The Vehicle Refueling Wars: A Comparison of Gasoline, Electric, and Fuel Cell Vehicles

This report explores the pros and cons of gasoline, electric, and fuel cell vehicles. You will learn that displacing the ICEV-gasoline refueling paradigm is difficult because of convenience, that centralized EV recharging has questionable viability, and that centralized FCV refueling shows promise because of comparable customer utility and H_2 station throughput of refueled vehicles.

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Overview of Fuel Types

In the early 20th century, vehicles were powered by gasoline and electricity—the (surprisingly common-at-the-time) steam-powered vehicles used gasoline and, later, kerosene as fuels. The electric starter cemented the internal combustion engine (ICE) vehicle (hereafter known as the ICEV) and gasoline as the dominant vehicle configuration, and this dominance became almost complete and lasted nearly a century. The recent introduction of alternative fuel sources, namely the return of electricity (in electric vehicles (EVs)) and the introduction of hydrogen (H_2, in fuel cell vehicles (FCVs[i])), has raised the tantalizing possibility that the century-long monopoly of ICEVs and gasoline will be broken.

However, the electricity/EV and H_2/FCV challengers must compete from both a performance and cost standpoint, and the gasoline/ICEV incumbent, with all its associated supporting infrastructure, will not be easy to unseat.

Vehicle Performance

Vehicle performance requirements include acceleration, top speed, range, and refueling/charging times. The challengers meet (and in the case of Tesla EVs, often exceeds) the acceleration and top speed performance of ICEVs. However, the performance of the challengers to ICEVs must be comparable for all the requirements so that the vehicle driver does not experience a loss of utility. The cost of the vehicles is another reason for the lower-than-forecast sales; while the cost of EV and FCV components (the two vehicle types share a considerable amount) has decreased, especially dramatically in the case of the energy storage system (ESS) and fuel cell system (FCS), more cost reductions are necessary. The costs of the three vehicles are dependent upon a number of factors that are outside the scope of this analysis, and the focus will be on performance and utility.

Fueling Infrastructure

From an installed infrastructure standpoint, an enormous amount of capital has been spent creating the gasoline infrastructure that allows gasoline stations to have become ubiquitous, with gasoline stations seemingly on every city corner. The companies involved in developing this infrastructure, especially those in the retail sector with those widespread stations, will have a strong incentive to continue to provide transportation fuel at these locations. These station owners of the centralized refueling model require either throughput of vehicles or high charging/refueling prices to avoid the financial model being compromised.

The three vehicle/fuel pathways will be examined below, with a qualitative analysis of the advantages and disadvantages of each in general, followed by a quantitative analysis of the specific areas that are lacking in the performance of the challengers.

Gasoline

To start, gasoline is incredibly useful as a transportation fuel, if the associated emissions are ignored. Gasoline is very energy dense, so a lot of energy can be stored on-board a vehicle in a small space without a lot of added weight, allowing for vehicle ranges that often provide impressive long-distance range utility. Gasoline can also be transferred quickly, so refueling is done quickly and easily. In 2012, there were 114,533 gasoline stations throughout the U.S. (although this number appears to be decreasing.)[ii] The average number of dispensers per station in the U.S. is estimated to be 8[iii]. This means that there were some 916,000 dispensers, and this installed infrastructure represents a significant incumbency advantage for the gasoline/ICEV paradigm.

However, the associated emissions of ICEVs cannot be ignored. When gasoline is combusted, the produced emissions include CO_2, the most important greenhouse gas (GHG), as well as criteria-air contaminants (CACs) that cause local pollution like particulate matter (PM), carbon monoxide (CO), sulfur oxides (SO_X), volatile organic compounds (VOCs), and nitrous oxides (NO_X)[iv] . Zero-emission vehicles (ZEVs) powered by electricity or hydrogen are seen as essential tools in the twin efforts to reduce GHGs that contribute to climate change and the CACs that cause significant health problems and toxic urban air sheds.[v]

Electricity

EVs have the advantage of the highest efficiency of the three vehicle types and for urban driving where long range is not a factor, EVs are thus currently the ideal vehicle from an efficiency standpoint. Further, depending on the situation of the EV owner, EVs can often be charged[vi] at home (or at work) when the vehicle is not in use, making analogous trips to the gasoline station nearly obsolete. This convenience factor can be a huge EV advantage. Home and work charging currently account for over 90%[vii] of EV charging and some EV owners never need to use commercial charging infrastructure. For those that do require commercial charging infrastructure, the number of commercial EVSE units has increased from 541 charging spots in 2010 to over 44,000 throughout the U.S. currently[viii], with an increasing focus on DC fast chargers (DCFCs) to reduce the charge event time. However, it should be noted that most vehicles are parked some 95% of the time, and charging an EV can be a convenient proposition for the vast majority of charging instances for many prospective EV owners.[ix]

However, EVs do have disadvantages, such as long charging times (even at the fastest rates) and shorter ranges due to the diminishing returns of added ESS capacity (where weight and cost are added as well). Long charging times mean that an EV that is to be driven imminently that must first be charged results in a loss of utility to the EV owner. This disadvantage is compounded for long-distance trips with multiple charging events required, exacerbated by the shorter range. Finally, many people live in urban areas and do not have access to home charging. Those in this increasingly common situation would have to rely on more expensive, relatively sparse, not always available, and sometimes unreliable commercial charging. The charging disadvantage is, for some people, the only reason needed to dissuade them from purchasing an EV. The ESS is also the least energy dense in comparison to compressed H_2 and gasoline, making the range of EVs a challenge to automakers to achieve a balance of long-distance driving utility and cost. These reasons, along with high cost, explain why EV sales in the U.S. account for less than 1% of new vehicles some six years after widespread market introduction in December of 2010.[x]

Hydrogen

FCVs have the intermediate efficiency of the three vehicle types as well as intermediate ESS energy density (in the form of compressed H_2). H_2 storage technology requires significant improvements to enable high long-distance driving utility, especially in cost[xi]. However, in addition to superior energy density and specific energy, degradation due to cycle life and calendar life as in an EV ESS does not occur. Further, FCVs can be refueled using the same centralized refueling paradigm as gasoline (enabling widespread ownership by urban apartment dwellers) and at a rate that is comparable to gasoline (enabling long-distance driving with high utility). It should be noted that H_2 stations worldwide are following the SAE J2601 standard, which is a direct contrast with the various and competing standards used in EV charging. However, H_2 stations are expensive (at $1M per dispenser), and are currently rare, with only 39 throughout the country (35 in CA, going up to an expected 64 by the end of 2018)[xii] and are expected to come online relatively slowly. H_2 also has yet-to-be-solved production and distribution issues, and as a result, only 2,000 FCVs have been sold in the U.S. since they were introduced to the market in late 2015.[xiii] However, an argument could be made that FCVs must reduce cost only since the utility of an ICEV driver is not compromised by switching to an FCV while EVs must both reduce cost and increase performance because the driver utility is compromised by switching to an EV.[xiv]

Comparing the 3 Fueling Options

To quantitatively compare the utility of the three vehicle types, an examination of the dispensing rate and station capacity will be used. The dispensing rate indicates the rate at which the fuel/electricity is input to the particular vehicle while the station capacity refers to the number of vehicles the station can accommodate in a given amount of time. In order for station capacity to be calculated, assumptions for the required range and fuel economy of each vehicle must be made in order to determine the charging/refueling time. The required range will be assumed to be 400 miles[xv] for all three vehicle types so that long-distance driving utility is not compromised. For the vehicle fuel economy, a MY 2017 Chevrolet Bolt (at 119 MPGe) will be assumed as a representative baseline vehicle. The dispenser rate and station capacity will both make use of the ratio of the tank-to-wheel (TTW) efficiencies of the other two vehicle types to the EV TTW efficiency, which allows for a comparison of power-train efficiencies alone, using the EV as the baseline vehicle.

Gasoline/ICEV

Dispenser Rate: Gasoline pumps dispense at up to 38 l/min[xvi], so equivalent electrical power is 20,770 kW (using 42,900 kJ/kg, 0.7646 kg/l[xvii]). The tank-to-wheel (TTW) efficiency of an ICEV is approximately 19.5%[xviii], which means that the gasoline dispenser power gets de-rated to 4,050 kW (by multiplying the power by the efficiency).

Station Capacity: The fuel economy of the ICEV, using the ratio of the TTW efficiency of the ICEV to the EV (that of the latter is shown below to be 83%), is 28.0 MPGe. At 28.0 MPGe and 400 miles, 14.3 gal of gasoline would be required, resulting in a refueling time of 1.42 min. Ignoring the time required for payment, engagement/disengagement of the fuel dispenser, and vehicle arriving/parking/departing at the dispenser, a single gasoline dispenser can accommodate up to 1,014 ICEVs per 24 h period.

Electricity/EV

Dispenser Rate: EVSE comes in different standards, all with different rates (and connection types)[xix]. The highest rate currently outside of Tesla EVSE is found in the DCFC, at 50 kW. The TTW efficiency of an EV is approximately 83%[x], so the current DCFC has a de-rated power of 42 kW. The fastest current charging is represented by the Tesla Supercharger, with the fastest of these being 145 kW[xx]. Using the TTW EV efficiency, the Supercharger dispenser power is de-rated to 120 kW. The current trend in EVSE is for 50 kW DCFCs to be supplanted by Ultra-Fast DCFCs that are intended to reach 350 kW[xxi]. Using the EV

TTW efficiency, the Ultra-fast DCFC dispenser power gets de-rated to 291 kW.

Station Capacity: At 119 MPGe and 400 miles, 112.4 kWh of electricity would be required, resulting in a charging time of 19.2 min. Ignoring the time required for payment, engagement/disengagement of the fuel dispenser, and vehicle arriving/parking/departing at the dispenser, a single Ultra-fast DCFC dispenser can accommodate up to 75 EVs per 24 hour period. It should be noted that ESS technology may not allow the full 350 kW charging power of the Ultra-fast DCFC for the entire charge event; currently, the peak power of 50 kW DCFCs is rarely reached and if it is, for only a small percentage of the charge event[xxii].

Hydrogen/FCV

Dispenser Rate: For a 3-5-minute fill of 5 kg[xxiii], the dispenser equivalent electrical power is 2,000-3,330 kW (using 119,930 kJ/kg[ix]). The TTW efficiency of an FCV is approximately 53%[x], so the H_2 dispenser power gets derated to 1,060-1,770 kW.

Station Capacity: The fuel economy, using the ratio of the TTW efficiency of the FCV to the EV, is 76.0 MPGe. At 76.0 MPGe and 400 miles, 5.3 kg of H_2 would be required, resulting in a refueling time of 3.2-5.3 min. Ignoring the time required for payment, engagement/disengagement of the fuel dispenser, and vehicle arriving/parking/departing at the dispenser, a single H_2 dispenser can accommodate up to 453 FCVs per 24 h period.

Summary of Fuels

The summarized values for rated equivalent electrical power, TTW efficiency, de-rated equivalent electrical power, and station capacity are presented in Table 1.

Table 1. Refuelling/charging dispenser rates and station capacity.

	Gasoline/ ICEV	Electricity/EV			Hydrogen/ FCV
		50 kW	145 kW	350kW	
Rated Dispenser Power (MW)	20.8	0.05	0.145	0.35	2.4-3.9
TTW Efficiency (MW)	19.5%	83%			53%
De-Rated Dispenser Power (MW)	4.1	0.0042	0.12	0.291	1.3-2.1
Refueling time (min)	1.4	135	47	19	3.2-5.3
# of Vehicles Accommodated in 24 Hours	1,014	11	31	75	271-453

After the power de-rating due to power-train efficiencies, the Ultra-fast DCFC power continues to be an order of magnitude lower than the gasoline power and of the H_2 power. This result means that in addition to loss of utility to the vehicle driver, the financial viability of the centralized refueling model, which requires throughput of vehicles, is compromised. Therefore, it is questionable that even Ultra-fast DCFCs can serve as a replacement to gasoline refueling in a centralized refueling paradigm. However, it should be noted that Ultra-fast DCFCs do represent an opportunity for ESS re-use in secondary applications. Vehicle ESS reach end-of-life status at 80% but still have useful energy storage capacity that can be used elsewhere in ground-based storage applications.

The gasoline dispenser equivalent electrical power is decreased substantially based on the much lower powertrain efficiency such that instead of being an order of magnitude larger than the H_2 refueling, it is now only twice as large. This result means that H_2 dispensers can accommodate vehicles at a comparable rate to gasoline dispensers such that centralized refueling stations could remain financially viable. H_2 refueling is thus comparable to gasoline refueling, as seen by both the vehicle driver and the refueling infrastructure owner, enabling the possibility that H_2 refueling could serve as a replacement to gasoline refueling in a centralized refueling paradigm without a significant loss of utility to the vehicle driver or revenue to the infrastructure owner.

Conclusions

The possible conclusions that can be reached is that the future of refueling includes:

1. Continuing to increase EVSE access, especially for home and workplace locations.

2. Meanwhile, the centralized refueling paradigm can shift from gasoline dispensers to H_2 dispensers to accomodate FCVs. The latter would allow incumbent transportation fuel companies that already have a centralized retail footprint to leverage these assets for a future transportation technology as the shift occurs. This model of H_2 dispensers being installed at existing retail stations has already been adoped by a large proportion (nearly 90% -- 58 out of 65 locations as of October 2017)[xxiv] of H_2 stations in California.

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Sources

[i] Hydrogen can be used in an ICE, but the efficiency is lower than in a fuel cell, and CACs are still produced. While hydrogen ICE (HICE) vehicles have been produced as prototypes and demonstrations, there are no serious efforts to develop this technology within the automotive industry.

[ii] http://247wallst.com/economy/2014/05/22/why-are-there-115000-or-150000-gas-stations-in-america/#

[iii] http://247wallst.com/economy/2014/05/22/why-are-there-115000-or-150000-gas-stations-in-america/#

[iv] VOCs and NOx gases are both involved in chemical reactions (accelerated by solar energy) to create ground-level ozone (O3), which is a respiratory irritant as well as a major contributor to urban smog.

[v] The production, transmission, and distribution of electricity and hydrogen (and gasoline, for that matter) produce both CACs and GHGs. However, well-to-tank (WTT) analyses consistently show that the levels of emissions for EVs and FCVs than for ICEVs (https://www.afdc.energy.gov/pdfs/argonne_phev_evaluation_report.pdf). Further, the CAC production being displaced from urban centers to power plants that are generally outside urban centers has a significant impact on urban air quality, even if the power plant is fossil fueled.

[vi] EVs are normally referred to as being "charged" rather than refueled. But electrons could be considered to be the "fuel" of an EV, so adding electrons is akin to refueling an EV.

[vii] Generated using fleet data from the fleetcarma.com web portal.

[viii] www.afdc.energy.gov

[ix] http://www.reinventingparking.org/2013/02/cars-are-parked-95-of-time-lets-check.html

[x] http://www.hybridcars.com/august-2017-dashboard/ EVs have been introduced to market periodically since the gasoline/ICEV paradigm became dominant, most recently with the GM EV-1 that was released in 1996. However, these EV market introductions were never throughout the U.S. until 2010.

[xi] Compressed H2 is seen as the technology for the foreseeable future but the general consensus is that some other technology will be needed ultimately because of the limits to specific energy and energy density of compressed H2 tanks.

[xii] According to the California Fuel Cell Partnership, as of September 22, 2017, there are 31 retail H2 stations open in California, 3 non-retail stations open, and an additional 30 stations in various stages of development (https://cafcp.org/sites/default/files/h2_station_list.pdf).

[xiii] http://www.hybridcars.com/august-2017-dashboard/

[xiv] https://www.texasmonthly.com/energy/electric-vehicles-energy-problem-hydrogen-may-answer/

[xv] Some analyses use 300 miles; however, in order to ensure no loss of utility from what a driver could expect from a conventional ICEV, 400 miles is chosen.

[xvi] This is true in both the U.S. (https://www.ecfr.gov/cgi-bin/text-idx?SID=34165648deb045b2bdd97fa32d242a90&mc=true&node=se40.19.80_122&rgn=div8) and Canada (http://laws-lois.justice.gc.ca/eng/regulations/SOR-2000-43/page-1.html#h-3)

[xvii] From http://www.shell.com/energy-and-innovation/shell-ecomarathon/for-participants/rules-and-competition-overview.html, page 26-27 of the official rules.

[xviii] Efficiency values taken from Helmers and Marx Environmental Sciences Europe 2012, 24:14, www.enveurope.com/content/24/1/14

[xix] https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf

[xx] https://electrek.co/2016/07/20/tesla-supercharger-capacity-increase-145-kw/

[xxi] https://qz.com/1072643/electric-vehicles-india-is-about-to-embark-on-the-most-ambitious-electric-car-transformation-in-the-world/

[xxii] T. DeWitt, J. Mackie, and E. Stokka (2016). DC Fast charging acceptance of PEVs at varying temperatures. SAE Thermal Management Systems Symposium, Mesa, AZ.
[xxiii] W. James (2014). An introduction to SAE Hydrogen Fueling Standardization. U.S. DOE FCTO Webinar.
[xxiv] California Fuel Cell Partnership internal data

Author Note

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