ABSTRACT
Fuel cell vehicles are the subject of extensive research and development because of their potential for high efficiency and low emissions. Because fuel cell vehicles remain expensive and the demand for hydrogen is therefore limited, very few fueling stations are being built. To try to accelerate the development of a hydrogen economy, some original equipment manufacturers (OEM) in the automotive industry have been working on a hydrogen-fueled internal combustion engine (ICE) as an intermediate step. Despite its lower cost, the hydrogen-fueled ICE offers, for a similar amount of onboard hydrogen, a lower driving range because of its lower efficiency. This paper compares the fuel economy potential of hydrogen-fueled vehicles to their conventional gasoline counterparts. To take uncertainties into account, the current and future status of both technologies were considered. Although complete data related to port fuel injection were provided from engine testing, the map for the direct-injection engine was developed from single-cylinder data. The fuel cell system data represent the status of the current technology and the goals of FreedomCAR. For both port-injected and direct-injected hydrogen engine technologies, power split and series Hybrid Electric Vehicle (HEV) configurations were considered. For the fuel cell system, only a series HEV configuration was simulated.

INTRODUCTION
Hydrogen is considered one of the most promising long-term alternatives as a fuel for automotive applications. Fuel cell vehicles (FCVs) are starting to hit the roads, in demonstration and validation projects around the world. FCVs offer significant benefits — for example, they achieve energy efficiencies of 40–50% in current road tests (compared to 18–20% in conventional vehicles). They can also achieve higher overall “well-to-wheel” efficiencies than advanced vehicles (like gasoline/battery hybrids) when hydrogen is produced from renewable energy sources. This significant improvement in energy efficiency means fewer oil imports, increased energy security, and reductions in greenhouse gas emissions. Despite their breakthrough benefits, fuel cells are not yet ready for the public market. One of the obstacles in developing cost-effective fuel cells is building a hydrogen refueling infrastructure. To try to solve this problem, OEMs, including Ford [1] and BMW [2], are conducting extensive research on a spark-ignition ICE that can run on hydrogen (H2-ICE).

For the past couple of years, the U.S. Department of Energy (DOE) has invested considerable effort into the research and development of hydrogen-fueled vehicles. Using hydrogen to power ICES is seen as a bridging technology toward a large-scale hydrogen infrastructure. Several projects are currently focusing on using a direct-injection hydrogen engine as a way to reach the 45% peak efficiency goal set by the FreedomCAR and Fuels partnership.

This paper evaluates the fuel economy benefits of fuel cell systems and hydrogen engines in comparison with a gasoline conventional vehicle by using Argonne National Laboratory’s Powertrain Systems Analysis Toolkit (PSAT). PSAT [3,4] is designed 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. Because of time and cost constraints, engineers cannot build and test each of the many possible powertrain configurations for advanced vehicles. PSAT, a forward-looking model, offers the ability to quickly compare several powertrain configurations.

To display the maximum potential of the technology, several powertrain configurations are considered for the hydrogen engine. All of the vehicles are sized to meet similar performance.

VEHICLE CONFIGURATIONS
Two hybrid families were considered in the study. For each option, hundreds of combinations are possible, including the number of electric machines, their location, transmission type, component size, and a multitude of other variables. In this study, two configurations were selected:
- Series configuration, for both fuel cell system [5,6] and hydrogen engine.

The fuel cell system and hydrogen engine technologies will be compared for each powertrain configuration and component size considered.

**VEHICLE DESCRIPTION**

The vehicle class used represents a midsize sedan. The main characteristics are defined in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Main Vehicle Characteristics</th>
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<tr>
<td>Glider mass (kg)</td>
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<tr>
<td>Frontal area (m²)</td>
</tr>
<tr>
<td>Coefficient of drag</td>
</tr>
<tr>
<td>Wheel radius (m)</td>
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<tr>
<td>Tire rolling resistance</td>
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Because the primary goal of the study was to evaluate the fuel economy potential of hydrogen-powered vehicles, the uncertainties and potential of each technology were considered.

Figure 1 shows the fuel cell system efficiencies used in this study. The current system is characterized by a peak efficiency of 55% with a specific power of 500 W/kg, while the future technology achieves a peak efficiency of 60% efficiency with a specific power of 650 W/kg, on the basis of the FreedomCAR goals.

In addition, the efficiency curves of the fuel cell system are developed in steady state. Keep in mind that the parasitic load is higher in real-world driving because of transient and non-optimum control.

The fuel efficiency maps for the hydrogen ICE configurations were developed on the basis of engine data from a supercharged port-fuel-injected 4-cylinder hydrogen engine. The engine test bench is shown in Figure 2. Figure 3 shows the engine efficiency map as a function of air/fuel ratio at an engine speed of 1500 RPM [8]. Note that leaner engine operation (higher $\lambda$) results in more efficient combustion at the same load point. On the other hand, leaner operation results in reduced peak torque and therefore a loss in power output. On the basis of these data, an engine operating strategy and map were derived to take advantage of the hydrogen lean-burn capabilities at low and medium loads [9].

On the basis of the current technology with hydrogen port injection shown before, an engine efficiency map for a direct-injected hydrogen multi-cylinder engine was developed. This map is based on data related to (1) single-cylinder hydrogen direct-injection and (2) hydrogen multi-cylinder port-injection. The maps for multi-cylinder hydrogen direct injection were established under the following assumptions:
• Hydrogen direct injection will increase the peak torque curve [10].
• An increased compression ratio will result in an increase in engine efficiency [11].
• Turbo-charging is expected to increase engine efficiency, in comparison with supercharging.

On the basis of these assumptions, an efficiency map for an optimized turbo-charged hydrogen combustion engine with direct injection was developed. The peak efficiency is expected to reach 45%, which also meets the FreedomCAR goal set by the U.S. Department of Energy [12].

COMPONENT SIZING

The vehicle components were sized to meet similar vehicle performance metrics:

- 0–60 mph < 9 s
- Gradeability of 6% at 65 mph
- Maximum speed > 100 mph

To quickly size the powertrain component models, an automated sizing process was developed. For the hybrid vehicles, the battery and electric machines are sized to capture all of the regenerative braking above 2 mph on the Urban Dynamometer Driving Schedule (UDDS), while the engine is sized to meet gradeability requirements. Figure 4 shows the component power where MC2 is the second electric machine for the power split and GC is the generator for the series engine configuration. The reference vehicle (Ref) represents current gasoline technology. As discussed previously, three configurations using hydrogen ICE were considered: conventional (conv), power split (Split), and series (Series ICE). Only the fuel cell hybrid vehicle was simulated. Note that using an H2-ICE in a conventional vehicle leads to increased component power. Hybridizing the vehicle leads to a significant decrease in engine power (from 125 to 78 kW for the future case). The series ICE configuration requires an engine larger than its power split counterpart as a result of the added component losses (both generator and electric machine).

The specific power (power at the wheel/vehicle mass) of the vehicles is used to validate the vehicle sizing. The values range from 60 to 80 W/kg, which is consistent with the vehicles currently on the market. We also notice that the value drops with increased electric machine power, which is expected because of the high torque at low speed, in comparison with the engines.

Figure 4: Component Power – Future Technologies

The vehicle mass is calculated by adding each component mass to the glider mass. The mass of each component is defined on the basis of its specific power density. Figure 5 shows the vehicle test mass for each vehicle. The error bars demonstrate the uncertainty due not only to the hydrogen engine and fuel cell system but also to the other components. Although all of the components are based on current state-of-the-art technologies, future characteristics are based on the FreedomCAR goals when available.

Figure 5: Vehicle Mass

VEHICLE CONTROL STRATEGY ALGORITHMS

POWER SPLIT CONFIGURATIONS - The first critical part of the control strategy logic is related to the engine ON/OFF logic. As Figure 6 shows, the engine ON logic is based on three main conditions:

- The requested power is above a threshold.
- The battery SOC is lower than a threshold.
- The electric motor cannot provide the requested wheel torque.

In addition to these parameters, further logic is included to ensure proper drive quality by maintaining the engine ON or OFF for a certain duration. To avoid unintended engine ON events resulting from spikes in power...
demand, the requested power has to be above the threshold for a pre-defined duration, called the debounce time. The engine OFF logic condition is similar to that of the engine ON. Both power thresholds used to start or turn off the engine and to determine the minimum duration of each event have been selected as input parameters of the optimization problem.

To be able to regulate the battery SOC, especially during the charge-depleting mode, the power demand that is used to determine the engine ON/OFF logic is the sum of the requested power at the wheel plus additional power that depends on battery SOC. This power can be positive or negative, depending on the value of the current SOC compared to the target.

SERIES ENGINE CONFIGURATION - Because the engine is completely decoupled from vehicle operation, numerous choices can be made in terms of control strategy. A control strategy based on SOC has been adopted. The difference between the SOC target and its current value is used to define additional power demand. The power demand at the wheel is added to the power demand to decide if the engine should be turned ON.

When the engine is on, it operates close to its best efficiency curve unless a component saturates (for instance, the battery could reach its maximum charging capability).

SERIES FUEL CELL CONFIGURATION - Because of the high efficiency of the fuel cell system, it appears natural not to use energy storage as the primary power source because this would involve an extra energy-conversion loss. Indeed, when the efficiency of the fuel cell system is compared with that of the ICE, the fuel cell system is found to have high efficiency at low power. Consequently, the default control strategy has been developed so that the main function of the battery is to store the regenerative braking energy from the wheel and return it to the system when the vehicle operates at low power demand (low vehicle speed), as shown in Figure 7. The battery also provides power during transient operations to smooth the fuel cell power request or when the fuel cell is unable to meet driver demand.

Component limits, such as maximum speed or torque, are taken into account to ensure the proper behavior of each component. Battery state-of-charge (SOC) is monitored and regulated so that the battery stays in the defined operating range.

COMPARISON OF SIMULATION RESULTS WITH TEST DATA

Figure 8 shows the fuel economy of the reference conventional gasoline vehicle compared to the vehicles currently on the road on the basis of the EPA 2008 combined values. Note that while the simulated vehicle does not represent the leading edge, it provides above-average fuel economy.

Because no fuel cell vehicle test data were available, we compared the values obtained from DOE’s hydrogen demonstration program [13]. Because the vehicle characteristics used in this program were not available, we could only compare the simulation results of the current fuel cell vehicle with the range of results. As shown in Figure 9, the fuel economy of the simulated vehicle compares favorably with test data.
Unfortunately, no vehicle test data using H2-ICE were available for validation. Because the engine maps were provided from test data (both single- and multi-cylinder engine data) and considering the extensive validation work previously performed on numerous vehicles, we are satisfied with the quality of the results.

FUEL ECONOMY RESULTS

As discussed previously, uncertainties were taken into consideration for each technology simulated. The graphs discussed in this paragraph highlight the fuel economy of the different vehicles, as well as the ratios.

Figure 10 and 11 show, respectively, the gasoline-equivalent vehicle fuel economy and the ratio compared to the reference gasoline. Note that the fuel economy drops when a hydrogen ICE is used in a conventional vehicle. This drop in fuel economy is due to, in part, the additional weight of hydrogen storage. The other likely cause of the reduction in fuel economy is the shifting transmission, which might need to be further optimized for the H2-ICE.

When comparing both H2-ICE hybrids, note that the series configuration achieves lower fuel economy than the input split. In fact, the series configuration cannot compensate for the additional mass and losses due to additional component efficiencies (90% for the generator and 81% for the electric machine). Both HEV configurations studied allow the vehicle load to be decoupled from the engine load. As the engine speed is independent of the vehicle speed, similar engine average efficiencies are achieved on the drive cycles (i.e., ~31% for port injection and ~41.5% for direct injection on UDDS).

In addition, even though the batteries for each configuration have been sized to capture all of the regenerative braking on the UDDS, the series is further penalized by a lower efficiency path from the wheel to the battery. This penalty is explained by the lower efficiency of the electric machine compared to the power split configuration. For example, if we recuperate 10 kW from the wheel, a 50-kW electric machine will operate at a higher efficiency point than a 100-kW electric machine.

The fuel cell vehicle, because of its high system efficiency, achieves the highest fuel economy of the hydrogen-powered vehicles (ratio of 2.46 for future technology). The fuel cell system achieves efficiencies of ~47% for the current case and ~51% for the future case on the UDDS driving cycle.

Both the hydrogen engine and the fuel cell would achieve significantly higher fuel economy than the conventional gasoline (ratios are respectively 2.2 and 2.4).

Tables 2 and 3 show the fuel economy values and the ratios for the combined driving cycle (both UDDS and Highway Fuel Economy Cycle – HWFET).
Figure 12 shows the fuel economy ratio on the UDDS driving cycle. Note that the power split and fuel cell configuration achieve similar fuel economy when future technologies are considered.

Figure 13 shows the fuel economy ratio on the HWFET driving cycle. First, as one expects, the fuel economy ratio is lower than that for the UDDS driving cycle (maximum of 2.1 on the HWFET instead of 3.2 on the UDDS for the future fuel cell technology). Another interesting finding is that the power split hybrid achieves a lower fuel-economy ratio than does the fuel cell, which explains the overall difference. Note that using a dual-mode power split rather than a one-mode power split would improve the power split fuel economy at high vehicle speed by decreasing the amount of electricity that goes through the series path.

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<tr>
<th>Table 2: Vehicle Fuel Economy Gasoline-Equivalent Ratio – EPA Combined 2008 Values</th>
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<td>Ref</td>
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<td>Current</td>
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<td>Future</td>
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<th>Table 3: Vehicle Fuel Economy Gasoline-Equivalent Ratio – EPA Combined 2008 Values</th>
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CONCLUSIONS

The potential fuel economy of two promising technologies using hydrogen fuel has been compared on the UDDS and HWFET driving cycles for a midsize car. The uncertainties of each technology were taken into account as part of the evaluation. The necessary developments to achieve the respective efficiency and cost goals are significant.

A power split configuration offers the best fuel consumption when using H2-ICE because of the added inefficiencies in the series configuration. Although the one-mode power split was used in this study, the two-mode power split might even provide greater fuel economy, especially at high vehicle speed.

The study confirms DOE’s position that while fuel cell vehicles achieve the highest fuel economy, H2 ICE is a bridging technology and might help in the development of the infrastructure needed for hydrogen fuel.

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