Research Report – UCD-ITS-RR-14-20

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December 2014

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European Electric Vehicle Congress
Brussels, Belgium, 3rd – 5th December 2014

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Abstract

In this paper, detailed comparisons are made between various types of light-duty vehicles fueled with natural gas and hydrogen. The natural gas vehicles are designed as charge sustaining hybrid vehicles (HEV) and the hydrogen fueled vehicles (FCV) are powered by a fuel cell. All the vehicles have a range of 400 miles between refueling stops. The paper discusses the on-board storage of natural gas (3600 psi) and hydrogen (10000 psi) in terms of the volume and weight of the tanks required and how fuel storage affects the vehicle design. Detailed computer simulations are presented for vehicle classes from compact cars to mid-size SUVs. The fuel economies of those vehicles are calculated for several driving cycles. The energy (MJ) and volume (L) of fuel storage required to meet the 400 mile range target for each vehicle using natural gas and hydrogen are compared.

The costs of the vehicles simulated are projected for 2015-2030. The differences between the costs of the natural gas hybrid vehicles and the fuel cell vehicles are calculated for the various vehicle types as the cost of the fuel cells, batteries and other powertrain components decrease. The CO_2 emissions from the CNG hybrid and fuel cell vehicles are determined and compared for hydrogen and electricity from natural gas. As a final step, the ways in which the introduction of the natural gas fueled vehicles could be a bridge to the mass marketing of fuel cell vehicles are considered.

Keywords: natural gas, hydrogen fuel cell, light-duty, storage, simulation

1 Introduction

There is considerable interest [1-3] in increasing the use of natural gas as a fuel in the transportation sector. Presently (2014) most of the activity in this area in the United States is concerned with the use of natural gas in heavy- and medium duty trucks and transit buses. There is much less interest in using natural gas for light-duty passenger cars, SUVs, and pick-up trucks. There is, however, considerable discussion of the use of hydrogen fuel cells in these light-duty vehicles. In fact, several auto manufacturers are planning [4, 5] to begin marketing fuel cell vehicles in 2015-2016. One of the impediments to marketing fuel cell vehicles is the lack of an extensive infrastructure for the hydrogen fuel. In addition, there is uncertainty regarding the acceptance of the public to the use of a gaseous fuel in their vehicles. In the past, there has been considerable discussion [6, 7] of the use of natural gas in light-duty vehicles as a bridge to the use of hydrogen in vehicles. One of the reasons this discussion has not been taken seriously has been the lack of success in the marketing the few natural gas vehicle models that have been offered for sale. These vehicles (ex. Honda Natural Gas Civic) were retrofits of existing gasoline fueled models to accommodate natural gas as the fuel. Because the volume of the natural gas tank is much larger than the gasoline tank, part of the trunk of the retrofitted vehicle is taken up by the natural gas tank and even then, the range of the natural gas vehicle is significantly less than that of the gasoline fueled model. In addition, the price of the natural gas model has been significantly higher than the standard gasoline model. Hence it was not surprising that sales of the natural gas model were very low.

The question addressed in this paper is whether light-duty vehicles designed from the ground-up to use gaseous fuels could be marketed successfully as natural gas vehicles and further how they would compare in the near-term with hydrogen fuel cell vehicles using the same chassis design to accept hydrogen storage tanks. In this way, natural gas vehicles could serve as a bridge to public acceptance and the mass marketing of fuel cell vehicles as their price becomes lower and hydrogen infrastructure is developed. The wide availability of natural gas and its projected relatively low price [8] into the future compared to gasoline makes the strategy of marketing natural gas vehicles a reasonable possibility.

In this paper, detailed comparisons are made between various types of light-duty vehicles fueled with natural gas and hydrogen. The natural gas vehicles are designed as charge sustaining hybrid vehicles (HEV) and the hydrogen fueled vehicles (FCV) are powered by a fuel cell. All the vehicles have a range of 400 miles between refueling stops. The paper discusses the on-board storage of natural gas (3600 psi) and hydrogen (10000 psi) in terms of the volume and weight of the tanks required and how fuel storage affects the vehicle design. Detailed computer simulations of the vehicles are presented for several driving cycles and the energy (MJ) and volume (L) of fuel required to meet the 400 mile range target for each vehicle using natural gas and hydrogen are compared.

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2 Storage of natural gas and hydrogen

Both the natural gas and hydrogen are stored on-board the vehicle as a compressed gas and the volume of the tanks is much greater than the volume of the gasoline tank in a conventional ICE vehicle. The technology for manufacturing storage tanks for compressed natural gas (CNG) is mature and commercial products are available [9]. Both steel and composite carbon fiber tanks are marketed. In the case of hydrogen, the technology for the tanks is still evolving [10-12] and all the tanks are manufactured using carbon fiber composites. The characteristics of the energy storage tanks for natural gas and hydrogen are summarized in Table 1. The hydrogen is stored at 10, 000 psi (680 atm.) and the natural gas at 3600 psi (245 atm.). The tank sizes given in Table 1 are for storing an amount of energy (MJ or kWh) equivalent to that in 5 gal. of gasoline or 5 kg of hydrogen. Note in the table that the weight and volume of the tank needed to store hydrogen are significantly greater than to store the same amount of energy with natural gas. This will be true even when the DOE goals for hydrogen storage are met. If both the natural gas and hydrogen tanks are constructed of carbon composite materials, the MJ/L factor for the natural gas tank is about 3x that of the DOE goal for hydrogen.

3 Vehicle designs and simulations

As indicated in the **Introduction**, the gas fueled vehicles being compared are charge sustaining hybrid-electric CNG vehicles and fuel cell hydrogen vehicles. All the vehicles were simulated using the ADVISOR vehicle simulation program that has been extensively modified at UC Davis [13, 14]. The input parameters used in the simulations for the various classes of vehicles are given in Table 2. In the case of the hybrid-electric vehicles, a single-shaft arrangement with a double clutch transmission was used as the driveline. The control strategy utilized all-electric drive if the power demand could be met with the electric motor and operation of the engine at higher power demands by charging the battery as needed [15, 16]. In this way, the engine was operated near peak efficiency most of the time. The fuel cell vehicles were also hybrids with a large electric motor and a battery to meet the peak power demands. The fuel cell recharged the battery and provided steady power demand for cruising and hill climbing. The batteries used in both drivelines were high power lithium batteries that would give long life (at least 10 years) for shallow SOC cycling. Ultracapacitors could be used in both the HEV and FC drivelines in place of the batteries [17, 18]. Engine map used in the CNG HEV simulations is given in Figure 1.

Table 1: Summary of gaseous fuel energy storage characteristics

Source or requirement	fuel	Gasoline equivalent Gal.	Tank volume (1) L	Tank weight (1) kg	MJ/L_{tank}	MJ/kg_{tank}
Present status	H_2 (2)	5 (1)	230	130	2.6	4.6
DOE goal 2015 (new)	H_2	5	128	130	4.7	6.5
Available composite	CNG (3)	5	80	33	7.5	18.2
Available metal	CNG	5	69	62	9.6	9.3

(1) 600 MJ fuel energy stored

(2) Hydrogen stored at 10000 psi

(3) CNG stored at 3600 psi

Table 2: Input parameters for the ADVISOR vehicle simulations

Vehicle type	C_DA m^2	f_r	Weight kg	Engine kW	Electric motor kW	Battery kWh	Fuel cell kW	Electric motor kW	Battery kWh
Compact	.6	.008	1388	97	15	1.0	60	95	1.0
Mid-size	.68	.008	1617	125	25	1.5	75	110	1.5
Full-size	.71	.008	1890	160	50	2.0	100	140	2.5
Small SUV	.72	.008	1700	140	25	1.5	85	120	1.5
Mid-size SUV	.75	.008	2100	150	40	2.0	100	125	2.0
Delivery truck	4.7	.008	7430	200	75	3.0	125	200	4.0

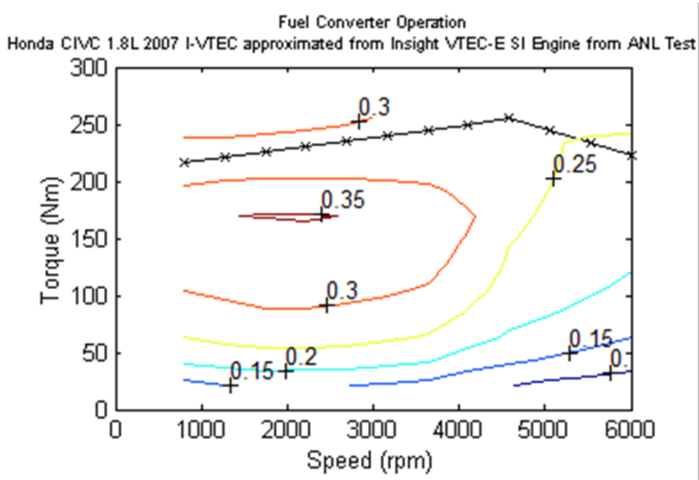

Figure 1: Engine map used in the CNG HEV simulations

Table 3: Comparisons of the Storage requirements (Liters) for CNG in an HEV and H_2 in a fuel cell vehicle

	CNG HEV [1]					H_2 FCV			
Vehicle type	**EPA Mpg ICE Vehicle**	**City mpg Gasoline Equiv.**	**HW mpg Gasoline Equiv.**	**CNG storage for 400 miles L [3]**		**City mpg Gasoline Equiv.**	**HW mpg Gasoline Equiv.**	**H2 storage for 400 miles L[3]**	**Ratio of mpg FC to HEV**
Compact car	28/39	52.8	59.3	106		75	88	224	1.46
Mid-size car	27/36	49.4	53.1	116		71	79	244	1.47
Full-size car	25/36	44.3	51.3	124		67	75	258	1.48
Small SUV	22/30	47.3	51.9	120		69	80	246	1.50
Mid-size SUV	17/24	40	46	158		62	70	277	1.50
UPS delivery truck		12.0	11.3	128 L for 100 mile range		19	16.4	258	1.52

(1) CNG at 3600 psi, 8 MJ/L (steel tank)

(2) H_2 at 10,000psi, present technology 2.6 MJ/L

(3) Gasoline energy content 119 MJ/gal.

The simulation results for the CNG HEV and H_2 FCV are summarized in Table 3. The fuel economies are given in terms of gasoline equivalent mpg which allowed the simple calculation of MJ for the required 400 mile range for all the vehicles except the delivery vehicle which has a 100 mile range. The fuel economy used for in the energy calculations was the average of the city and highway values. For the tank volumes shown in Table 3, it was assumed that the CNG vehicles used steel tanks and the H_2 fuel cell vehicles used composite tanks presently available (2.6 MJ/L). For all the vehicle classes, the volume of the hydrogen tanks was about 2x that of the CNG tank. Even if/when the DOE hydrogen energy storage goal (4.7 MJ/L) is met, the volume of the CNG tanks would be slightly smaller (about 15%) than the hydrogen tanks for the 400 mile vehicle range. Note also in Table 3 that the equivalent fuel economy of the corresponding fuel cell vehicle is about 1.5x that of the CNG vehicle.

In the cost analysis in the next section, it will be assumed that the chassis and body for the CNG and H_2 vehicles in each class are essentially identical. The vehicles, of course, will differ in terms of driveline and fuel storage tanks, but it is assumed that these components can be installed with minimal change in the chassis.

4 Cost of CNG hybrid and fuel cell vehicles (2014-2030)

In this section, the present and future costs of the CNG and H_2 vehicles will be calculated/projected. As noted previously, it is assumed that all the vehicles are ground-up designs such that the installation of the driveline and the fuel storage tanks do not detract from their utility and styling compared to corresponding gasoline fueled vehicles. In the past, the CNG tanks have been retrofitted into the trunk of the vehicle significantly reducing the trunk space. Figures 2 shows the advantages of a ground-up design in storing gaseous fuels onboard vehicles. The performance of the CNG and H_2 vehicles are at least as good as the corresponding gasoline vehicles. Further it is expected that the driveability of the alternative fueled vehicles will be more desirable than the gasoline vehicles due to their electric drivelines.

A relatively simple approach was followed to determine the vehicle costs. A baseline price of the vehicle without the driveline and storage tank was estimated by taking the present price (2014) of the corresponding gasoline vehicle and subtracting the estimated price of the engine/transmission unit ($40/kW). Next the total cost of the driveline components and storage tanks for each vehicle was calculated and their showroom price determined assuming a mark-up of 1.5. The OEM costs assumed for the various components are given in Table 4 for the period between 2015 and 2030. Cost information for alternative fueled vehicles is also given in [19]. There is considerable uncertainty regarding these costs because the sales volume of the vehicles and thus the components needed to assemble them are difficult to assess. The component costs given in Table 4 assume relatively high sales volumes especially in the years beyond 2020. The results of the price calculations for the CNG HEV and H_2 FCV are given in Table 5. The projected prices of fuel cell powered mid-size cars determined in this study are compared with those in a recent study [20] by Ogden in Table 6. The prices in the two studies are in good agreement.

Honda GX CNG Civic

Gaseous fuel storage in a ground-up fuel cell vehicle

Figure 2: Gaseous fuel storage in retrofitted and ground-up designed passenger cars

Table 4: Assumed component costs in the cost analysis

Component	**2015**	**2020**	**2025**	**2030**
Fuel cell system $/kW	70	60	50	45
Electric motor/elect. $/kW	45	35	30	27
Lithium battery $/kWh	600	450	400	375
H_2 storage $/kWh	20	15	12	10
CNG storage $/kWh	9	7	6	5
Engine/trans. $/kW	42	42	42	42

Table 5: Results of the price calculations for the CNG HEV and H_2 FCV

Vehicle type	**Baseline Vehicle price $**	**Vehicle price W/o driveline $**		**2015**	**2020**	**2025**	**2030**
Compact	19000	14800					
CNG HEV				26514	25231	24646	24161
H_2 FCV				33275	29510	27540	25690
Mid-size	25000	19000					
CNG HEV				33805	32215	31495	30925
H_2 FCV				40900	36490	34190	31985
Full-size	31000	23500					
CNG HEV				42603	40548	39595	38868
H_2 FCV				48775	43790	41200	39550
Small SUV	25000	19000					
CNG HEV				35605	33813	33010	32377
H_2 FCV				43165	38305	35817	33393
Mid-size SUV	33000	24750					
CNG HEV				42570	40508	39570	38847
H_2 FCV				52418	46860	44043	41265

Table 6: Projected prices of fuel car powered mid-size cars

Year	Present study	Ogden, etc. [20]
2010		49K
2015	41K	43K
2020	37K	39K
2025	34K	35K
2030	32K	31K

5 The relative economics, energy use, and CO_2 emissions

Relative economics

The results in Table 5 indicate that the showroom prices of the CNG hybrid vehicles will be significantly lower than those of the fuel cell vehicles early in the period being considered, but the cost differences will narrow by the later years. It seems likely that the cost differences will be even greater in the early years than shown in Table 5 when the production and sales volumes of fuel cell vehicles are being ramped up. The cost differences indicate that CNG HEVs can offer an opportunity to familiarize the public with the fueling and operation of gaseous fuel vehicles during the period when fuel cell technology is maturing.

Relative utilization of natural gas and CO_2 emissions

It is of interest to compare the efficiency (mi/kWh nat.gas) of using natural gas in various alternative vehicles- namely HEVs, EVs, and fuel cell vehicles. The calculation of the different natural gas efficiencies requires assumptions regarding the conversion of natural gas to electricity and hydrogen and the efficiencies (mpg gasoline equiv.) of the vehicles of interest. The following assumptions have been made in this example:

Natural gas to electricity 40%
Natural gas to hydrogen 70%

EV 250 Wh/mi of electricity from the wall plug
CNG HEV 50 mpg gasoline equivalent
H_2 FCV 75 mpg gasoline equivalent

The resulting natural gas efficiencies (mi/kWh nat. gas) are the following:

EV 1.6 mi/kWh nat. gas
HEV 1.52
FCV 1.59

These values do not include the energy required to distribution the electricity or natural gas and the energy required to compress the natural gas and hydrogen for use in the vehicles. According to References [21, 22], the compression of natural gas and hydrogen use 2.3% and 7.2%, respectively, of the energy content of the gases. In most cases, the compressors used to compress the gases are driven by electric motors. It is assumed in this example that the efficiency of the compression system is 70%. This means, for example, that the energy required to generate the electricity from natural gas to compress the hydrogen is 7.2%/.7x.4 or 25.7%. The corresponding energy for the compression of natural gas is 8.2%. If the loss in the distribution of the electricity is 10%, the compression energy values for natural gas and hydrogen become 9.1% and 28.5%, respectively. Hence the natural gas efficiencies (mi/kWh nat. gas) for the three alternative vehicles become

EV 1.44 mi/kWh nat. gas
HEV 1.39
FCV 1.14

These values indicate that the energy efficiency of the FCV is slightly less than that of the EV and HEV when the energy required for compression of the hydrogen is included.

Next consider the CO_2 emissions from the FCV, HEV, and EV vehicles assuming all the hydrogen and electricity are generated from natural gas. The CO_2 emissions can be calculated from the energy efficiency (mi/kWh nat. gas) values for each of the vehicles by using the factors

1 kWh nat.gas = .0766 kg nat.gas
1 mole CH4 → 1mole CO_2 or 1 kg nat. gas
→ 2.75 kgCO_2

Hence

EV .146 kgCO_2/mi
HEV .151 kgCO_2/mi
FCV .185 kgCO_2/mi

The CO_2 emissions of the EV and HEV are nearly the same and the FCV has 22% higher emissions than the other electrified vehicles when the hydrogen is obtained from reforming natural gas. In the near-term, it is likely this will be the case, but for longer term more of the hydrogen will be obtained from renewable sources and the resultant CO_2 emissions for the FCV would be much lower.

6 Natural gas-hydrogen bridge considerations

The discussions in the previous sections indicate that hybrid-electric vehicles fueled with natural could offer a bridge to hydrogen fuel cell vehicles during the early, near-term period in which the fuel cell technologies are maturing. Both vehicles use gaseous fuels with similar infrastructure and refueling practices. It could be possible to combine the fueling for natural gas and hydrogen in the same station in order to reduce the cost of providing infrastructure for gaseous fuels. The cost of both types of stations is high, because fast fueling for the fuels is desired [23].

The vehicle cost analysis indicates that the cost of the HEV vehicles of the various classes will be lower than the corresponding FCV. The cost differences will be significant (at least $5-10K) before 2020 and narrow gradually in later years. Cost incentives could be offered by the Federal and State governments to reduce the cost differences in the early years. These incentives could be comparable to those currently be offered for plug-in electric vehicles. The present (2014) cost of natural gas is low making fuel expenditures for the CNG HEV relatively low and the likely cost of hydrogen for the FCVs lower than would otherwise the case. Since natural gas is a “natural” fuel and hydrogen is a “processed” fuel, it seems reasonable to assume that CNG will always be lower cost ($/MJ) than H_2. This and the fact that CNG is less difficult and expensive to store onboard vehicles should result in natural gas vehicles remaining marketable even after fuel cell vehicle technology is mature and less expensive. The analysis of the CO_2 emissions indicates that the emissions of the EVs and CNG HEVs are nearly the same and that the emissions of the FCVs using hydrogen from natural gas are about 20% higher. Hence during the early years after the introduction of FCVs, CNG HEVs would not result in higher GHG emissions (neglecting methane leakage which is uncertain at the present time) than FCVs. When hydrogen from renewable sources becomes available and the public is as familiar with gaseous fueled vehicle as they are now with liquid fueled vehicles, the stage will be set for the mass marketing of FCVs and the movement to sustainable personal transportation.

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