipe, and with 5 kg H_2 in the tank, they could travel around 300 miles. One major hurdle these car companies will face, however, is the lack of hydrogen filling station infrastructure. Similar to BEVs, the availability of hydrogen to fill these cars is a road-block, and although California has made efforts, hydrogen refueling station availability is limited. Although the high range of the vehicle would require fewer filling stations, their location would still be difficult to identify, as FCEV owners could require filling at any point in their daily drive pattern.

One approach to increase the range of BEVs while still maintaining high fuel economy is to replace the ICE in a PHEV with a fuel cell. In the fuel cell-based PHEV (FC-PHEV), the increased efficiency of the fuel cell should result in higher fuel economy when compared to an ICE-based PHEV. Furthermore, the ability of the FC-PHEV to charge at home may not require as many filling stations, since the majority of driving could be accommodated by the battery. The purpose of this paper is to demonstrate the utility of a FC-PHEV, where the ICE of the Volt is replaced with a fuel cell, and how this approach mitigates several issues of a BEV or FCV.

Methodology

To get a sense of the fuel economy of the FC-PHEV, the vehicle was modeled using FASTSim, a simulation tool developed by the National Renewable Energy Laboratory (NREL). This modelling tool allows simulation of a variety of vehicles (including the Chevy Volt and Nissan Leaf) and predicts their fuel economy using simulated drive cycles, like the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Driving Schedule (HWFET). To simulate a FC-PHEV, it was decided to modify the parameters for the Chevy Volt to include a fuel cell and hydrogen tank, using published data from the US Department of Energy. Table 1 illustrates the parameters that were modified in the FASTSim tool. In this model, the term "generator" refers to the ICE or fuel cell in a PHEV or FC-PHEV, respectively. Each vehicle would also have an electric engine to convert electricity to motive force.

Table 1. Values for the generators for the Volt-ICE and Volt-FC modeling

	Generator efficiency	Generator specific power (kW/kg)	Fuel and fuel storage mass (kWh/kg)	Generator cost (Base + $/kW)	Fuel tank cost ($/kWh)
Volt-ICE	12-40%	0.32	9.89	$531 + $14.5/kW	$0.07/kWh
Volt-FC	45-56%	0.35	1.8	$0 + $55/kW	$15-19/kWh
Fuel Cell Ref.	[2]	[3]	[4]	[5] (assumes high volume)	[4] (assumes high volume)

Other parameters within FASTSim (e.g. vehicle, batteries and electric engine sizes and weights) were kept constant between the ICE and FC versions of the Volt. During simulation, the program subjects the simulated vehicle to a driving cycle based on the UDDS (city) and HWFET (highway) driving tests, and calculates the power required to meet the driving demands. This power is initially obtained from the battery, until the SOC reaches 20%, at which point the generator turns on. The fuel economy was determined by calculating the energy from the battery and generator used during the drive cycle, and dividing it by the distance traveled. Using both UDDS and HWFET drive tests allows prediction of the city and highway fuel economies, with the “combined” economy calculated as 55% city fuel economy and 45% highway fuel economy. Two fuel cell parameters were investigated: fuel cell size (power) and hydrogen tank size (energy). By changing the fuel cell size, the impact of the stack on economy can be estimated. Selecting larger tanks will enable longer range for the Volt-FC. Table 2 illustrates the parameters that were investigated as part of this simulation.

Table 2. Parameters for Volt-FC and Volt-ICE modeling

	Generator Power (kW)	H_2 stored (kg)	Fuel Stored (kWh)
Volt-FC10	10	2.5	82.5
Volt-FC30	30	2.5	82.5
Volt-FC50	50	2.5	82.5
Volt-FC30L	30	5	165
Volt-ICE	62	9 (gal gasoline)	313

Once the fuel economy for the Volt-ICE and Volt-FC were calculated using FASTSim, comparisons were made to existing vehicles to evaluate the accuracy of the FASTSim model, and correction factors were applied to bring the model into closer agreement with real-world data. The adjusted data were used to compare economy and driving costs between the modeled data and real-world vehicles, including all electric BEVs, conventional vehicles (CVs), and hybrid electric vehicles (HEVs).

Results

The weights and costs of the generators (ICE or fuel cell) from the FASTSim model are shown in Table 3. As can be seen, the weight of the fuel cell generator is lower than that of the ICE generator, because a smaller generator is used for the fuel cell in order to reduce costs. In this case, a 30 kW fuel cell is about the same cost as a 62 kW ICE. After including the tanks, the fuel cell-H_2 tank combination results in a weight of 178 kg, while the ICE-gasoline tank weighs 216 kg. However, the tank costs are considerably higher for the hydrogen than for gasoline ($2805 vs. $22, respectively). These high tank costs render the fuel cell generator less economical than the ICE generator. Reducing hydrogen storage costs will be critical to adoption of hydrogen-based vehicles.

Table 3. Generator and tank model output values

	Generator			Tank		
	Size (kW)	Weight (kg)	Cost ($)	Size (kWh)	Weight (kg)	Cost ($)
Volt-FC10	10	29	550	82.5	46	1403
Volt-FC30	30	86	1650	82.5	46	1403
Volt-FC50	50	143	2750	82.5	46	1403
Volt-FC30L	30	86	1650	163	92	2805
Volt-ICE	62	194	1430	313	32	22

The fuel economies of the Volt-FC and Volt-ICE were compared based on their battery-only and generator-only operation. This comparison is important since the range-extending vehicles will operate part-time on the battery, and part-time on the generator. For trips of shorter duration, the battery operation will dominate, while longer trips operate more on the generator. Figure 2 compares the various Volt-FCs to the Volt-ICE, and it can be seen that the fuel cell and ICE options exhibit similar battery-only fuel economies. This is expected, since the batteries are the same for all vehicles. In fact, the fuel cell range-extender gives a slightly higher battery-only fuel economy than the Volt-ICE since the weight of the fuel cell stack and H_2 tank is lower than the weight of the gasoline generator. When the vehicle operates on the generator-only mode, however, the Volt-FCs demonstrate significantly higher fuel economies than the Volt-ICE. This is due to the significantly higher efficiency of the fuel cell over the gasoline engine (see Figure 3.)

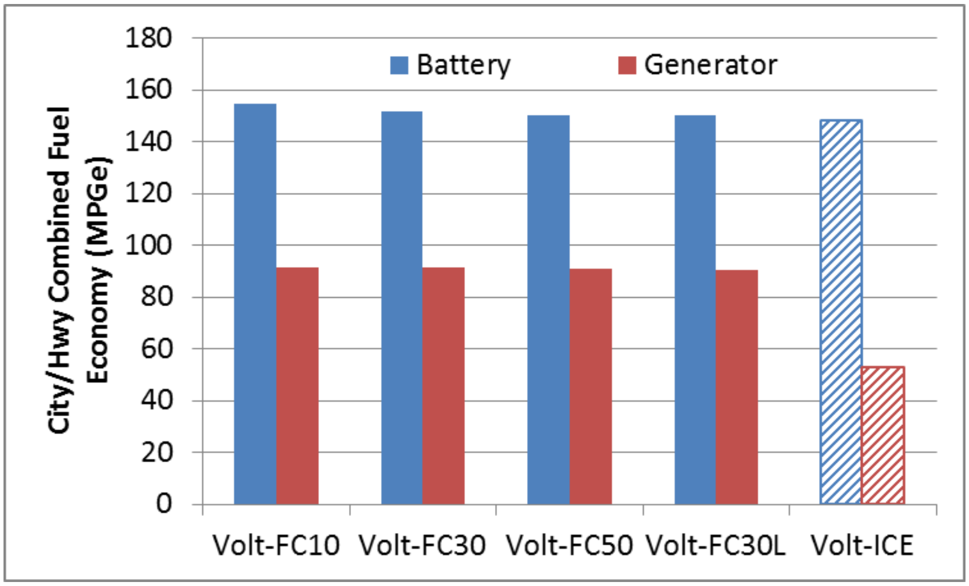

Figure 2. Fuel economy for Volt-FCs, as a function of fuel cell stack size

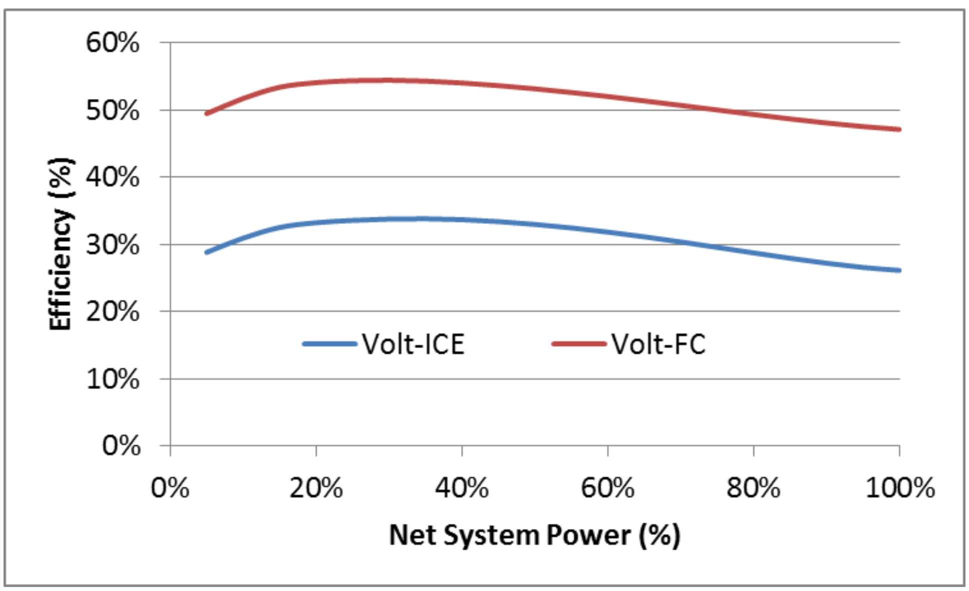

Figure 3. Generator efficiency curves. Data for Volt-FC and Volt-ICE from ref. [2] and FASTSim, respectively.

The range of the various Volt-FCs was also determined, as shown in Figure 4. As can be seen, the Volt-FC simulations with 83 kWh (2.5 Kg H_2) estimated a range of nearly 200 miles. By increasing the amount of hydrogen to 165 kWh (5 kg H_2) for the Volt-FC30L, the range increased to 350 miles. Given that the typical BEV has a range of about 80 miles, the Volt-FC ranges are considerably improved, and are even approaching the typical CV range of 400 miles.

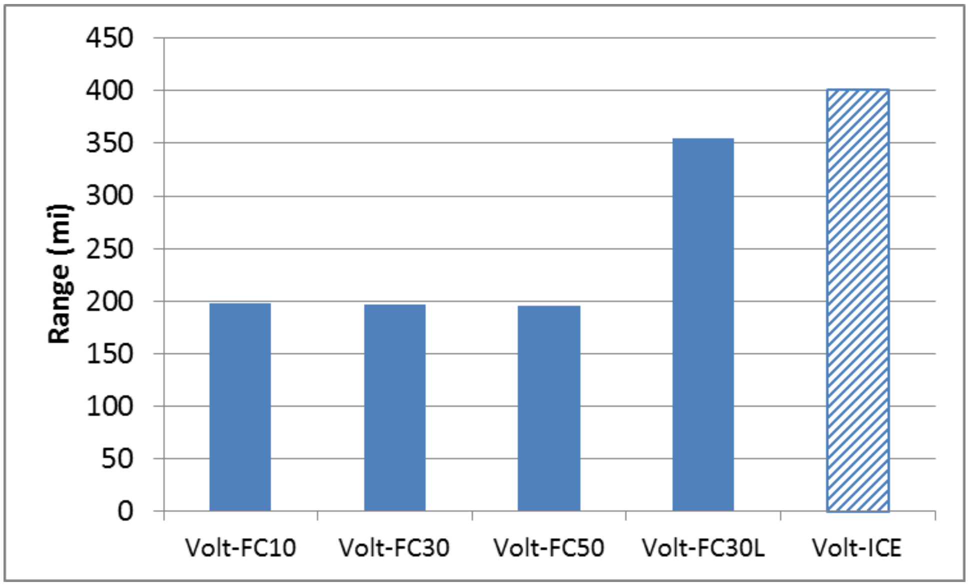

Figure 4. Range of Volt-FCs

Model Comparison

The values for the Chevy Volt-ICE from the FASTSim model were compared to actual reported values, and are tabulated in Table 4.

Table 4. Model results vs. real world fuel economy

	FASTSim Volt-ICE		Actual Volt-ICE		Adjusted Volt-FC30L	
	Generator	Battery	Generator	Battery	Generator	Battery
Combined (MPGe)	53	148	37	98	63	99

The FASTSim appears to have over-estimated the fuel economies by about 40-50% for both the generator and battery performance. Using this as a correction factor, assuming the same over-estimation for the Volt-FC, one can estimate the real-world performance of the Volt-FC30L as shown in the table.

Using these adjusted estimates, the fuel economy for the Volt-FC30L was compared to that of the BEV, CV, Hybrid and PHEV presented earlier (see Figure 5). It is recognized that this fuel economy is an estimate. However, it indicates a significant improvement over existing vehicles.

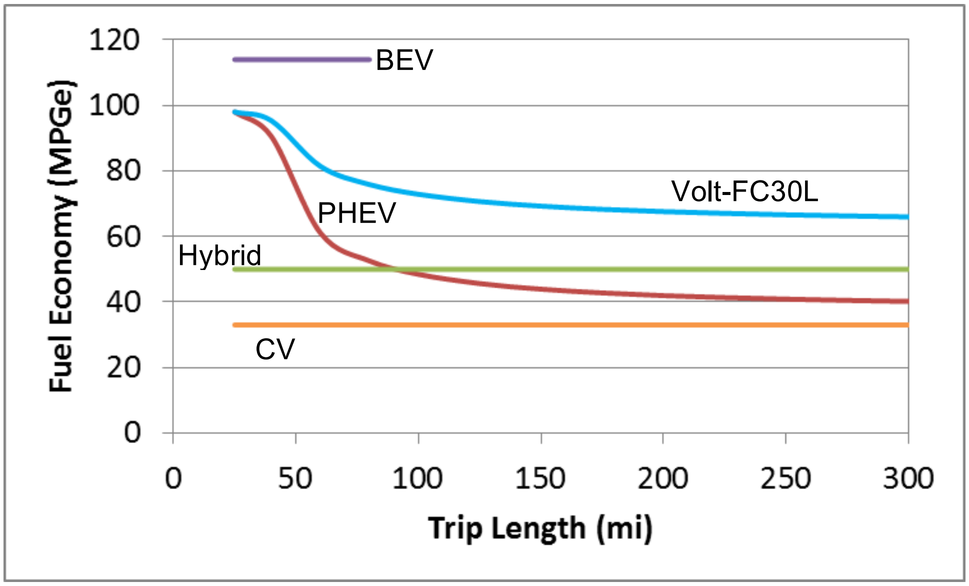

Figure 5. Fuel economies for various vehicles as a function of trip distance

With these estimates of fuel economy, it is interesting to speculate as to the cost of traveling with these various types of cars. Table 5 lists the various costs for different sources of energy. Gasoline costs were obtained from the AAA fuel gauge report, and represent national averages as of Jan 7, 2015.The cost of hydrogen is highly debated, and depends on the production method. In this case, it was assumed that hydrogen was produced via steam methane reforming from natural gas.[6] This method results in high GHG emissions, but is the most economical at this time. An alternative method to produce hydrogen would be through electrolysis. A study showed that wind-powered electrolysis may be able to produce hydrogen at $4/kg, with an additional cost for compression and delivery.[7]

Table 5. Costs for different energy sources

Cost	$/gal	$/kg	$/kWh
Gasoline	$2.19	-	$0.07
Hydrogen	-	$4*	$0.12
Electricity	-	-	$0.12

*Hydrogen costs were based on ref [6].

Using these costs, and the fuel economies of the various cars, the cost per mile traveled can be plotted as a function of trip length (see Figure 6). In this figure, the fuel economies for city and highway driving were used, and it was assumed that 45% of the trip was on the highway, and 55% was in the city. While this driving pattern is not true for all trip lengths, it serves as a reasonable average. As can be seen, although the energy cost for gasoline was the lowest, the poor fuel economy of CVs resulted in the highest costs per mile traveled.

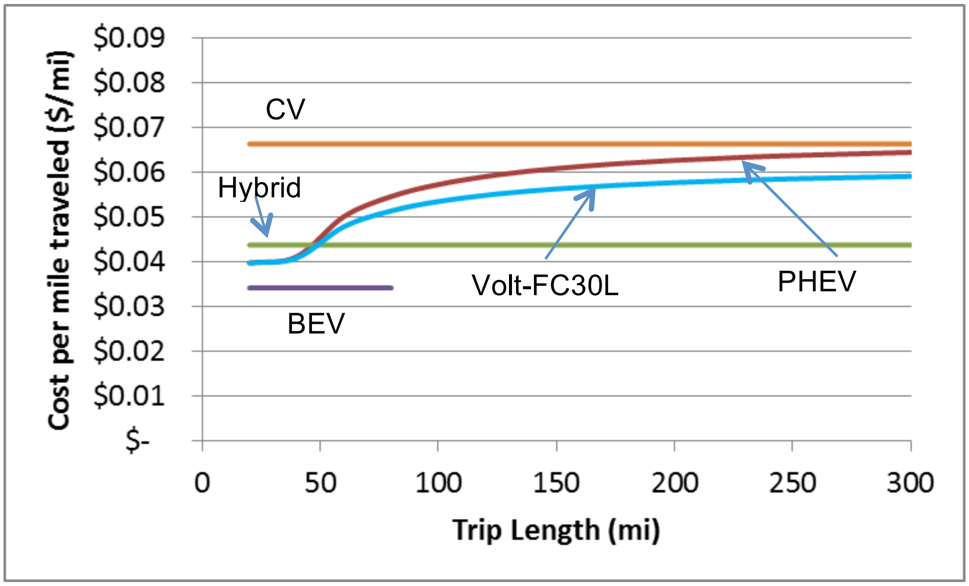

Figure 6. Cost per mile traveled for different vehicles, with gasoline at $2.19/gal

For short distances, the BEV is the cheapest vehicle to operate, at just over $0.03/mi. However, at these distances, both the Volt-FC30L and PHEV are quite economical, at $0.04/mi. Over longer trips, the BEV would still be the least expensive, however its range does not permit 200 mile trips without recharging. At these long distances, the Hybrid is the most economical vehicle on a single fill-up. The PHEV demonstrates a cost that is similar to that of the CV, which is due to the requirement that some PHEVs (e.g. the Chevy Volt) require the use of Premium gasoline, which is approximately 15% more expensive than regular-grade. Therefore, while the PHEV may have a high fuel economy, the gasoline costs are also higher, resulting in a slight increase in the cost per mile driven. The Volt-FC30L shows a cost per mile that is roughly equivalent to that of the PHEV, assuming $4/kg H_2. However, it should be noted that the FC-PHEV cost about $3000 more than the ICE PHEV, and using these gasoline costs, the fuel savings would not be sufficient incentive to purchase an FC-PHEV.

In this analysis, regular-grade gasoline costs were modeled at $2.19/gal, which is the national average as of January 7, 2015. Over the previous 10 years, regular-grade gasoline prices ranged from $1.51/gal to $4.11/gal, with an average of $2.90/gal.[8] However, the cost of electricity varied only slightly, from $0.08/kWh in 2004 to $0.13/kWh in 2014, with an average of $0.11/kWh.[8] Assuming the current electricity and hydrogen generation costs remain constant, and using $2.90/gal for regular-grade gasoline, the cost per mile traveled for the Hybrid and CV models increases substantially (see Figure 7). At these gasoline prices, the Volt-FC30L and Hybrid models cost about the same per mile, and are about 30% lower than the PHEV cost per mile. For gasoline costs above $2.90/gal, the fuel cell vehicle would cost less to drive than a Hybrid.

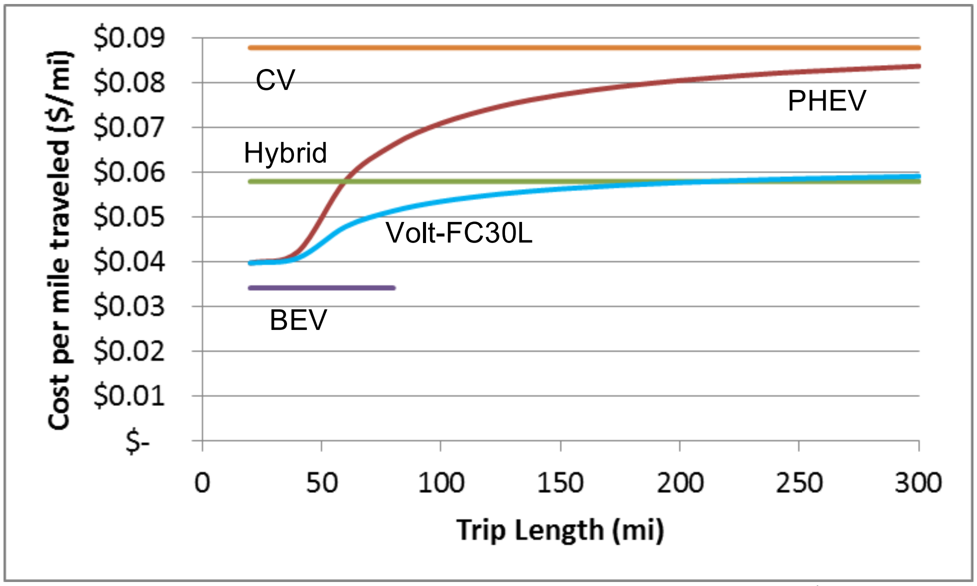

Figure 7. Cost per mile traveled for different vehicles, with gasoline at $2.90/gal

Electricity prices would not be expected to change with gasoline prices, since electricity is predominately generated through natural gas and coal. Similarly, the hydrogen production costs would not be expected to increase, since the majority of hydrogen is produced via natural gas reforming. Thus, higher gasoline prices would make the BEV and Volt-FC30L more economical when compared to the CV, Hybrid and even the PHEV. Since the FC-PHEV has a higher initial cost than the PHEV (about $3,000, using high volume production values), higher gasoline costs would be required to recover the increased cost through fuel savings. For example, at $2.90/gal, the FC-PHEV would save about $0.025/mi, and would recover the initial cost differential between ICE-PHEV after about 122,000 miles, which represents about 10 years at 12,000 miles per year. If gasoline prices were to climb to $3.50, the FC-PHEV would save about $0.04 per mile, and would recover the initial cost after 73,000 miles, or about 6 years.

Availability of charging stations is currently a roadblock for both BEVs and FCEVs, although BEVs benefit from at-home charging. Since 70% of all trips are 40 miles or less [9], PHEVs could be charged mostly at home, and would fill up with gasoline only for longer trips. FC-PHEVs would depend on hydrogen filling stations, but the addition of the battery could reduce the total number of stations. For example, a FC-PHEV with a 40 mile battery range would use almost no hydrogen during a 20 mile commute to and from work, and the vehicle could be charged at home each night. In the event of a longer trip, hydrogen would need to be used but the rapid fill-rates of hydrogen could permit filling the tank during the trip without drastically increasing the travel time. Assuming longer trips occurred on highways and freeways, hydrogen filling stations could be located along these routes, and would not be as needed in residential neighborhoods. While it is possible to electrolyze water in the home, and generate hydrogen, it is more economical to produce hydrogen at a larger scale. Therefore, it is most likely that larger hydrogen filling stations will be used, rather than at-home hydrogen filling stations. However, since the majority of trips for the FC-PHEV would occur using only the battery, there would be less consumption of hydrogen, and therefore a lower demand for filling stations. The size, placement and number of hydrogen filling stations needed for a FC-PHEV needs to be investigated further.

Conclusions

The combination of a fuel cell with a battery would operate very well as a plug-in hybrid electric vehicle. Modeling showed that the fuel cell's increased efficiency would enable much greater fuel economy (~40%) than the equivalent internal combustion engine, and provide a significantly higher range than a battery electric vehicle (>200 miles). The FC-PHEV would also result in improved performance over BEVs in cold weather applications. Assuming hydrogen costs of \$4/kg H_2, the FCREV could travel at costs 30% lower than a conventional vehicle and 25% lower than an ICE-based PHEV. However, with given cost projections of fuel cell stacks and hydrogen storage tanks, the FC-PHEV would not be more economical until after 122,000 miles had been traveled, assuming \$2.90/gal gasoline. If gasoline prices were to increase to \$3.50/gal, a FC-PHEV would need to travel 73,000 miles before recovering the additional investment cost vs. an ICE-PHEV. Due to the ability to charge at home, the FC-PHEV may require fewer H_2 filling stations than a fuel cell electric vehicle, although more research into filling station locations is needed.

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