Fuel Economy of Hybrid Fuel Cell Vehicles

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Introduction

Automobile manufacturers are introducing gas-electric hybrids to overcome the drop off in the efficiency of the internal combustion engines (ICE) at part loads. According to different studies, hybridization has the potential to reduce the fuel consumption of gasoline ICE vehicles by 20-30% on standard U.S. drive cycles [1-2]. In contrast to ICE, fuel cell systems (FCS) have the characteristic that the efficiency does not degrade at part load and in fact can be much higher. This is particularly advantageous in transport applications because the vehicles are mostly operated at part load conditions. A recent study concluded that the fuel economy of hydrogen fuel cell electric vehicles (FCEV) can be 2.5-3 times the fuel economy of the gasoline ICE vehicles [3].

The purpose of this study is to assess the potential improvement in fuel economy of a FCEV by hybridizing it with an energy storage system (ESS). The study is based on a mid-size family sedan as the vehicle platform, a direct-hydrogen pressurized FCS as the energy converter and a lithium-ion battery pack as the ESS. In comparing the fuel economies of fuel cell hybrid electric vehicles (FCHEV) with different degrees of hybridization we require that they have the same acceleration performance by holding the combined rated power of the FCS and ESS as constant. Consequently, the FCS is downsized as the degree of hybridization is increased by making the ESS larger.

Vehicle and Fuel Cell System

A mid-size family sedan was selected as the reference ICE vehicle platform for which the major parameters that affect its fuel economy are 1695-kg gross weight, drag coefficient of 0.32, 2.2-m^2 frontal area, and coefficient of rolling friction of 0.009.

The FCS analyzed in this study uses pressurized hydrogen as fuel. At the rated power point, the polymer electrolyte fuel cell (PEFC) stack operates at 2.5 atm and 80ºC to yield an overall system efficiency of 50% (based on lower heating value of hydrogen). The system pressure is lower than 2.5 atm at part load and is determined by the operating map of the compressor-expander module (CEM) [4]. The nominal flow rate of cathode air is two times what is needed for complete oxidation of hydrogen (50% oxygen utilization).

Our interest is in FCHEV in which the FCS is operated in a load-following mode and the ESS in a charge-sustaining mode. In this type of a hybrid system, FCS provides the traction power under normal driving conditions and the ESS provides boost power under transient conditions. ESS also stores part of the energy that must otherwise be dissipated when the vehicle brakes. To be competitive with the ICE propulsion system in terms of drivability and performance, the FCS in this type of a hybrid vehicle must satisfy the following requirements.

a) FCS alone must be capable of meeting the vehicle power demands under all sustained driving conditions. These include a specified top sustained speed, taken as 100 mph (miles/hour) in this study, and ability to maintain the vehicle at 55-mph speed at 6.5% grade for 20 minutes.
b) With the assistance of ESS, the FCS must have the response time to allow the vehicle to accelerate from 0 to 60 mph in a specified time, taken as 10 s in this study.
c) FCS must have 1-s transient response time for 10% to 90% power.

We used the following approach to select FCS parameters to meet the above requirements.

a) We define the minimum power rating of the FCS to be the higher of the power demand at 100-mph sustained speed and the power needed at 55 mph at 6.5% grade.
b) We further require that the FCS be 50% efficient at the rated power point. This requirement determines the cell voltage at rated power.
c) We meet the 1-s transient time target by overloading the CEM electric motor for short time.

We iterated between the FCS and vehicle parameters to determine that the FCEV (1900-kg gross vehicle weight including 136-kg payload) needs 120-kWe FCS peak power to accelerate from 0 to 60 mph in 10 s, 65 kWe to sustain 100-mph top speed, and 62-kWe to maintain 55 mph at 6.5% grade with 600-kg payload. Accordingly, we consider four FCS and vehicles with characteristics summarized in Table 1. In listing the estimated weights, the hydrogen storage medium has been included with the FCS and the ESS with the electric drive train. It is assumed that hydrogen is stored as compressed gas at 5000 psi and in sufficient quantity for 320-mile driving range.

Table 1. Fuel cell systems and vehicles

		Gasoline ICE	FCEV 120kWe	FCHEV 100kWe	FCHEV 80kWe	FCHEV 65kWe
Power						
IC Engine / Fuel Cell System	kW	114	120	100	80	65
Electric Motor (Peak/Continuous)	kW		105 / 65	105 / 65	105 / 65	105 / 65
Energy Storage System (Peak)	kWe			20	40	55
Transmission						
Transmission Type		5-Spd	1 Spd	1 Spd	1 Spd	1 Spd
Weights						
Glider (Body & Chassis)+Payload	kg	1165	1165	1165	1165	1165
ICE / Fuel Cell System	kg	310	380	345	310	280
Drive-Train	kg	220	355	370	385	400
Gross Vehicle Weight	kg	1695	1900	1880	1860	1845
Accessory Power						
Mechanical	W	700	0	0	0	0
Electrical	We	500	500	500	500	500
Simulation Results - Performance				Initial SOC = 0.7		
Maximum Speed	mph	>115	100	100	100	100
0-60 mph	s	10.5	10.0	9.8	9.7	9.6
0-30 mph	s		3.7	3.5	3.5	3.5
50-80 mph	s		11.0	10.8	10.6	10.5
Maximum Vehicle Acceleration	m/s^2		4.1	4.2	4.2	4.3
6.5% at 55 mph	%	Yes	Yes	Yes	Yes	Yes

Electric Drive Train. Figure 1 shows the configuration of the electric drive train considered in this study. The input voltage of the inverter for the AC traction motor floats with the output voltage of the PEFC stack. A bi-directional DC/DC converter (95% average efficiency) is used to step-up the ESS voltage to match the PEFC stack voltage during discharge or to step-down the inverter output voltage to the appropriate level for charging the battery during regenerative braking.

The mechanical energy at the motor shaft is transmitted to the wheels via a one-speed reduction gear (94% peak efficiency) and a final drive (differential with specified gear ratio, 93% peak efficiency). A parametric study was performed to determine the optimum gear ratio and the motor (94% peak efficiency) power needed to obtain 100-mph top speed and be able to accelerate from 0 to 60 mph in 10 s.

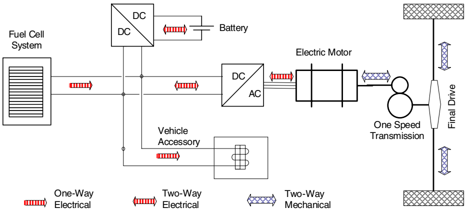

Figure 1. Electric drive train for hybrid vehicles

In our simulations, we have used a Li-ion battery pack as the ESS, each cell of which has 6 A-h C_5 capacity and operates at 2.4 -3.9 V and 0.3-0.9 state of charge (SOC). The numbers of cells in the ESS were determined to deliver peak pulse discharge power of 20, 40 or 55 kWe for 10 s.

Energy Management. A hierarchical set of priorities is used to regulate the flow of power into and out of the energy storage system. The highest priority is placed on maintaining the ESS near its target SOC so that it can provide assist power in transients when the FCS is unable to meet the vehicle power demand. The next level of priority is to maintain the ESS in a position (i.e., lowest SOC) that maximizes its ability to accept regenerative braking energy when it becomes available. In order to accommodate the two conflicting priorities our strategy is to attempt to discharge the ESS immediately after a regenerative braking event that raises the SOC above the target value (0.7 in this work). During this time the priority is given on drawing the maximum power from the ESS with the FCS providing the balance to meet the vehicle power demand.

Simulation Methodology. The vehicle analysis code PSAT [3] and the fuel cell system analysis code GCtool [5] were tightly integrated to conduct full dynamic simulations of FCHEV on the prescribed drive cycles (FHDS, FUDS, US06, J1015, NEDC) and performance cycles. The choice of vehicle parameters was first validated by comparing the calculated fuel economy of the reference gasoline ICEV with the published values of 29 mpg on FHDS and 20 mpg on FUDS. Special care was taken in determining the fuel economy of hybrid vehicles on a consistent and reproducible basis by running simulations such that there was no net transfer of energy into or out of the ESS.

Fuel Economy

Figure 2 compares the simulated fuel economy of FCEV with the fuel economy of ICEV on the highway (FHDS) and urban schedules (FUDS). In order to reflect the real world driving experience, EPA adjusts the fuel economy of ICEV measured in laboratory tests by a factor of 0.78 for FHDS and 0.9 for FUDS. We apply the same correction factors to our simulation results for the FCEV. Also, as is done for ICEV, the combined fuel economy is calculated as a weighted average over FHDS and FUDS.

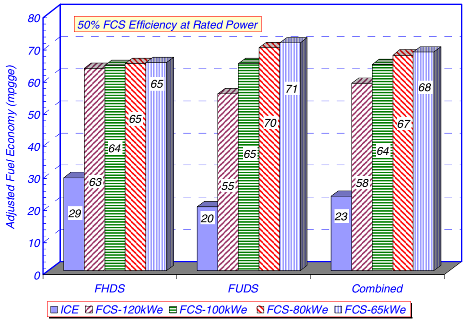

Figure 2. Effect of hybridization on fuel economy

On FHDS, the simulated fuel economy of the stand-alone FCEV after adjustment is 63 mpgge (miles per gallon gasoline equivalent) compared to 29 mpgge for the ICEV, and hybridization is seen to have a small effect (<3.2% improvement) on the fuel economy of FCEV. On FUDS, the simulated fuel economy of the stand-alone FCEV after adjustment is 55 mpgge compared to 20 mpgge for the ICEV. The fuel economy of FCEV on FUDS improves to 65 mpgge with a small ESS (20 kWe) and to 70 mpgge with a larger ESS (40 kWe). Further increase in the size of the ESS to 65 kWe results in a marginal improvement in the fuel economy.

On combined FHDS and FUDS, the simulated fuel economy of the stand-alone FCEV is 2.5 times the fuel economy of the ICEV. With hybridization, the fuel economy multiplier for the combined schedules increases by about 17% to 2.9. The multiplier increases by about 3% on the highway portion and by about 29% on the urban portion of the combined cycle.

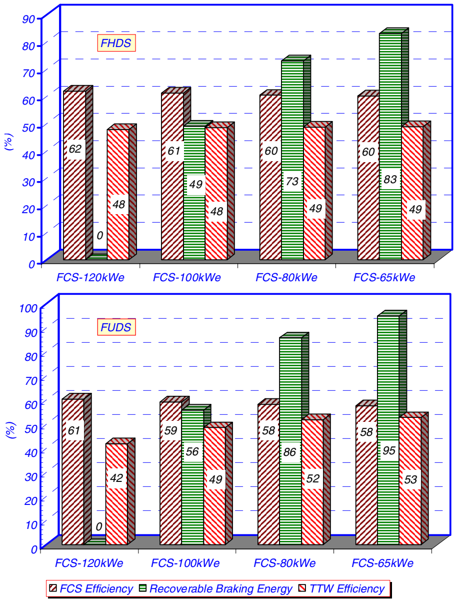

Figure 3. Effect of hybridization on efficiency

On FHDS, Fig. 3 indicates that the cumulative efficiency of the FCS decreases from 62% to 60% as the FCS is downsized from 120 kWe to 65 kWe. This decrease in FCS efficiency is offset by the recovery of braking energy. Our simulations indicate that a 20-kWe ESS can recover 49% of the braking energy on FHDS and that 83% of the braking energy can be recovered with a 55-kWe ESS. On FHDS, braking involves only 13% of the traction energy so that increase in recoverable braking energy with increase in ESS size marginally compensates for the corresponding decrease in FCS efficiency with the downsizing of FCS. The result is that on FHDS the tank-to-wheel (TTW) efficiency of FCEV improves by only 2.1% with hybridization.

On the stop-and-go FUDS, braking involves nearly 50% of the traction energy so that increase in recoverable braking energy with increase in ESS more than compensates for the corresponding decrease in FCS efficiency with the downsizing of FCS. The result is that the TTW efficiency on FUDS increases significantly with the degree of hybridization. Figure 3 indicates that the TTW efficiency for the 65-kWe FCS and 55-kWe ESS is about 26% higher than for the stand-alone 120-kWe FCS.

Effect of Drive Cycles. Figure 4 illustrates the effect of drive cycles on the simulated fuel economy of hybrid fuel-cell vehicles. The results are given on the basis of mpgge and have not been adjusted for real world driving experiences. The maximum increase in fuel economy with hybridization is about 3% on FHDS, 29% on FUDS, 7% on the aggressive US06 drive schedule, 17% on the New European Drive Cycle (NEDC), and 34% on the Japanese J1015 drive schedule.

One parameter that determines the potential improvement in fuel economy with hybridization is the fraction of the traction energy that is involved in braking in a given drive cycle. The potential improvement is small in FHDS because the braking energy is only 13% of the traction energy and is large in FUDS and the J1015 cycle in which it is 50% and 53%, respectively. The braking energy fraction is 34% in US06 driving schedule and 35% in NEDC.

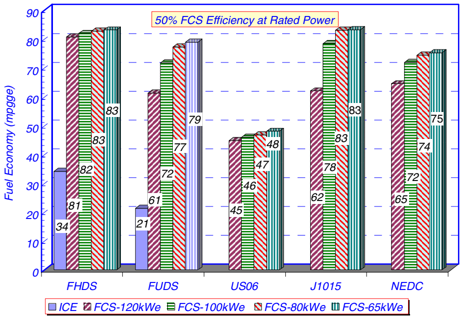

Figure 4. Effect of drive cycles on fuel economy

The fraction of the braking energy that is actually recovered depends on the size of the ESS and the braking power involved. The recoverable braking energy is < 64% on US06 drive schedule because it involves hard braking but can be > 99% on J1015 drive schedule that has soft braking.

Conclusions

- The fuel economy of hydrogen FCEV can be 2.5-2.6 times the fuel economy of conventional ICEV.
- With a Li-ion battery pack, the fuel economy of a FCHEV on the combined cycle can be 17% higher than that of the FCEV. The extent of increase depends on the degree of hybridization.
- The increase in fuel economy with an ESS depends on the drive cycles: 3% on FHDS, 29% on stop-and-go FUDS, 7% on the aggressive US06 cycle, 34% on J1015, and 17% on NEDC.
- The potential gain in fuel economy with hybridization is greater for an ICEV than for a FCEV.

Acknowledgements

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References

1. M. A. Weiss, J. B. Haywood, A. Schafer, and V. K. Natarajan, "Comparative Assessment of Fuel Cell Cars," Massachusetts Institute of Technology, Laboratory for Energy and the Environment, Publication No. LFEE 2003-001 RP, February 2003.
2. "Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis," Vol. 2, General Motors Corporation, June 2001.
3. R. K. Ahluwalia, X. Wang, A. Rousseau, and R. Kumar, "Fuel Economy of Hydrogen Fuel Cell Vehicles," Journal of Power Sources, Vol. 130, 2003, pp. 192-201.
4. R. K. Ahluwalia and X. Wang, "Direct Hydrogen Fuel Cell Systems for Hybrid Vehicles," Journal of Power Sources, 2004 (in print).
5. H. K. Geyer and R. K. Ahluwalia, "GCtool for Fuel Cell Systems Design and Analysis: User Documentation," Argonne National Laboratory Report, ANL-98/8.