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Comparing Apples to Apples: Well-to-Wheel Analysis of Current ICE and Fuel Cell Vehicle Technologies

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ABSTRACT

Because of their high efficiency and low emissions, fuel-cell vehicles are undergoing extensive research and development. When considering the introduction of advanced vehicles, a complete well-to-wheel evaluation must be performed to determine the potential impact of a technology on carbon dioxide and Green House Gases (GHGs) emissions. Several modeling tools developed by Argonne National Laboratory (ANL) were used to evaluate the impact of advanced powertrain configurations. The Powertrain System Analysis Toolkit (PSAT) transient vehicle simulation software was used with a variety of fuel cell system models derived from the General Computational Toolkit (GCtool) for pump-to-wheel (PTW) analysis, and GREET (Green house gases, Regulated Emissions and Energy use in Transportation) was used for well-to-pump (WTP) analysis. This paper compares advanced propulsion technologies on a well-to-wheel energy basis by using current technology for conventional, hybrid and fuel cell technologies.

INTRODUCTION

Over several decades, Argonne National Laboratory (ANL) has developed and used a number of computer models in support of the U.S. Department of Energy's (DOE's) advanced automotive R&D program to address vehicular life cycle, which ranges from design and manufacturing through recycling. In addition, advanced batteries, fuel cells, engines, and many vehicle configurations have been developed/tested in DOE's facilities at ANL. This combination of analytical, developmental, and testing experience has been supported through modeling and analysis at all levels, from components (i.e., GCtool) to the whole vehicle (PSAT).

GCtool is a software package developed specifically for designing, analyzing, and comparing fuel cell and other power-plant configurations, including automotive, space-based, and stationary systems. Its strength is dynamic, total-system fuel cell modeling. GCtool provides a convenient, flexible framework for integrating various component models, in C or any C-linkable language, into simple or complex system configurations. A library of subcomponent models and properties is available, and users can easily add their own models as needed.

PSAT allows users to evaluate fuel consumption and vehicle driving performance for many different vehicle configurations. ANL developed this forward-looking model to study transient effects and the interactions among components with accurate control commands. PSAT has been validated for several vehicle configurations and classes and is used to perform studies for the DOE and FreedomCAR Partnership.

A well-to-wheels (WTW) analysis of a vehicle/fuel system covers all stages of the fuel cycle, from energy feedstock recovery (well) to energy delivery at the vehicle's wheels. A WTW analysis is also referred to as a fuel-cycle analysis. Since 1995, ANL has been developing the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)model as an analytical tool for estimating the WTW energy use and emissions associated with transportation fuels and advanced vehicle technologies. During this time, Argonne has applied the GREET model to analyze WTW energy and emission impacts of various transportation fuels and vehicle technologies [1–4].

GCTool, PSAT, and GREET were used in this study to simulate fuel cells and vehicles and their contribution to Green House Gases (GHGs). An earlier study by ANL [5] concluded that fuel cell vehicles had great potential to reduce carbon dioxide and GHGs. In that paper, conventional engine technologies were compared with advanced fuel cell systems. This paper provides an update of the preliminary results by comparing additional drivetrain configurations, all based on current technologies.

GCTOOL FUEL CELL SYSTEM MODELING

GCTool was developed at ANL for steady-state and dynamic analysis of fuel cell systems. It allows users to establish realistic system constraints and conduct constrained optimization studies. The analyses are typically conducted in design or off-design modes, but mixed modes are also permitted. In the design mode, the components are sized to meet specified performance targets. In the off-design mode, GCTool determines the performance of components of a given size and their physical attributes.

GCTool has an extensive library of model classes for components and devices that appear in practical energy conversion systems. In particular, the library includes various types of fuel cells (polymer electrolyte, solid oxide, phosphoric acid, and molten carbonate), hydrogen storage devices (compressed gas, liquid hydrogen, metal hydrides, glass microspheres, etc.), catalytic reactors (such as for auto-thermal reforming, steam reforming, water-gas shift, preferential oxidation, and sulfur removal), and heat exchangers (counterflow, air-cooled condenser, finned radiator, etc.). Several thermodynamic codes are available in GCTool for equations of state of mixtures of gases, liquids, and condensables, which can be used for gaseous (e.g., hydrogen and methane), liquid (methanol, ethanol, octane, etc.), and synthetic fuels (gasoline and diesel).

GCTool is focused on design and searches for optimum configurations. The detailed algorithms in GCtool (thermodynamic and chemical transport) are generally inappropriate for use in vehicle studies because of the greatly increased computer run time. For this reason, engineering models of fuel cell systems and components using the GCTool architecture have been developed for vehicle analysis, as has a procedure to automate the linkage to MATLAB-based vehicle codes (i.e., PSAT).

PSAT VEHICLE MODELING

PSAT was developed under MATLAB/Simulink, thereby allowing users to realistically estimate the wheel torque needed to achieve a desired speed by sending commands to the different components, such as the throttle for the engine, displacement for the clutch, gear number for the transmission, or mechanical braking for the wheels. In this way, we model a drver who follows a predefined speed cycle. Moreover, as components react to commands as in reality, we can implement advanced component models, take transient effects into account (such as engine starting, clutch engagement/ disengagement, or shifting), or develop realistic control strategies. Finally, PSAT has been validated by using several vehicles [6–9].

GREET

A WTW analysis of vehicle/fuel system covers all stages of the fuel cycle — from energy feedstock recovery (wells) to energy delivered at vehicle wheels (wheels). Since 1995, with funding from DOE, ANL has been developing the GREET model as an analytical tool for use by researchers and practitioners to estimate WTW energy use and emissions associated with transportation fuels and advanced technology vehicles. Only the feedstock and fuel stages (called "well-to-pump” or "upstream") values are used from GREET; the vehicle operation stage (called "pump-to-wheels" or "downstream") is evaluated by using PSAT and GCtool-Eng, as shown in Figure 1.

VEHICLES DEFINITION

The reference vehicle is based upon an SUV (Sport Utility Vehicle) platform, and the vehicle’s characteristics are listed in Table 1.

Table 1. Reference Vehicle Validation

	Units	Test	PSAT
Vehicle Assumptions			
Vehicle Mass	kg	2104	
Glider Mass	kg	1290	
Engine		VL, V6, SOHC, 210hp	
Frontal Area	m^2	2.46	
Drag Coefficient		0.41	
Rolling Resistance		0.0084	
Wheel Radius	m	0.368	
Model Validation			
Acceleration (0-60mph)	s	10.5	10.5
Combined Fuel Economy	mpg	20	21

Figure 1. WTW Simulation Process

Fuel economy values mentioned in Table 1 are EPA unadjusted values. The combined fuel economy obtained with PSAT is higher than the reference value because the effect of cold start was not taken into account.

Eleven powertrain configurations have been simulated to evaluate the potential of fuel cell technologies:

- Conventional vehicle (CONV) with gasoline engine (SI) and automatic transmission (reference).
- Conventional vehicle (CONV) with diesel engine (CI) and automatic and manual transmissions.
- Starter-alternator parallel hybrid (PAR ISG) with gasoline and diesel engines.
- Pre-transmission parallel hybrid (PAR PRE-TX) with gasoline, diesel, and hydrogen engines (H_2 ICE).
- Fuel cell vehicle (FC) with no energy storage.
- Fuel cell hybrid (FC) with two hybridization degrees (small and large energy storage).

Series hybrid configurations have not been included in the study because the components could not be sized within reasonable power to achieve sufficient acceleration. The vehicles are defined in more detail in Appendix 1.

METHODOLOGY ASSUMPTIONS

Several papers by Santini [10] have emphasized the need for a defined set of rules that should be adopted to ensure a fair and consistent assessment. To fulfill the recommendations, the following hypotheses have been made:

- The components of each configuration have been sized to achieve performance similar to that of the reference vehicle (0–60 mph in 10.5 s +/-0.2 s and maximum speed >100 mph). Other WTW studies, such as MIT [11], took the approach of keeping a constant powertrain-specific power, but this does not adequately consider the different torque characteristics of each component technology.
- All of the components are based on current technology. The gasoline engine is a single overhead camshaft, two valves per cylinder; the diesel engine is a high-pressure direct injection engine and has two valves per cylinder. Batteries are NiMH. To better understand the results, note that testing has yielded all of the component data, except for those for fuel cell technology. The pressurized direct hydrogen fuel cell system model has been developed by using GCtool to represent today's technology, as based upon available data.
- The results for a powertrain configuration or technology are dependent on the driving schedule; each of the 13 options have been simulated on the Federal Urban Driving Schedule (FUDS), the Federal Highway Driving Schedule (FHDS), the US06, the Normalized European Driving Cycle (NEDC), and the Japan 1015 Mode. The driving cycles have been selected to allow easy evaluation of each powertrain anywhere in the world.
- PTW efficiencies have been provided to remove the influence of powertrain, vehicle weight, and body structures.
- Vehicle aerodynamic drag, tire rolling resistance, and glider mass have been kept constant throughout the configurations. The differences between each vehicle are only due to their configurations and control strategies.
- Several hybrid technologies have been taken into account to demonstrate the different benefits that can result from each technology.
- No cold start has been taken into account, either for the configurations with an engine or fuel cell.
- Because the goal of this paper is to focus more on the impact of drivetrain configurations rather than fuel production, we will only consider one hydrogen production path: from reforming at a station, which is the solution that is expected to be used first.

STUDY RESULTS

In this section, we will discuss the impacts of each vehicle configuration on fuel economy, powertrain efficiency, and GHGs as a function of driving schedule. The results are listed in Appendix 2.

Figure 2 details the fuel economies for the different configurations on the Combined cycle (including FUDS and FHDS). Note that substantial gains can be achieved through dieselization or hybridization. The hybrid fuel cell configuration combines high fuel-cell-system efficiency and regenerative braking to achieve the highest fuel economy. However, excessive hybridization diminishes the gain in fuel economy for two reasons: (1) the smaller battery configuration recovers most of the regenerative braking and (2) decreasing the fuel cell system power leads to a decrease in the average efficiency of the fuel cell system.

The results are intuitive in that diesel hybrids are more fuel-efficient than gasoline hybrids. But the analysis also shows that fuel economy of hydrogen-fueled ICE hybrids could exceed that of conventional vehicles (gasoline or diesel) and is within 10% of the diesel hybrid. Finally, note that the fuel economy of a conventional diesel with a manual transmission is comparable with that of a hybrid gasoline vehicle.

Figure 3 details the well-to-pump (WTP), pump-to-wheels (PTW) and WTW powertrain efficiencies for the combined cycle. The results imply that:

- Dieselization can increase the efficiency by more than 20%,
- Hybridization alone leads to an improvement of more than 30%,

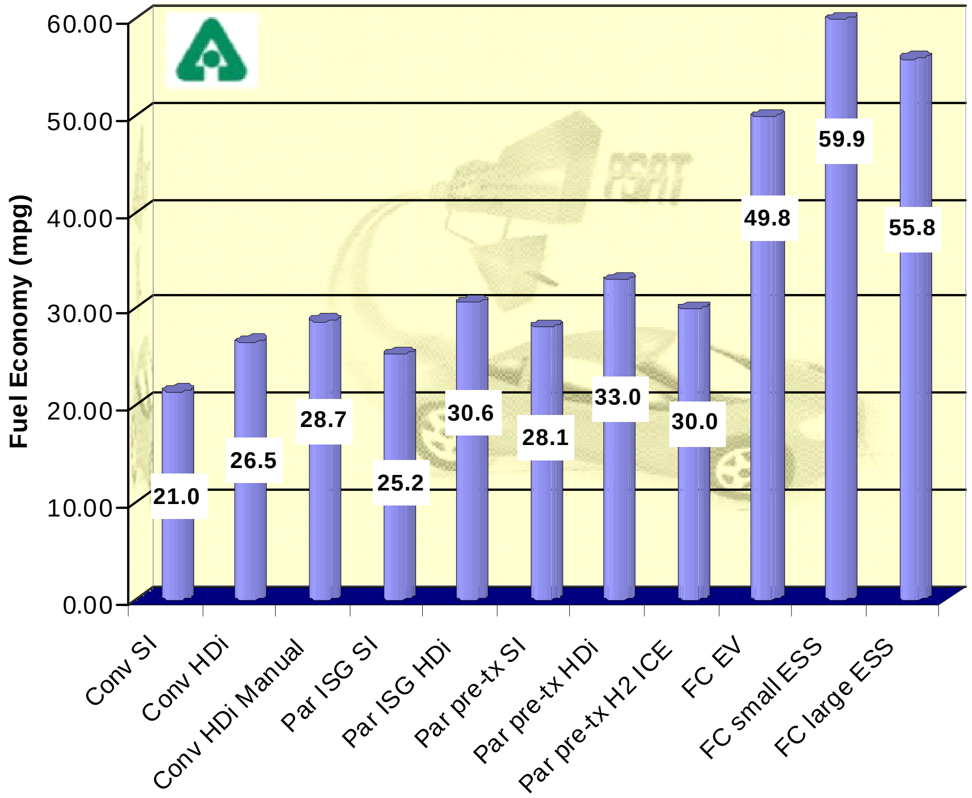

Figure 2. Fuel Economy Gasoline Equivalent – Combined Cycle

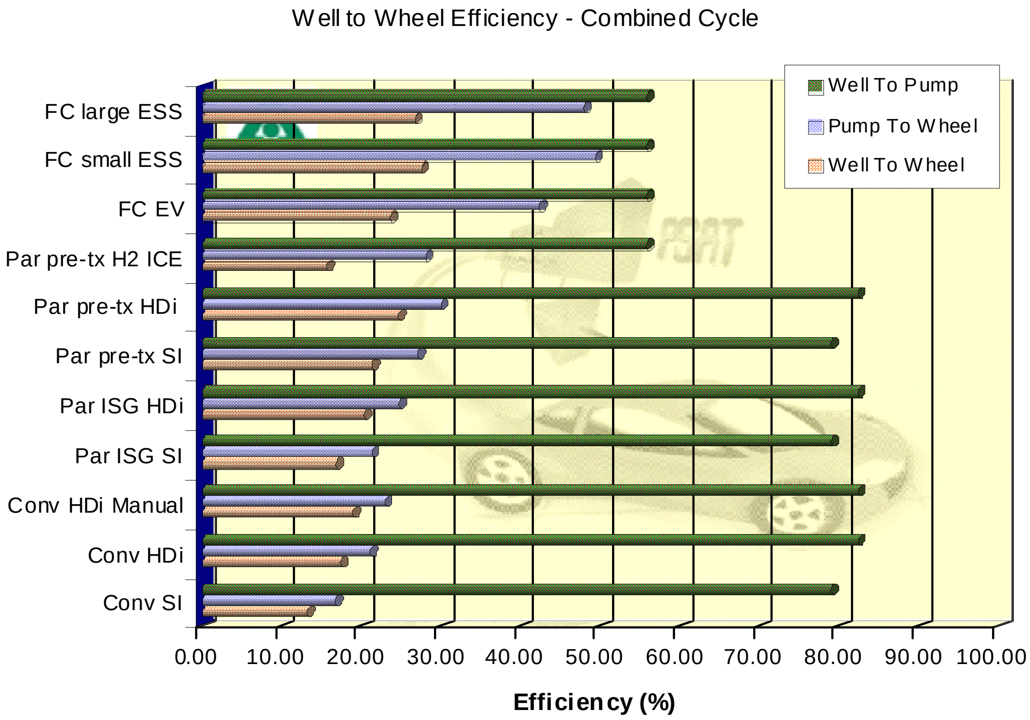

Figure 3. Well-to-Wheel Powertrain Efficiency – Combined Cycle

- Dieselization and hybridization lead to an improvement of more than 50%, and
- A gain of more than 150% can be obtained with the hybrid fuel cell.

From the WTW perspective (cf. Figure 3), note that conventional gasoline vehicles are rather inefficient (~14%). When producing hydrogen from reforming at a station, fuel cell vehicles have a lower advantage in terms of efficiency.

The results differ as a function of driving schedule. Figure 4 compares the efficiency results of the pre-transmission parallel hybrid and the reference vehicle for various cycles. The cycles with low power demand (low speed or steady-state operations) appear to be the most suited for hybrid operations. The US06 cycle, which is the most transient of the five, is consequently the least effective for HEV applications.

These results are logical considering the sources of savings for hybrid vehicles: regenerative braking, no engine idling, and better powertrain efficiency at low power demands. Transient drive cycles with low average vehicle speed are best suited for hybrid vehicles. As a consequence, the hybrid's fuel economy gains on the Highway or US06 cycle are less than those for the Urban or the Japan 1015.

Studies by Santini [12] pointed out that on a fixed time budget, vehicle miles travelled by vehicle vary inversly with the average driving speed. In other words, personal vehicles based in congested urban areas may accumulate fewer miles of driving per year than suburban-based vehicles. Thus, owners of hybrid vehicles living in congested areas may drive less than hybrid owners living in suburban area, nullifying the large fuel economy advantage they hold over comparable conventional vehicles.

Figure 5 shows the implications associated with the fuel used, assuming the vehicles are driven the same number of hours per day, by showing the ratio of gallons used per 10 hours compared to the reference vehicle. The error bars are used to show the range for all the cycles considered (FUDS, FHDS, US06, NEDC, and Japan1015). The difference between drive cycles is not of great importance anymore. By analyzing the results of each cycle (cf Appendix 2), one can see that some cycles, which had low improvements in fuel economy ratio compared to the reference (US06 as example), lead to significant savings in fuel. Finally, interest in starter-alternator configurations also depends on the driving cycle; as in the gasoline case (Parallel Start-alt SI), there is no gain in fuel economy in an FHDS cycle.

Figure 6 shows energy loss during the NEDC cycle for each component for the configurations considered. The engine is, by far, the least efficient of the components (accounts for more than 75% of the total losses for the reference case). Fuel cell vehicles lose only half the energy of the best parallel case.

Moreover, a hybrid fuel cell powertrain consumes less energy than a system containing only a fuel cell. The weight advantage of the fuel cell system is not sufficient to compensate for the loss in regenerative energy.

GHG emissions are an important consideration from a tailpipe emission perspective for most countries. A clean vehicle, such as a fuel cell vehicle, does not mean that there are no emissions from a well-to-wheel perspective. Figure 7 shows that fuel cell vehicles could contribute to a 60% decrease in GHG emissions, in comparison with the most advanced hybrid engine configuration. However, for current technologies, the pre-transmission diesel HEV appears the best option.

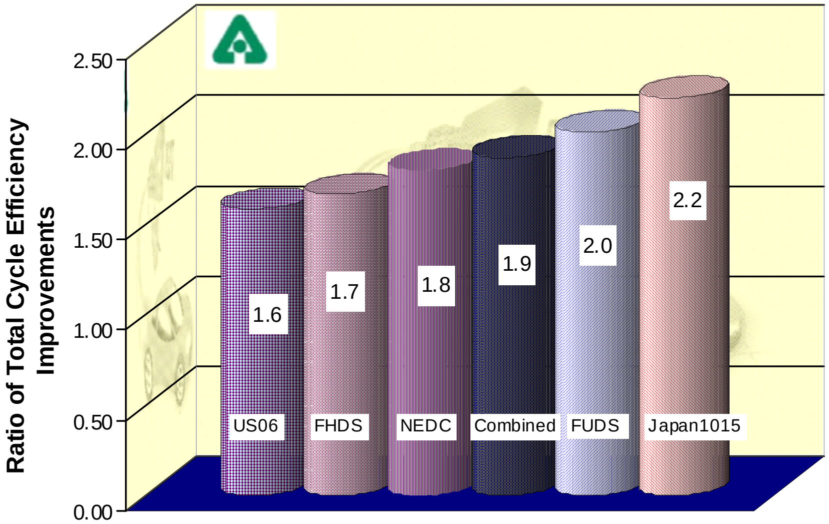

Figure 4. Driving Cycle Impact on Powertrain Efficiency Improvements — Example of the Pre-Transmission Parallel HEV with Diesel Engine

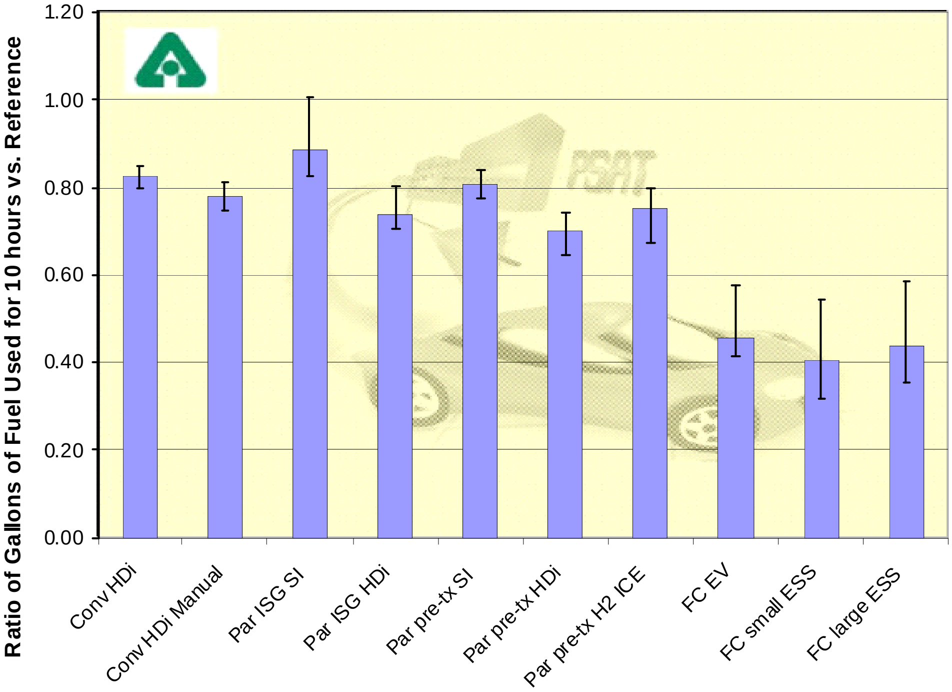

Figure 5. Ratio of Gallons of Fuel Saved /10 h for Each Drivetrain Configuration

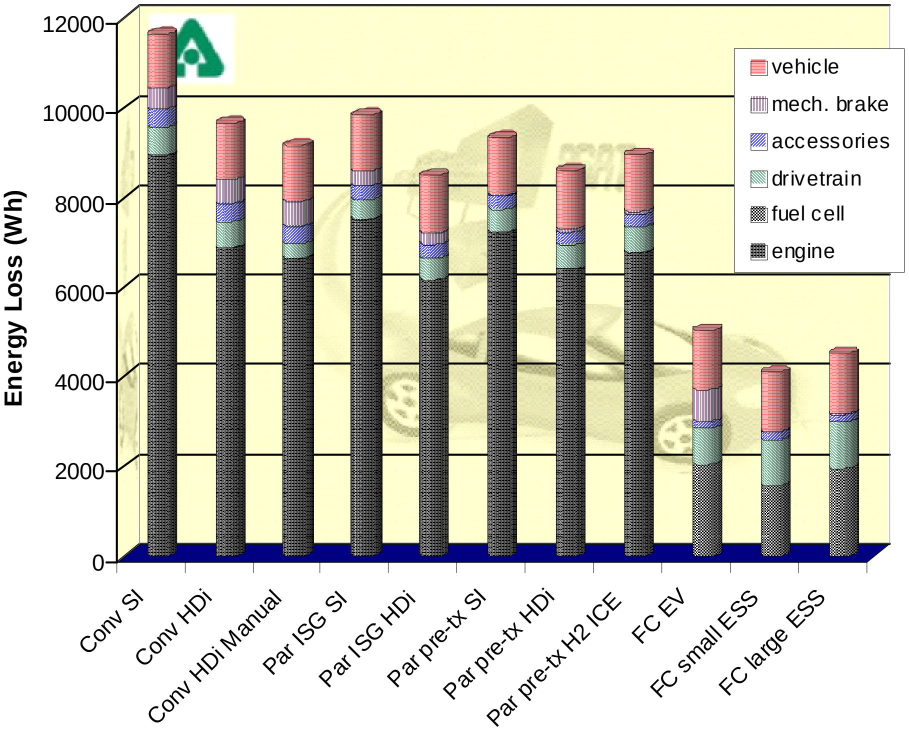

Figure 6. Vehicle Energy Loss Comparison (Wh) – NEDC Cycle

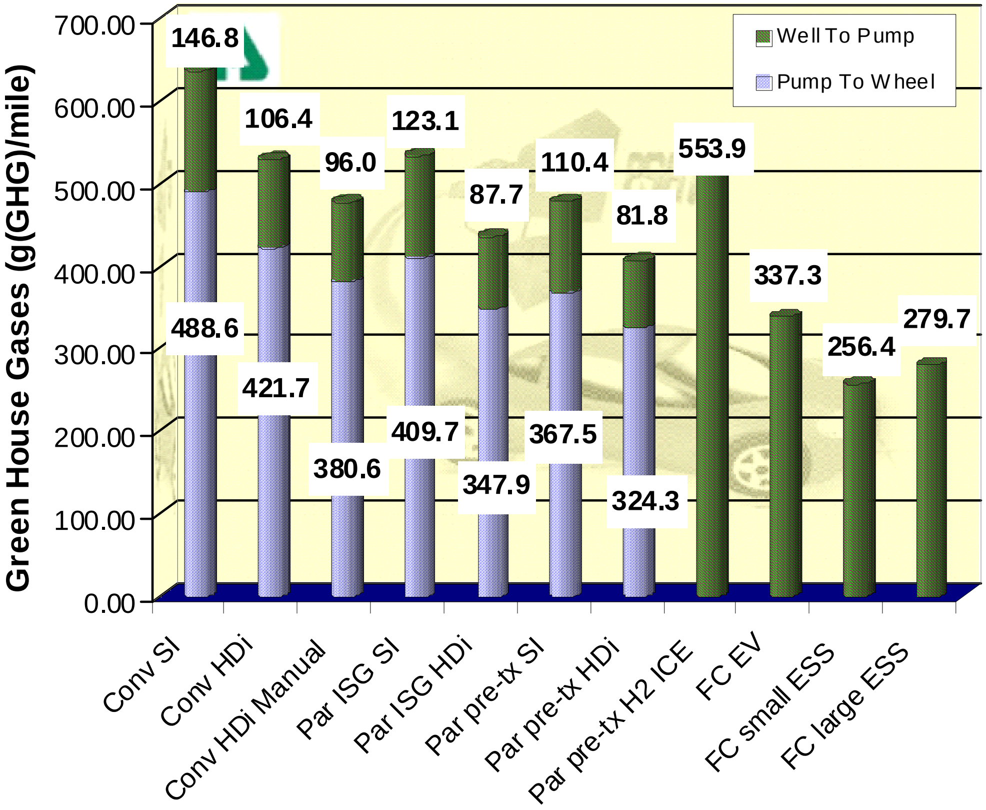

Figure 7. Greenhouse Gas Emissions (g/mi) – FUDS Cycle

CONCLUSION

Current technology capabilities have been compared and their potential from a WTW perspective has been evaluated by using a unique set of tools (GCTool, PSAT, and GREET). Hybrid electric vehicles with gasoline engines achieve performance comparable with that of conventional diesel vehicles. On the other hand, hybrid electric vehicles with a diesel engine appear to be competitive in terms of total energy cycle when hydrogen is produced from natural gas. The study also demonstrated that increasing the degree of hybridization for fuel cell vehicles by using NiMH technology does not always mean increased fuel economy. Despite the appearance that low-speed driving cycles would save more fuel than would high-speed ones, we demonstrated that the potential savings for 10 hours of driving are similar from one cycle to another. One of the major issues with fuel cells is hydrogen production, and so an intermediate step toward the hydrogen economy could involve using hydrogen ICEs to allow the development of the upstream side. The results of this study are comparable with those from the General Motors study [1], and yet they provide more information on the vehicle side. An additional study will be presented to compare future technologies and assess the benefits of potential 2010 fuel cell technology.

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APPENDIX 1 – VEHICLE DESCRIPTIONS

		Conv SI	Conv HDi	Conv HDi Manual	Par ISA SI	Par ISA HDi	Par pre-tx SI	Par pre-tx HDi	Par pre-tx H2 ICE	FC EV	FC small ESS	FC large ESS
Power												
IC Engine	**kW**	154	130	130	115	130	100	80	81	0	0	0
Fuel Cell	**kW**	0	0	0	0	0	0	0	0	160	120	80
Electric Motor #1 : Peak Power	**kW**	0	0	0	15	15	50	50	50	180	180	180
Electric Motor #1: Cont. Power	**kW**	0	0	0	7	7	25	25	25	80	80	80
Generator: Peak Power	**kW**	4	4	4	0	0	0	0	0	0	0	0
Generator: Cont. Power	**kW**	2	2	2	0	0	0	0	0	0	0	0
Starter	**kW**	2	2	2	0	0	0	0	0	0	0	0
12V Battery	**kW**	1.24	1.52	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
High Power Energy Storage #1	**kW**	0	0	0	17.68	17.68	60.8	60.8	60.8	0	40	80
Engine												
Displacement	**L**	4	4	4	4	4	1.9	2	2.4			
Specific Power	**W/kg**	568.3	309.5	309.5	469.4	342.1	568.2	307.7	602.2			
Max Efficiency	**%**	33.7	40.5	40.5	33.7	40.5	33.7	40.5	37			
Fuel Cell												
Specific Power	**W/kg**									398.5	372.0	282.7
Efficiency @ 25% power	**%**									61.8	61.4	61.7
Electric Motor												
Specific Power	**W/kg**				750.0	750.0	750.0	750.0	750.0	750	750	750
Max Efficiency	**%**				92	92	92	92	92	92	92	92
Transmission												
Transmission Type		Automatic 5spd	Automatic 5spd	Manual 5spd	Manual 5spd	Manual 5spd	Manual 5spd	Manual 5spd	Manual 5spd	NA	NA	NA
Fixed Ratio		NA	NA	NA	NA	NA	NA	NA	NA	1.6	1.6	1.6
Transfer Case		1	1	1	1	1	1	1	1	1	1	1
Final Drive Ratio		3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55
Battery Pack - 12V												
Type		PbA	PbA	PbA	PbA	PbA	PbA	PbA	PbA	PbA	PbA	PbA
Cell Capacity (C/3)	**Ah**	66	66	66	66	66	66	66	66	66	66	66
High Power Energy Storage #1												
Type					NiMH	NiMH	NiMH	NiMH	NiMH		NiMH	NiMH
Number of Cells					170	170	190	190	190		125	250
Cell Capacity (C/3)	**Ah**				6.5	6.5	28	28	28		28	28
Weights												
Vehicle Test Mass	**kg**	2104	2253	2239	2133	2268	2286	2370	2261	2445	2490	2575
Fuel												
Lower Heating Value	**MJ/kg**	43.00	42.5	42.5	43	42.5	43	42.5	120	120	120	120
Fuel Density	**kg/L**	0.749	0.835	0.835	0.749	0.835	0.749	0.835	0.018	0.018	0.018	0.018
Vehicle												
Hybridization degree	**%**	0.00	0.00	0.00	14.13	12.71	38.29	43.68	43.37	0.00	25.58	50.39
Accessory Power												
Mechanical	**W**	700	700	700	600	600	500	500	500	0	0	0
Electrical	**W**	500	500	500	600	600	700	700	700	800	800	800

APPENDIX 2 – VEHICLE RESULTS

		Conv SI	Conv HDi	Conv HDi Manual	Par ISA SI	Par ISA HDi	Par pre-tx SI	Par pre-tx HDi	Par pre-tx H2 ICE	FC EV	FC small ESS	FC large ESS
GREET Inputs												
WTT efficiency	**%**	79.0	82.4	82.4	79.0	82.4	79.0	82.4	55.8	55.8	55.8	55.8
PTW GHG Emission	**g(GHG)/MJ**	73.9	78.1	78.1	73.9	78.1	73.9	78.1	0.0	0.0	0.0	0.0
WTT GHG Emission	**g(GHG)/MJ**	22.2	19.7	19.7	22.2	19.7	22.2	19.7	119.8	119.8	119.8	119.8
Simulation Results - City												
SOC adjusted FE gasoline equivalent	**mpg**	18.4	22.5	25.0	21.7	27.1	25.2	30.1	26.9	43.3	59.0	53.9
PTW Efficiency	**%**	14.9	18.7	21.0	19.7	22.8	26.4	28.7	26.8	38.9	50.1	48.5
WTW Efficiency	**%**	11.8	15.4	17.3	15.6	18.8	20.8	23.6	14.9	21.7	28.0	27.0
WTW Energy Use	**MJ/miles**	8.4	6.6	5.9	7.0	5.4	6.3	5.0	8.3	5.0	3.8	4.2
WTW GHG Emission	**g(GHG)/miles**	635.3	528.1	476.7	532.8	435.6	477.9	406.1	553.9	337.3	256.4	279.7
Simulation Results - Highway												
SOC adjusted FE gasoline equivalent	**mpg**	26.9	33.9	35.1	31.4	36.2	32.7	37.4	34.7	61.1	61.0	58.3
PTW Efficiency	**%**	20.1	25.5	26.4	24.2	27.9	28.2	31.9	30.1	48.4	48.5	47.2
WTW Efficiency	**%**	15.9	21.0	21.8	19.1	23.0	22.3	26.3	16.8	27.0	27.0	26.3
WTW Energy Use	**MJ/miles**	5.7	4.4	4.2	4.9	4.1	4.8	4.0	6.4	3.6	3.6	3.8
WTW GHG Emission	**g(GHG)/miles**	433.9	351.6	338.7	373.9	328.0	363.1	324.1	429.6	239.0	242.8	255.6
Simulation Results - Combined												
SOC adjusted FE gasoline equivalent	**mpg**	21.4	26.5	28.7	25.2	30.6	28.1	33.0	30.0	49.8	59.9	55.8
PTW Efficiency	**%**	16.8	21.1	23.0	21.3	24.8	27.1	30.0	28.1	42.4	49.4	47.9
WTW Efficiency	**%**	13.2	17.4	18.9	16.9	20.4	21.4	24.7	15.7	23.6	27.6	26.7
WTW Energy Use	**MJ/miles**	7.2	5.6	5.1	6.1	4.8	5.6	4.6	7.4	4.4	3.7	4.0
WTW GHG Emission	**g(GHG)/mile**	544.7	448.6	414.6	461.3	387.2	426.2	369.2	498.0	293.0	250.3	268.8
Simulation Results - US06												
SOC adjusted FE gasoline equivalent	**mpg**	19.1	22.4	23.5	19.3	24.3	23.8	26.7	25.5	33.5	37.8	35.8
PTW Efficiency	**%**	23.0	27.6	29.2	25.6	31.0	31.8	34.7	33.3	44.2	48.6	46.5
WTW Efficiency	**%**	18.2	22.8	24.1	20.2	25.6	25.1	28.6	18.6	24.7	27.1	26.0
WTW Energy Use	**MJ/miles**	8.1	6.6	6.3	8.0	6.1	6.7	5.7	8.9	6.5	6.0	6.5
WTW GHG Emission	**g(GHG)/miles**	611.8	530.0	505.8	604.7	492.9	510.4	457.5	596.1	434.0	402.6	434.8
Simulation Results - NEDC												
SOC adjusted FE gasoline equivalent	**mpg**	19.4	23.5	25.0	23.9	27.3	25.4	27.5	26.4	45.4	59.2	53.9
PTW Efficiency	**%**	15.6	19.6	20.8	20.0	22.8	24.3	26.7	25.4	39.9	48.8	46.4
WTW Efficiency	**%**	12.3	16.1	17.2	15.8	18.7	19.2	22.0	14.2	22.3	27.2	25.9
WTW Energy Use	**MJ/miles**	7.9	6.3	5.9	6.4	5.3	6.3	5.5	8.5	4.8	3.9	4.3
WTP Energy Use	**Mbtu/miles**	1578.7	1049.2	987.1	1269.2	888.0	1245.2	920.8	3559.1	2016.1	1623.6	1792.0
WTW GHG Emission	**g(GHG)/miles**	10907.6	9626.0	9056.1	8769.1	8147.5	8603.6	8448.3	567.9	321.7	259.1	286.0
Simulation Results - Japan1015												
SOC adjusted FE gasoline equivalent	**mpg**	16.5	19.9	21.4	21.7	25.7	23.6	28.4	25.9	41.4	61.9	56.5
PTW Efficiency	**%**	13.0	16.4	17.6	18.9	20.8	23.0	27.3	25.1	36.4	49.2	47.5
WTW Efficiency	**%**	10.2	13.5	14.5	14.9	17.1	18.2	22.5	14.0	20.3	27.5	26.5
WTW Energy Use	**MJ/miles**	9.2	7.4	6.9	7.0	5.7	6.8	5.4	8.4	5.3	3.8	4.2
WTW GHG Emission	**g(GHG)/miles**	12584.7	11283.1	10519.7	9651.9	8797.6	9352.8	8247.4	563.7	352.9	252.4	279.6