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Vehicle System Impacts of Fuel Cell System Power Response Capability

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ABSTRACT

The impacts of fuel cell system power response capability on optimal hybrid and neat fuel cell vehicle configurations have been explored. Vehicle system optimization was performed with the goal of maximizing fuel economy over a drive cycle. Optimal hybrid vehicle design scenarios were derived for fuel cell systems with 10 to 90% power transient response times of 0, 2, 5, 10, 20, and 40 seconds. Optimal neat fuel cell vehicles where generated for responses times of 0, 2, 5, and 7 seconds. DIRECT, a derivative-free optimization algorithm, was used in conjunction with ADVISOR, a vehicle systems analysis tool, to systematically change both powertrain component sizes and the vehicle energy management strategy parameters to provide optimal vehicle system configurations for the range of response capabilities.

Results indicate that the power response capability of the fuel cell system significantly influences the preferred powertrain component characteristics and the resulting fuel economy in a neat fuel cell vehicle. Slower transient capability leads to larger component sizes and lower fuel economy. For a hybrid fuel cell vehicle, optimal combinations of component sizes and energy management strategy parameters can be found that lead to only a minor variation in vehicle fuel economy with respect to fuel cell system power response capability.

INTRODUCTION

ADVISOR is a vehicle simulator capable of simulating conventional, hybrid electric, electric, and fuel cell vehicles [1, 2]. It uses drivetrain component characteristics to estimate vehicle fuel economy and emissions over defined drive cycles as well as other quantitative performance metrics (i.e., maximum-effort acceleration, gradeability). Roughly 30 different drive cycles and numerous complex test procedures can be used to assess the vehicle fuel economy, emissions, and performance under various simulated test conditions.

Because of the complexity of hybrid electric vehicles (HEVs), including issues such as component sizing, energy management strategy, and battery state-of-charge (SOC) balancing, optimization becomes necessary to give results that can be accurately compared with other vehicles. ADVISOR executes quickly, allowing a single drive cycle (~1000 seconds) to be run on the order of 20 seconds on a standard PC. It is well suited to being linked to optimization routines that may need to evaluate several thousand designs to determine the best.

ADVISOR v3.1 was used in this study as the ‘objective function’ call within the MATLAB environment. Various optimization algorithms have been linked to ADVISOR to both understand the differences in their approach and their effectiveness in satisfying the needs of finding optimal solutions in the challenging design space of hybrid electric vehicles [3]. It was concluded that the non-gradient based methods of the DIRECT algorithm were extremely effective in finding the regions likely to contain local and possibly global optimum solutions, but required considerable amount of solution time to converge onto the answer within a small tolerance.

Previous work relating to optimization of hybrid vehicles has included efforts at University of California, Davis [4] that examined whether, and under which conditions, hybridization of a fuel cell vehicle would be beneficial. More recently, collaborative work was performed with Virginia Polytechnic Institute and State University (Virginia Tech) on sizing of components for fuel cell hybrids, which this work will build upon [5]. Atwood, et. al. concluded that some level of fuel cell system hybridization was beneficial to the design. Based on a revision to their published results, it was shown that the best City/Highway fuel economy could be obtained at a fuel cell to total power (fuel cell + battery) ratio of 0.26. This translated to a fuel cell providing a net peak power of 52 kW and a 150 kW battery pack for a GMC Suburban vehicle (a total of 202 kW was required to meet the performance requirements). An assumption of [5] was that the vehicle mass will remain constant for all cases. As a result, there was no mass penalty associated with a larger fuel cell system.

In a recent study completed at NREL, optimization tools were applied to the design of a hybrid fuel cell sport utility vehicle (SUV) for a variety of driving schedules [6]. It was assumed that the hydrogen fuel cell system would have 10 to 90% power transient response capability of 2 seconds. This correlates to the U.S. Department of Energy (DOE) Fuel Cells for Transportation Program technical target for a fuel cell stack in 2004 [7]. This performance target has been set such that, in a vehicle application, there would be no performance degradation.

A fuel cell stack itself can respond to changes in flowrate and pressure quickly. However, for a complete fuel cell system (including fuel, air, water, and thermal management subsystems) it may be difficult to provide fast transient load-following capability. For example, the rotational inertia of an air compressor may limit how quickly the inlet air flowrate and pressure provided to the fuel cell can be changed. It may not be possible to provide inlet flow conditioning (flowrate, pressure, temperature, and humidity level) within a short time-frame to provide pure load-following capability. This will be especially true for a system that includes a fuel reformer composed of additional hardware and support systems that all have their own individual transient limitations.

The DOE has set a technical target to provide an integrated fuel cell system with reformer operating on gasoline with a 10 to 90% power transient response time of 5 seconds by 2004. While in [7] the current status of such technology is denoted as having a 15 second transient response capability. Mays, et. al. notes that the transient response capability of existing fuel cell systems is on the order of 20 seconds to reach maximum power [8]. They suggest that this should be sufficient for hybrid vehicle applications. Additionally, Adams, et. al. provides test results in their paper that indicate a fuel cell system dynamic response on the order of 0.8 seconds [9]. Clearly, there is variability in this fuel cell system attribute. This paper will address how the rest of the vehicle powertrain system may be designed around a fuel cell system with specific operating characteristics.

Potter and Reinkingh evaluated the impacts of the fuel cell system dynamic response in neat and hybrid transit bus applications [10]. Of the cases they evaluated, a system with a response rate of 5-10 kW/s (10-20% per second) provided a system that could satisfy the drive cycle demands and offer a good balance between cost, mass and volume impacts. They varied component sizes in discrete steps based on existing technology, while in this study we will allow the component attributes to vary continuously to provide optimal configurations.

As was eluded to in [10], it may be possible to reduce system mass, volume, and/or cost with alternative fuel cell system designs if the transient response capability is not a critical parameter with respect to the vehicle fuel economy. For example, a fuel cell system air compressor would need to be sized to handle rapid changes in mass flow to satisfy the needs of the fuel cell stack if the fuel cell system is to have full fast transient capability. However, if other systems in the vehicle (i.e. batteries in a hybrid vehicle) can filter the fast transient and allow the fuel cell system to follow a slower transient then it may be possible to downsize the air compressor or various other support subsystems. The fuel cell system design trade-off will not be discussed in this paper but would have significant cost, volume, and mass implications.

In this study, the impacts of fuel cell system power response capability on the optimal vehicle design will be explored for both hybrid and neat[1] fuel cell SUV. Both component sizing and energy management strategy parameters will be varied to provide the best possible vehicle in each design case. Derivative-free optimization algorithms will be employed to provide sufficient confidence that the design is the best possible design within a large non-linear and discontinuous design space. The operating behavior of the optimal vehicles will be discussed and conclusions will be drawn based on the results provided. The specific fuel cell system design necessary to provide the indicated transient response capability or the subsystem that would induce such a transient response limitation is not considered in this study.

OPTIMIZATION PROBLEM DEFINITION AND CONFIGURATION

VEHICLE MODELING ASSUMPTIONS

For this study, the HEV vehicle characteristics are assumed to be based on a current production baseline conventional mid-size SUV similar to a Jeep Grand Cherokee. Table 1 and Table 2 outline the vehicle assumptions and the components used.

Table 1: Vehicle Assumptions

Vehicle Type	Rear wheel drive mid-size SUV (i.e. Jeep Grand Cherokee) VEH_SUV_RWD.m
Baseline conventional vehicle mass	1788 kg
HEV glider mass (no powertrain)	1202 kg
Rolling Resistance	0.012
Wheel Radius	0.343 m
Frontal Area	2.66 m^2
Coefficient of Aerodynamic Drag	0.44

The HEV components are based on the current state of the art technology for which data is available. The fuel cell and motor/controller data files are based on proprietary data, and have not been included in a public release of ADVISOR at this time.

[1] In a neat fuel cell vehicle the fuel cell system is the only source of energy. This vehicle does not have an energy storage system to supplement the fuel cell power or to capture regenerative braking energy.

Table 2: Baseline Components

Component (ADVISOR filename)	Description
Fuel Converter (FC_HH52_Honeywell.m)	Efficiency vs. net power performance data for 52 kW net pressurized fuel cell system based on Honeywell stacks
Motor/Controller (MC_AC119_VPT.m)	AC induction motor developed by Virginia Power Technologies 83 kW @ 275 Vmin
Energy Storage System (ESS_NIMH45_Ovonic.m)	Ovonic 45 Ah nickel metal hydride battery modules

In this analysis, the total mass of the vehicle will vary with respect to the size and the mass of the powertrain components. The optimizer will have control over both the component sizes and the energy management strategy parameters. All parameters will be allowed to vary over a continuous range. There will be no delay or fuel penalty associated with fuel cell system start-up and shutdown during the cycle. A fuel consumption penalty is included, however, to account for inefficiencies during warm-up of the fuel cell system.

The fuel cell data and model used in this analysis represents a pressurized hydrogen fuel cell system. The transient response time range evaluated is appropriate for either a hydrogen or a gasoline reformed fuel cell system. The absolute fuel economy results would be somewhat different for a reformed system since the system efficiencies will be different. However, the trends with respect to transient response capability will be applicable to either a hydrogen or gasoline reformed fuel cell system.

For this study, it will be assumed that the power response capability of the fuel cell system will be the same during both ramp-up and ramp-down events.

We will assume that the fuel storage system will be sized to provide 563 km (350 miles) of range. The mass associated with storing a sufficient amount of hydrogen to provide the desired range was calculated and will remain constant for all analyses (average fuel consumption of 3.62 L/100 km {65 mpg} gasoline equivalent and a fuel storage specific energy of 2000 Wh/kg was assumed).

All component masses are assumed to scale linearly with respect to peak power except for the energy storage system. The energy storage system mass is assumed to scale linearly with respect to the number of modules in the pack and by the following relationship with respect to capacity:

$$scaled\ mass = base\ mass * (C1 * ess\_cap\_scale + C2) \quad (1)$$

Where C1 and C2 are 0.9832 and 0.01602, respectively and ess_cap_scale is the factor by which the capacity of the battery pack has been increased relative to the baseline component characteristics. The coefficients, C1 and C2, were derived from nickel metal hydride battery technology data in the ADVISOR data file library.

INTERFACING BETWEEN ADVISOR AND OPTIMIZATION TOOLS

The ability to use ADVISOR in a "GUI-free" or batch mode was introduced and documented with the release of ADVISOR v3.1. This mode was specifically developed to make it easy to use ADVISOR as an automated function or response-generating tool to be connected to optimization routines as shown in Figure 1. As currently configured, this functionality provides the user with nearly all of the functionality available from the GUI, and in some instances even more functionality.

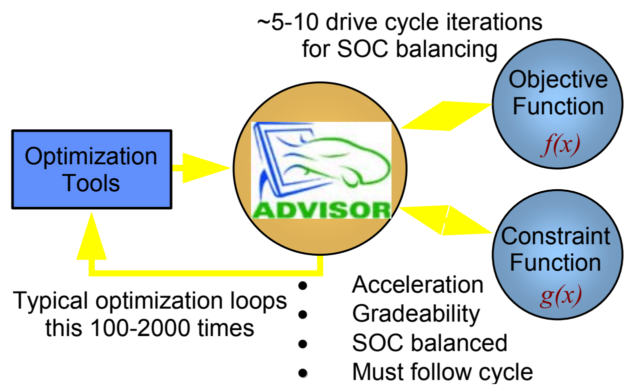

Figure 1: ADVISOR Linkage with Optimization Tools for Vehicle Systems Analysis

The general approach for linking the optimization tools to ADVISOR includes three primary files and five basic steps. The files include a main function routine for configuring the workspace and performing post-processing operations, a function for generating the objective response value, and a function for generating the constraint response values. Most optimization software tools will require minor variations to this implementation process but use the same general approach. As a result, it requires minimal effort to apply multiple algorithms to the solution of the same problem.

The basic optimization process, using ADVISOR, can be summarized as follows,

1. Initialize the MATLAB workspace
2. Modify the design variable values in the workspace with input from optimizer
3. Run simulation to generate objective responses
4. Run simulation to generate constraint responses
5. Process results with optimization tool and return to step 2 until convergence criteria is satisfied

Each of the first four operations is achieved using the unique options as input to the adv_no_gui function as defined in the ADVISOR documentation [11].

OPTIMIZATION PROBLEM DEFINITION

The design variables for this study consist of 8 variables: 4 defining sizing of the fuel cell, motor, and batteries, and 4 defining energy management strategy variables including the maximum and minimum fuel cell power,

Table 3: Design Variables

ADVISOR name	Description	Units	Lower Bound	Upper Bound
fc_pwr_scale	Fuel Cell System Peak Power Scale	--	1 (52 kW)	3 (156 kW)
mc_trq_scale	Motor/ Controller Peak Power Scale	--	0.8 (66 kW)	2.5 (207kW)
ess_module_num	Battery Pack Number of Modules	#	11 (143 V)	35 (455V)
ess_cap_scale	Battery Module Maximum Ah Capacity Scale	--	0.333 (15 Ah)	2 (90 Ah)
cs_min_pwr	Minimum Power Setting (% of Peak Power)	%	0	50
cs_max_pwr	Maximum Power Setting (% of Peak Power)	%	50	100
cs_charge_pwr	Charge Power Setting (% of Peak Power)	%	0	50
cs_min_off_time	Minimum Off Time Setting	s	10	1000

Table 4: Vehicle Performance Constraints

Type	Description	Condition
Acceleration	0-96.5 km/h (0-60 mph)	<= 11.2 s
	64-96.5 km/h (40-60 mph)	<= 4.4 s
	0-137 km/h (0-85 mph)	<= 20.0 s
Gradeability	@ 88.5 km/h (50 mph) for 20 min. at Curb Weight + 5 passengers and cargo (408 kg)	>= 6.5%
Drive Cycle	Difference between drive cycle requested speed and vehicle achieved speed at every second during the drive cycle	<= 3.2 km/h (2 mph)
SOC Balancing	Difference between final and initial battery state of charge	<= 0.5%

battery charge power, and the minimum fuel cell off-time. The ADVISOR variables and their upper and lower bounds are listed in Table 3.

In order to ensure performance equivalence, constraints were established that ensure that the vehicle will have the same acceleration, gradeability, and charge-neutrality of the baseline conventional SUV upon which this fuel cell vehicle is based. Table 4 includes all of the vehicle performance constraints used in the optimization problem. Finally, the objective of this study will be to maximize fuel economy (i.e. minimize fuel consumption).

In a conventional internal combustion engine-powered hybrid, a manufacturer would need to consider cost and emissions in addition to fuel economy when optimizing the vehicle. Since a hydrogen fuel cell-powered hybrid is essentially a zero emissions vehicle, we have eliminated emissions from the problem. At this time, cost models are under development by other U.S. Federal National Labs that will allow us to include vehicle cost in the equation for future studies. For more detailed descriptions of the ADVISOR design variables and data files mentioned in Tables 1-4, please refer to the documentation for ADVISOR v3.1 [12].

As a result of the constraints and objectives defining this problem, the evaluation of a single design point in ADVISOR will include an iterative zero-delta SOC-balanced fuel economy calculation for the applicable drive cycle(s) individually, a 20 minute gradeabilty test, and a 0-137 km/h (0-85 mph) acceleration test. On a Pentium 4 1500 MHz machine a single evaluation will, on average, take ~75 seconds of processing time.

PARAMETRIC SWEEP OF POWER RESPONSE CAPABILITY

The optimization problem defined in the previous section was performed using ADVISOR and DIRECT for a range of fuel cell system transient response times. For hybrid vehicles, optimal vehicle configurations were derived for 10% to 90% power transient response times of 0, 2, 5, 10, 20, and 40 seconds over 3 different driving schedules including the combined City/Highway test, the US06 cycle, and the New European Drive Cycle (NEDC). For neat fuel cell vehicles, optimal designs were generated for response times of 0, 2, 5, and 7 seconds for 2 driving schedules including the combined City/Highway test and the US06 cycle. Response times greater than 7 seconds in a neat fuel cell vehicle required unreasonably large systems to satisfy the performance constraints.

DISCUSSION OF SIMULATION RESULTS

In all, 26 different optimal vehicles were derived in this study. The optimizer called on ADVISOR to evaluate more than 75,000 vehicle designs and was able to complete these analyses within a 10 day period by distributing the analysis among 3 to 7 available desktop PCs in parallel.

The results of this study will be presented in two parts. First, the characteristics of the optimal vehicle configurations will be compared. Then the detailed operating characteristics of some of these vehicles will be explored.

CONFIGURATION CHARACTERISTICS

A review of the results of the optimal hybrid vehicle configurations provides insight into how the vehicle system may adapt to or take advantage of the performance characteristics of one of the components within the system. Figure 2, provides a summary of the optimal vehicle component characteristics with respect to the transient response capability of the fuel cell system.

As the transient response capability decreases (longer response time) the battery energy content will increase. The battery is relied upon to provide propulsion power more often during the drive cycle for a slow responding fuel cell system. Also, the fuel cell power and the battery power capabilities are, in general, inversely related, meaning that the system needs a specific amount of total power and will trade fuel cell power for battery power and vice versa. Note that some variation in the component sizes is also due to the variation of the vehicle mass. Specifically, we see that the motor power increases with increasing response time. The motor size must increase directly with the vehicle mass to provide equivalent vehicle performance.

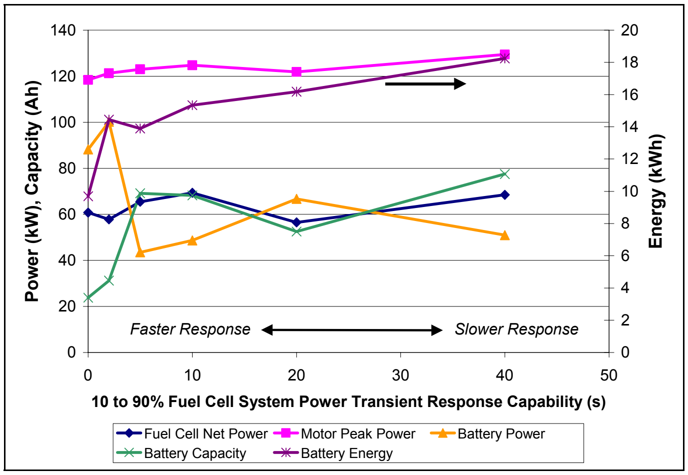

Figure 2: Component Characteristics of Hybrid Vehicles Optimized for Maximum Fuel Economy on Combined City/Highway Driving

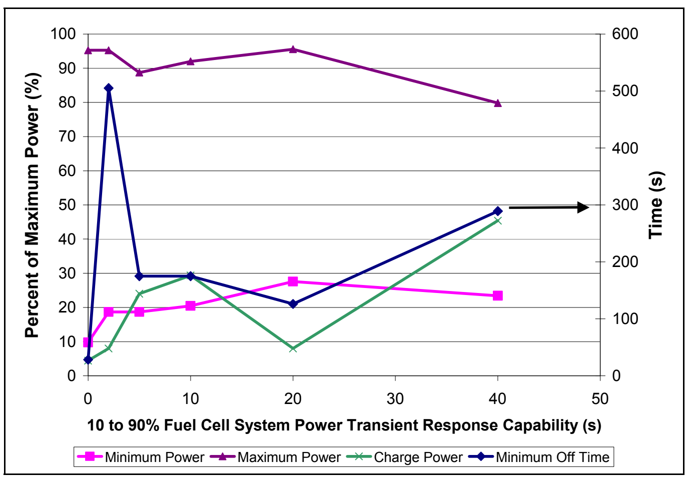

Figure 3: Energy Management Strategy Parameters of Hybrid Vehicles Optimized for Maximum Fuel Economy on Combined City/Highway Driving

Along with the component sizes, the optimizer also varied the energy management strategy parameters. Figure 3 provides a summary of the energy management strategy parameters for the optimal hybrid vehicle configurations. As the power response time grows longer, the control will try to close down the width of the fuel cell operating range. Notice how the minimum power setting increases with increasing response time and the maximum power setting decreases with increasing response time. Since the fuel cell will take longer to respond both on the ramp-up and the ramp-down events in cases with longer response times, it is desirable to stay closer to the middle of the operating zone. This is also a very efficient operating area for the fuel cell system.

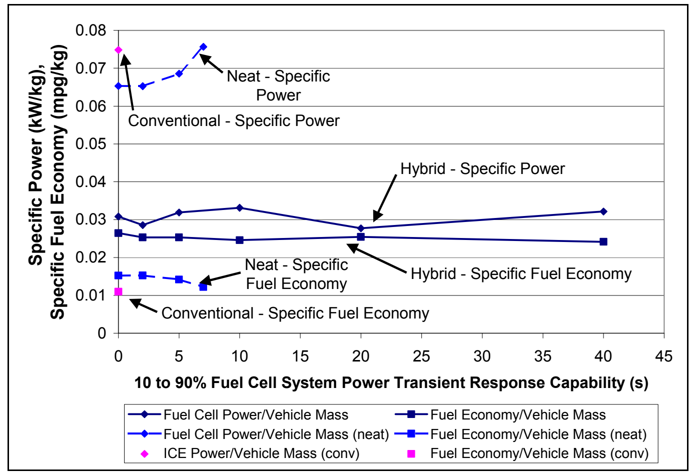

Figure 4: Fuel Economy Impacts of Transient Response Capability for Hybrid and Neat Fuel Cell Vehicles on Combined City/Highway Driving

The corresponding fuel economy results for these combinations of component sizes and energy management strategy parameters are provided in Figure 4. For comparison, the neat fuel cell cases and a baseline conventional vehicle are also included. The fuel economy results have been normalized by the mass of the vehicle such that we can isolate the fuel economy impacts of the powertrain system variation with respect to the transient response capability. Likewise, the fuel cell power capability has been normalized by the vehicle mass and is provided for each case.

The first conclusion that can be drawn from Figure 4 is the fuel economy impacts of the fuel cell system and that of hybridization. With a 0 second response time, the neat fuel cell vehicle normalized fuel economy (dashed line with squares) is 38% better than that of the conventional vehicle (square). Likewise, the hybrid fuel cell vehicle normalized fuel economy (solid line with squares) is 73% better than that of the neat fuel cell vehicle. The mass differential between these vehicles has a significant impact on these relative improvements. On an absolute fuel economy basis the step from conventional to neat fuel cell provides a 65% gain while the step from neat fuel cell to hybrid fuel cell offers a 50% gain.

From Figure 4, we can also conclude that for a neat fuel cell vehicle configuration, the fuel economy begins to drop significantly with increasing transient response time. This is in part because the fuel cell size (peak power) is growing rapidly with respect to transient response time. It must do so in order to provide equivalent performance.

On the other hand, for the hybrid cases, the transient response time has almost no impact on either the fuel economy or the fuel cell power requirement. Basically, in a hybrid system we have the flexibility to optimize the combination of component characteristics and energy management strategy parameters to nullify the fuel economy impacts of a slow responding fuel cell system.

OPERATIONAL CHARACTERISTICS

Once all of the optimal vehicle configurations had been derived and saved, it was possible to review the detailed operating characteristics of each vehicle independently within ADVISOR. This provides some insight into the reasons for and the impacts of the choices made by the optimization tools.

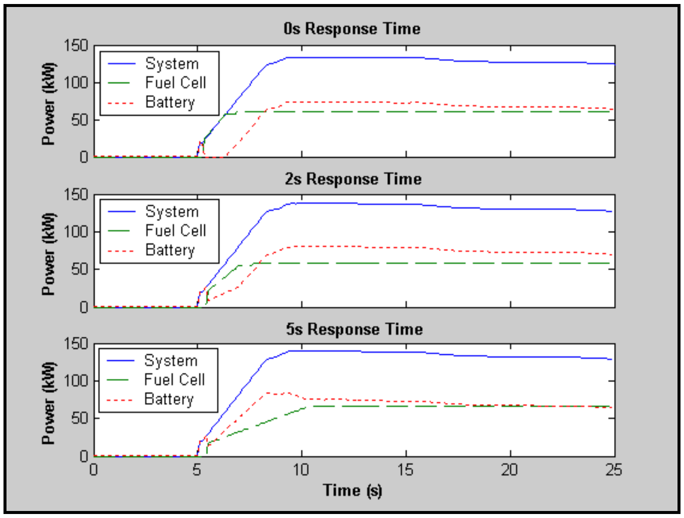

Figure 5: Distribution of Power During Acceleration Event for Hybrid Fuel Cell SUV

First, it is important that we review what the transient response time really means. The impacts of the power response capability on vehicle operation are clearly apparent during a maximum effort acceleration test. Figure 5 provides the component and system power output during an acceleration test for three different hybrid vehicles. These vehicles have 10 to 90% power transient response times of 0 seconds, 2 seconds, and 5 seconds from top to bottom, respectively. The system power is simply the sum of the fuel cell power and the battery power outputs. It is nearly the same in all three cases because the total power delivery to the wheels is determined by the traction characteristics of the vehicle. In comparing the three plots we see that with a shorter response time (0 second case) the fuel cell initially provides the entire vehicle power demand up to its maximum capability. The fuel cell initially provides a majority of the power demand in the 2 second case. In the 2 second case, the battery power is used to supplement the system power while the fuel cell power is ramping up at a rate of ~22 kW/s. Likewise, it is apparent that the battery provides a majority of the power demand in the 5 second case while the fuel cell power ramps at a rate of ~10 kW/s.

Figure 6 shows only the fuel cell system power output during the acceleration test for the same three hybrid configurations (0, 2, and 5 seconds). The differences in ramp rates are more clearly defined. Likewise, Figure 7 provides the same set of fuel cell performance data for the neat fuel cell vehicle cases during an acceleration test.

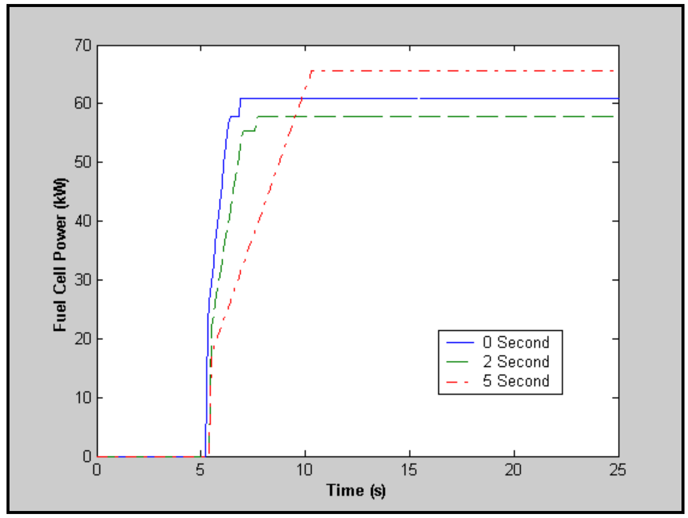

Figure 6: Fuel Cell System Power Delivery during Acceleration for <u>Hybrid</u> Fuel Cell SUV

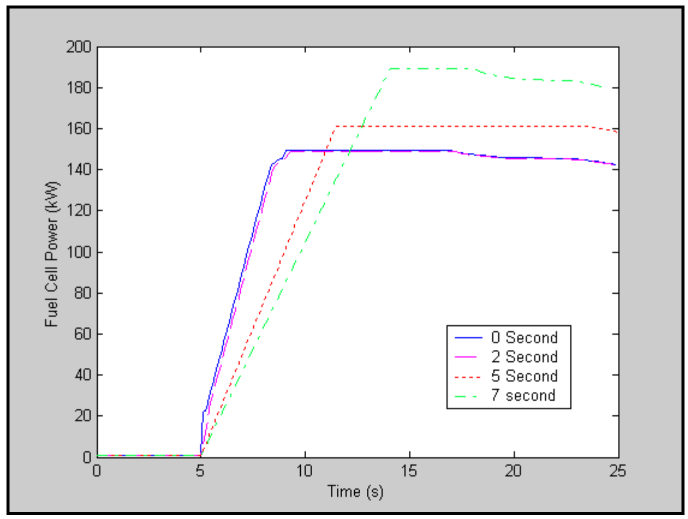

Figure 7: Fuel Cell System Power Delivery During Acceleration for <u>Neat</u> Fuel Cell SUV

For a neat fuel cell vehicle the battery is not present to supplement the capability of the fuel cell. Therefore, as was seen in Figure 4 the power capability of the fuel cell must be significantly larger so that it can compensate for its slow response during a fast transient. Notice the difference in the scales between Figure 6 and Figure 7.

Although the fuel cell is the only power source in a neat fuel cell vehicle, in Figure 7, the actual power delivered to the driveline from the fuel cell is different in each case. As a result, the acceleration performance of each vehicle is slightly different. We have enforced three acceleration time constraints (0-60 mph, 40-60 mph, and 0-85 mph) on these vehicles and all of the constraints must be satisfied. Typically only one constraint will be active while the performance is better than required for the other two acceleration constraints. In the 7 second case, the 0-60 mph constraint is active while in the 2 second case, the 0-85 mph constraint is active.

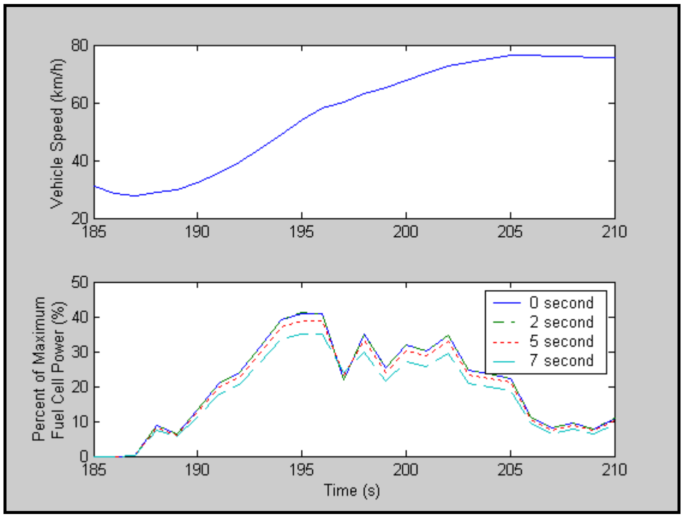

Figure 8: Neat Fuel Cell System Power Delivery Limitations During a Portion of the FTP

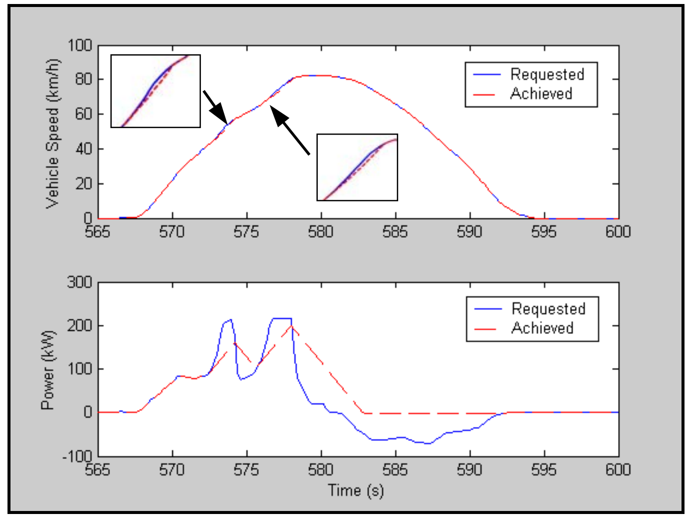

Figure 9: Operation of a Fuel Cell System with a 5 Second Transient Response Time in a Neat Fuel Cell Vehicle on a Portion of the US06 Cycle

In Figure 8, the actual operating point as a percent of the maximum capability of the fuel cell system is shown for each of the neat fuel cell vehicles during a short acceleration event within the Federal Test Procedure (FTP) driving schedule. A longer transient response time leads to an optimal vehicle with a larger fuel cell system such that it can satisfy all of the performance constraints. As a result, we see that the fuel cell itself operates at a lower percentage of its peak capability on normal drive cycles with respect to increasing transient response times.

Sections of the US06 cycle have extreme power transients. Figure 9 highlights the operational impacts of the power response capability of the fuel cell system in a neat fuel cell vehicle. The top plot shows the vehicle speed trace from a portion of the US06 cycle. The actual trace value (solid line - Requested) and the achieved speed (dashed line - Achieved) are nearly identical. However, the vehicle speed falls away from the trace near 573s and 576s. As the vehicle begins to miss the

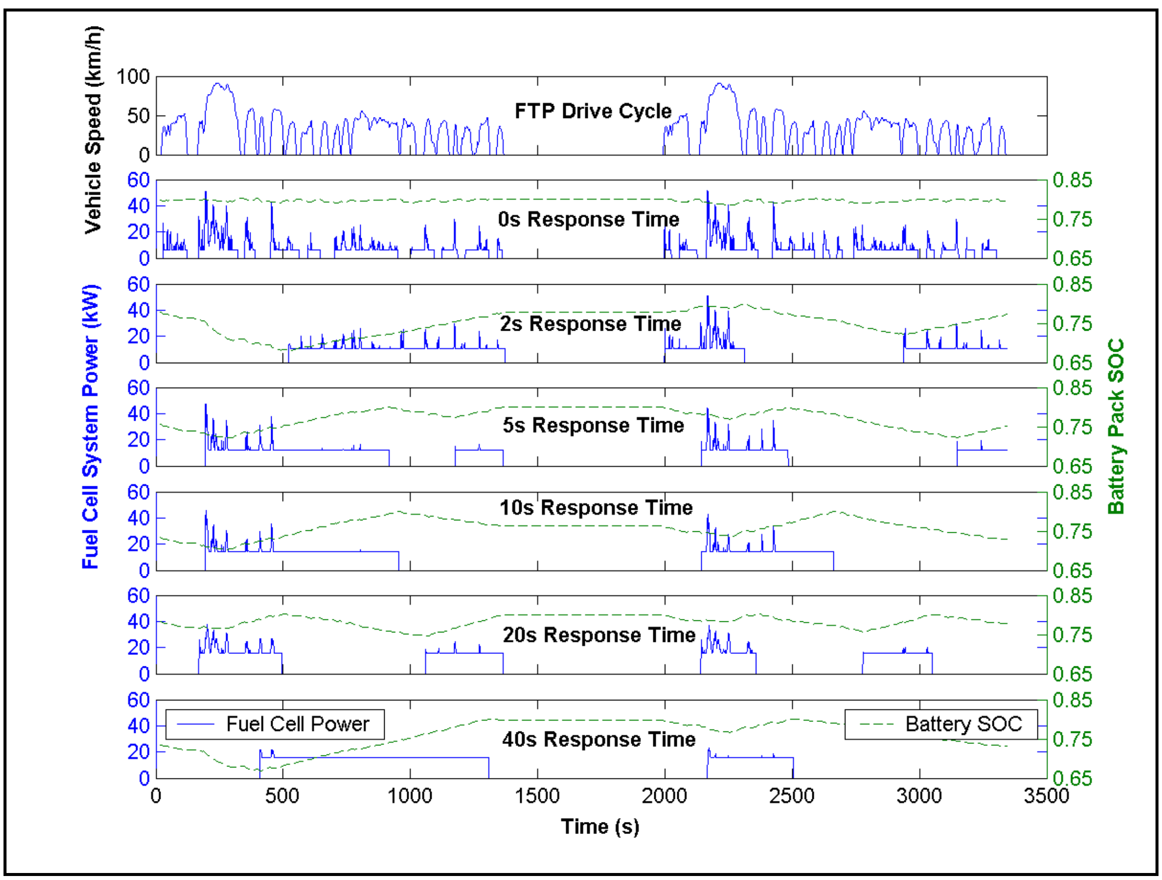

Figure 10: Fuel Cell and Battery Operating Characteristics of Hybrid Vehicles Optimized For Combined City/Highway Driving Vary with Respect to Fuel Cell System Transient Response Capability

requested speed more power is requested of the fuel cell. The lower plot shows the power requested (solid line) by the drivetrain of the fuel cell system such that the vehicle can follow the speed trace. The dashed line defines the power actually delivered by the fuel cell system. Clearly the fuel cell system in this case with a transient response rate of ~40 kW/s is unable to respond to the fast power transients. Both on the rising side and the falling side the fuel cell power achieved lags what is requested. It is unclear how the excess power during a falling event may impact the vehicle performance in a real vehicle.

Thus far we have looked at the vehicle details and their operation during small portions of driving cycles. It is also interesting to compare the vehicle system operation of the various vehicles on a complete drive cycle. In Figure 10, the fuel cell power output and the battery pack state of charge over an FTP (2 urban dynamometer driving schedules) is provided for the 6 different hybrid vehicles optimized for operation on the City/Highway test procedure. The top portion of the figure provides the actual driving schedule. The six plots below provide the component operating conditions for the 0, 2, 5, 10, 20 and 40 second response time cases.

As one may expect, the vehicle with a fuel cell system with the 0 second response time operates almost entirely under a load following (i.e. when on, the power varies proportional to the drivetrain load) approach. While the vehicle with a slow response fuel cell system (40 second response time) operates almost entirely with a thermostatic-type control (i.e. when on, the system operates at a single power level). The vehicles between the 0 second and 40 second cases show some combination of the behavior of the two boundary cases. It is also clear that the 0 second vehicle case uses its battery pack very little with the SOC remaining within a very narrow band while the other vehicles exercise the battery pack significantly through an ~15% SOC window. It should be noted that the total capacity of the battery packs vary from case to case but that in general the longer the response time the larger (more capacity) the battery pack. SOC is simply a relative measure of the available capacity in a battery pack therefore a 10% variation of SOC in a large pack represents significantly more energy throughput than the same SOC variation for a smaller battery pack.

CONCLUSION

In this study, the impacts of fuel cell system power response capability on optimal hybrid and neat fuel cell vehicle configurations have been explored. Optimal hybrid vehicle design scenarios for an SUV were derived for fuel cell systems with 10 to 90% power transient response times of 0, 2, 5, 10, 20, and 40 seconds. A derivative-free optimization algorithm was used with ADVISOR to systematically change both powertrain component sizes and the vehicle energy management strategy parameters to provide optimal vehicle system configurations for the range of transient response times. Several conclusions can be drawn from the results collected and analyzed.

For a hybrid fuel cell vehicle, as the transient response capability of the fuel cell system increases (shorter response times) when trying to maximize fuel economy, the optimal vehicle configuration will shift from one with a large capacity battery pack and a thermostatic control strategy to one with a smaller battery pack and a more load following strategy. System costs and packaging considerations were not considered in this analysis and would likely influence the optimal design characteristics.

For a neat fuel cell vehicle, a small fuel cell transient response time is critical to satisfy vehicle performance constraints and to provide significant fuel economy improvement over that of a typical conventional vehicle.

In contrast, it was demonstrated that system optimization could be used to find combinations of component sizes and energy management strategy parameter settings for a hybrid fuel cell vehicle that will nearly nullify the effects of transient response time with respect to fuel economy.

The results presented in this study were derived assuming that a hydrogen fuel cell system would be used in an SUV. Both hydrogen and gasoline reformed fuel cell systems will have unique power response capabilities. The trends highlighted above will apply similarly to a gasoline reformed fuel cell system in a vehicle application.

Future areas of exploration may include,

- Resolve the details of the actual fuel cell system configuration and control to provide systems with the transient response characteristics described in this paper. This would help identify the design advantages (mass, volume, and/or cost) of alternative fuel cell system designs.
- Resolve the current optimal designs using gradient-based optimization tools within a small design space centered around the current best case designs.
- Generate optimized vehicle designs based on parametric sweeps of other system attributes such as fuel cell system specific power, specific cost, power density, and efficiency. These attributes will impact the balance between fuel cell and battery in addition to the energy management strategy employed in the vehicle.

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