Global Assessment of Hydrogen Technologies
DE-FC36-02GO12042

TASK 1 REPORT
DOE/GO/12042-2

Technology Evaluation of Hydrogen Light-Duty Vehicles

Fouad H. Fouad, Ph.D., P.E., Principal Investigator
Robert W. Peters, Ph.D., P.E.
Virginia P. Sisiopiku, Ph.D.
Andrew J. Sullivan, P.E.

Lead Investigators on this Task:

Virginia P. Sisiopiku
University of Alabama at Birmingham
1075 13th Street South
Birmingham, Alabama 35294

and

Aymeric Rousseau
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, Illinois 60439

December 2007

TABLE OF CONTENTS

Table of Figures

Table of Tables

Acronyms

CAFÉ	Corporate Average Fuel Economy
FCV	Fuel Cell Vehicle
FHDS	Federal Highway Driving Schedule
FUDS	Federal Urban Driving Schedule
GHG	Greenhouse Gas
GUI	Graphical User Interface
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LHV	Lower Heating Value
PAFC	Phosphoric Acid
PEFC	Proton Exchange Membrane
PSAT	Powertrain System Analysis Toolkit
SOC	State-Of-Charge
SOFC	Solid Oxide
SUV	Sport Utility Vehicles
UDDS	Urban Dynamometer Driving Schedule
ZEV	Zero Emission Vehicle

1 Introduction

This task analyzes the candidate hydrogen-fueled vehicles for near-term use in the Southeastern U.S. The purpose of this work is to assess their potential in terms of efficiency and performance. This report compares conventional, hybrid electric vehicles (HEV) with gasoline and hydrogen-fueled internal combustion engines (ICEs) as well as fuel cell and fuel cell hybrids from a technology as well as fuel economy point of view. All the vehicles have been simulated using the Powertrain System Analysis Toolkit (PSAT).

First, some background information is provided on recent American automotive market trends and consequences. Moreover, available options are presented for introducing cleaner and more economical vehicles in the market in the future. In this study, analysis of various candidate hydrogen-fueled vehicles is performed using PSAT and, thus, a brief description of PSAT features and capabilities are provided. Detailed information on the simulation analysis performed is also offered, including methodology assumptions, fuel economic results, and conclusions from the findings.

1.1 The Automobile Market

The automobile American market is very different from the European or the Asian markets. Sport utility vehicles (SUV), pick-up trucks and mini-vans are the preferred cars of Americans. These vehicles are bigger than the biggest cars overseas and consume a lot more fuel, and have gained popularity in the American market. As shown in Figure 1, in 2001, light trucks represent a total of fifty percent of the sales in the U.S., and the number is still increasing.

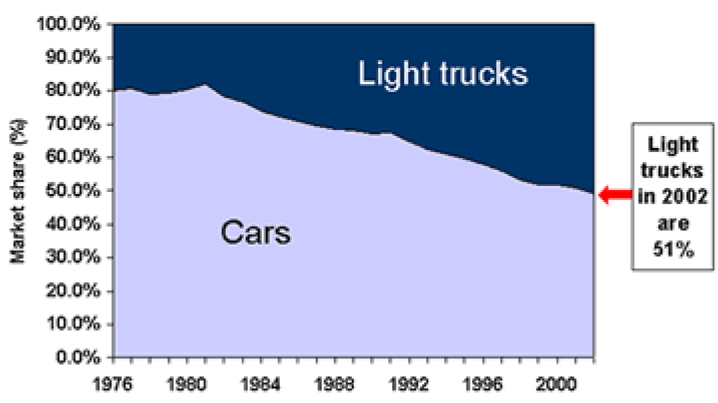


Figure 1: SUVs and Pick-up trucks increase in the US market [1].

One of the reasons for this trend is the fact that the price of the fuel in the US is still low compared to foreign countries, about 0.3 euro per liter. In addition, the emission regulations for SUVs and pick-up trucks are less restrictive than for lighter cars. Indeed, they can have 30% more CO_2 and 75% more nitrogen oxides. Moreover, the federal law allows them to consume 30% more fuel than regular cars. Examples of favorite SUV and pick-up truck models are shown in Figure 2.

Best SUV sale: Ford Explorer

Best « Pick-up» sale: Ford F-150

Figure 2: SUVs and Pick-up trucks [2].

1.2 Consequences

1.2.1 Climate changes

Almost all environmental scientists agree that human-caused emissions are changing the earth's climate, leading to grave potential consequences: more severe weather, desertification, and inundation of coastal area. The U.S. accounts for 25% of global carbon emissions, the largest greenhouse gas and most important cause of climate change. Of that 25%, about one third is caused by the transportation sector. Cars and light trucks make up 62% of transportation related emissions. Therefore, cars and light trucks make up about 20% of all U.S. carbon emissions, or about 5% of the world's total.

In other words, global warming cannot be slowed or prevented without a significant reduction in vehicle emissions.

1.2.2 Economical point of view

Hydrocarbon reserves are decreasing whereas the world consumption is constantly increasing. The US Office of Transportation Technology Analytic Team foresees that half of the oil reserves will be gone in 2020 if the oil consumption remains constant, as shown in Figure 3 [3].

In the U.S., cars and light trucks use 37% of the nation's oil, 43% of which is imported. Increasing today's passenger car average efficiency by roughly 25% would eliminate the need to import oil from the Persian Gulf. The U.S. spends $200,000 on foreign oil every minute.

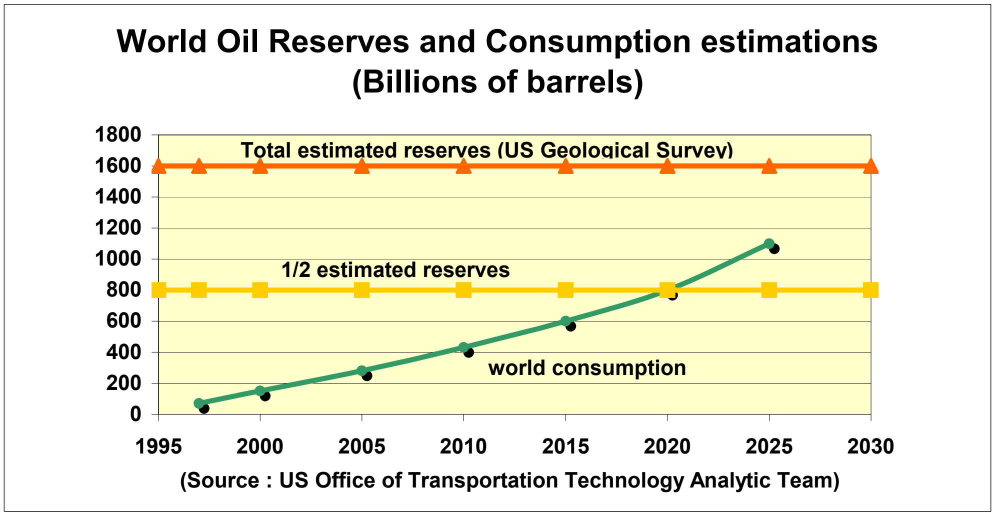


Figure 3: Foreign oil dependency [3].

Figure 4 illustrates the expanding gap between projected domestic oil production and projected U.S. transportation oil demand while the price of U.S. gasoline remains low by world standards. The future oil gap is based on the Energy Information Administration's current projections of oil prices, vehicle miles driven, and the U.S. fleet vehicle fuel economy [4]. Significant changes in these factors would have corresponding influences on the size of the gap, greater or smaller. For example, a large increase in the price of oil could be expected to reduce the gap because it would likely spur reactions such as reduced driving and greater domestic production from marginal wells.

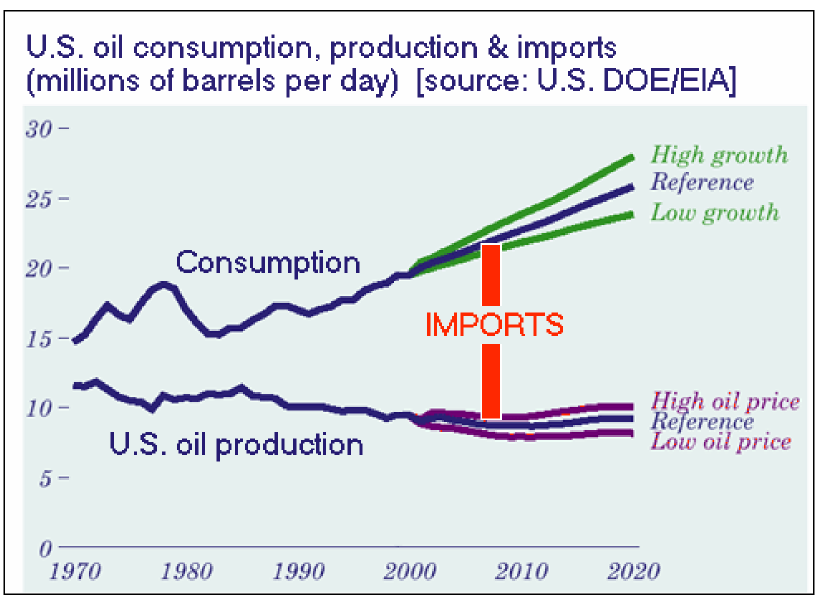


Figure 4: Projected transportation oil use [5].

1.3 Solutions

It should be noted that Americans are not insensitive to environmental aspects. Indeed, for more than 20 years, the U.S. government has used regulations to oblige car companies to make their models more efficient. However, with the increase of car functionalities and the rise of sport utility vehicles and light trucks, the overall US fleet efficiency is falling (from an average of 26mpg 17 years ago, to 24mpg today).

1.3.1 Emission regulation

Some regulations have been set to reduce emissions. All vehicles built before 2004 have to respect the norm Tier 1. From this date, Tier 2 will replace this norm. All cars have to perform emission tests regularly during their life [6].

The Tier 2 standard brings significant emission reductions relative to the Tier 1 regulation. In addition to more stringent numerical emission limits, the regulation introduces a number of important changes that make the standard more stringent for larger vehicles. Under the Tier 2 standard, the same emission standards apply to all vehicle weight categories, i.e., cars, minivans, light duty trucks, and SUVs have the same emission limit. Since light-duty emission standards are expressed in grams of pollutants per mile, large engines (such as those used in light trucks or SUVs) will have to utilize more advanced emission control technologies than smaller engines in order to meet the standard.

The Tier 2 regulation brings new requirements for fuel quality. Cleaner fuels will be required by advanced emission after treatment devices (e.g. catalysts) that are needed to meet the regulations.

1.3.2 Fuel economy regulation

Increasing the fuel efficiency of automobiles is another option that the United States can consider to reduce consumption of fossil fuels and the threat of global warming.

Corporate Average Fuel Economy (CAFE) is the sales weighted average fuel economy, expressed in miles per gallon (mpg), of a manufacturer’s fleet of passenger cars or light trucks, manufactured for sale in the United States, for any given model year.

The “Energy Policy Conservation Act,” enacted into law by Congress in 1975, added Title V, “Improving Automotive Efficiency,” to the Motor Vehicle Information and Cost Savings Act and established CAFE standards for passenger cars and light trucks. The Act was passed in response to the 1973-74 Arab oil embargoes. The near-term goal was to double new car fuel economy by model year 1985.

The average vehicle fuel economy is currently set at 27.5 mpg for cars and 20.7 mpg for light trucks (the standards have been stagnant for almost a decade). In any given model year, it requires that the average for an automaker's entire fleet meet its goals. Manufacturers can still make vehicles that get less than the standards, as long as they balance them with more efficient vehicles. Indeed, manufacturers earn "credits" for exceeding CAFE standards, and these credits can be used to offset fuel economy shortfalls.

If a manufacturer does not meet the standard, the manufacturer is liable for a civil penalty of $5.00 for each 0.1 mpg its fleet falls below the standard, multiplied by the number of vehicles it produces. For example, if a manufacturer produces 2 million cars in a particular model year, and its CAFE falls 0.5 mpg below the standard, it would be liable for a civil penalty of $50 million.

To reduce emissions and increase automobile fuel economy, research can be done to improve actual components. Indeed, the lighter the car will be, the best the fuel economy will be. Nowadays, plastic and aluminum replace steel everywhere in the car. Moreover, improvements can still be done on car aerodynamics as well as on the catalyst. Another solution for improved performance is developing new technologies.

1.3.3 Hybrid vehicles

There are currently many different hybrid-electric vehicles utilizing either an engine that burns gasoline, diesel fuel, or alternative fuels such as methanol, ethanol or compressed natural gas, or a fuel cell in conjunction with batteries. Use of two different energy sources defines a hybrid.

More efficient vehicles can make a big difference to society in terms of environmental benefits, and the serious deterioration of urban air has motivated regulators to require cleaner cars. Use of production HEVs is expected to reduce smog-forming pollutants over the current national average. The first hybrids on the market will cut emissions of global-warming pollutants by a third to a half, and later models may cut emissions by even more.

1.3.3.1 HEV advantages

Conventional internal combustion engines (ICE) convert the liquid fuel energy into shaft energy. All energy from the combustion process centers around the crankshaft with the exception of that lost in the form of heat. A typical ICE vehicle only uses approximately 16% of the liquid fuel energy to move the vehicle. The heat (from the thermodynamic cycle of the engine) emitted in the combustion process wastes the majority of the energy while frictional losses from the hundreds of moving parts in the engine, transmission and the mechanical connection to the drive wheels consume the rest. On the contrary, a battery contains no moving parts. The only energy wasted is a very small amount of heat during the course of a discharge cycle.

An internal combustion engine is inefficient not only because of the amount of energy loss incurred in the transfer of energy from the liquid state to the drivetrain, but it also becomes more inefficient when the engine is idling.

To solve emission and inefficiency problems, the electric vehicle was created. Indeed, no gases are emitted by electric vehicles and the peak motor efficiency is much higher than the engine one (90% instead of 35%). However, the electric vehicle presents some limitations due to its batteries.

Hybrid power systems were conceived as a way to compensate for the shortfall in battery technology. Because batteries could supply only enough energy for short trips, an onboard generator, powered by an internal combustion engine, could be installed and used for longer trips. In the old days, it was thought that by biasing the system toward battery-electric power and operating on wall-plug electricity as much as possible, efficiency and emissions would be about as optimal as possible until better batteries came along. The natural conclusion of this concept was that, with better batteries, the need hybrids will be diminished. But after 20 years of study, it seems that hybrids are taking center stage and electric vehicles are only being used in niche market applications where fewer miles are traveled.

Essentially, a hybrid combines an energy storage system, a power unit, and a vehicle propulsion system. The primary options for energy storage include batteries, ultra-capacitors, and flywheels. Although batteries are by far the most common energy storage choice, research is still being done in other energy storage areas. Depending on the hybridization degree, batteries can be either the main energy source or the auxiliary one. Hybrid power unit options are spark ignition engines, compression ignition direct injection engines, gas turbines, and fuel cells.

The HEVs available for sale are cost competitive compared to similar conventional vehicles. Any cost premium that may be associated with HEVs of the future can be offset by overall fuel savings and federal/state incentives. Automobile manufacturers are making HEVs with comparable performance, safety, and cost because they know that these three elements are most important to consumers.

Also by combining chemical power with electric power, it is important to note that hybrids will offer the same or greater range than traditional combustion engines have. HEVs are able to operate approximately two times more efficiently than conventional vehicles. For example, Honda's Insight is able to go 700 miles on a single tank of gas [7] and the Toyota Prius can cover about 600 miles [8]. For the driver, hybrids offer similar or better performance than conventional vehicles. More importantly, because such an option is available now, hybrids are a practical way for consumers to choose a cleaner transportation mode today.

The main advantages of HEVs over conventional vehicles are as follows:

- Regenerative braking capability helps minimize energy loss and recover the energy used to slow down or stop a vehicle.
- Engines can be sized to accommodate average load, not peak load, which reduces the engine's weight.
- Fuel efficiency is greatly increased (hybrids consume significantly less fuel than vehicles powered by gasoline alone).
- Emissions are greatly decreased, and
- HEVs can reduce dependency on fossil fuels when running on alternative fuels.

1.3.3.2 Hybrid vehicles families

There are many HEV configurations and design options available. These can be grouped in three categories: series (range-extending HEVs), parallel (power assist HEVs), and dual-mode HEVs. The main characteristics of each category are presented next.

Series hybrid

In a series HEV, an electric generator, coupled with an engine, supplies electricity to the motor to propel the car and to the batteries when they need to be recharged. Generally, the engine/generator set keeps the battery charged between 60-80%. When the battery reaches its lower limit, the power unit starts. Similarly, when the battery reaches its upper limit, the engine shuts off. Figure 5 provides an example of a series engine hybrid electric vehicle.

The main interest of this configuration is that engine and vehicle speeds are decoupled and only the electric motor is connected to the wheels. The engine does not need to speed up or slow down as the load varies. As a consequence, the engine can run at optimum

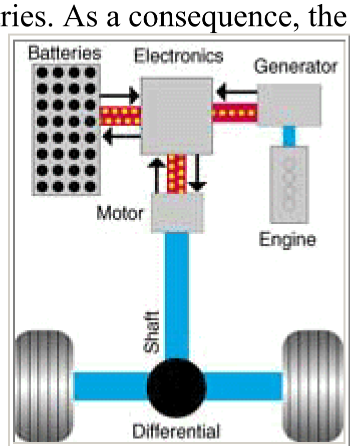


Figure 5: Series engine hybrid electric vehicle [9].

performance (best engine efficiency area) greatly improving the fuel economy. Moreover, the engine never idles, thus reduces the overall emissions. However, because the motor is the only one connected to the wheels and the engine/generator set is sized for sustained grade ability, this configuration requires large batteries, motor and engine. The engine/generator set can be replaced by a fuel cell, in which case the configuration is called hybrid fuel cell vehicle.

Due to the component size, a series hybrid vehicle is heavy and thus this configuration is used for trucks or buses rather than for cars, as the mass penalty is less important for large vehicles than for smaller ones.

Parallel hybrid

Parallel hybrids have mechanical connections to the wheels from both the electric motor and the engine. The motor can be located anywhere between the output engine shaft and the wheels. These vehicles do not need a dedicated generator as the electric motor can be used as a generator to recharge the batteries. In a parallel HEV, the electric motor can assist the engine during start-up and acceleration. Figure 6 shows an example of a parallel hybrid electric vehicle.

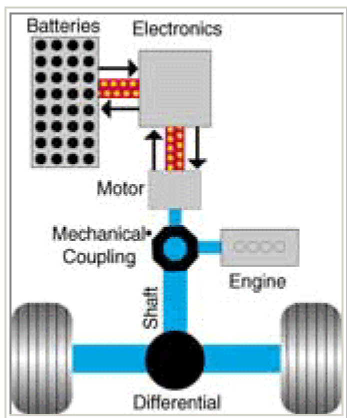


Figure 6: Parallel hybrid electric vehicle [9].

Because the electric motor and the engine are both coupled directly to the wheels, they can share the power during accelerations. Therefore, it is possible to downsize both the engine and the motor compared to series hybrids (the vehicle mass is then decreased). It is also possible to increase the hybridization degree by downsizing the engine and upsizing the motor. For some configurations, the engine can operate close to its best efficiency curve while, the motor assists it or recharges the battery.

Dual-Mode Hybrid

Dual mode hybrids combine the best aspects of both series and parallel hybrids to create an extremely efficient system.

As shown in Figure 7, this system divides the engine power along two paths: one goes to the generator to produce electricity and the other goes through a mechanical gear system to drive the wheels. In addition to this, a regenerative system uses the kinetic energy of deceleration and braking to produce electricity, which is stored in the battery.

The main components of this configuration are: a power split device (transmission), an electric motor, a generator and an engine. According to the situation, all these elements

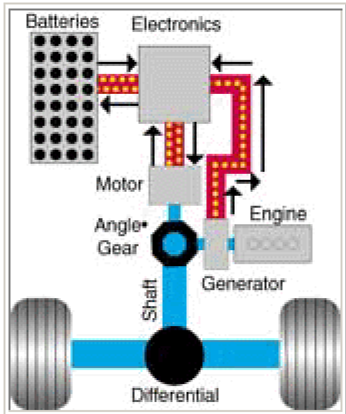


Figure 7: Dual mode hybrid electric vehicle [9].

operate differently. Indeed, the engine is not always ON and the electricity from the generator may go directly to the wheel to help propelling the car, or go through an inverter to be stored in the battery. The different possibilities are the following:

- When starting out, moving slowly or when the state of charge of the battery is high enough, the engine is not efficient, so it is turned OFF and the motor alone propels the car.
- During normal operation, the engine power is split, with part going to drive the vehicle and part being used to generate electricity. The electricity goes to the motor, which assists in propelling the car. The generator acts as a starter to activate the engine.
- During full throttle acceleration, the battery provides extra energy.
- During deceleration or braking, the motor acts as a generator, transforming the kinetic energy of the wheels into electricity.

The most known example of this configuration is the Toyota Prius.

1.3.3.3 Fuel cell vehicles

Fuel cell technology

Developed in the 1960's for the space program, fuel cells generate electricity directly by chemically combining stored hydrogen with oxygen, producing hot water as a by-product. The process is essentially the reverse of electrolysis, where electricity is used to split water into hydrogen and oxygen.

A fuel cell consists of two electrodes sandwiched around an electrolyte (Figure 8). Oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat. Hydrogen is fed into the anode (negative pole where fuel is oxidized) of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode (positive pole needed for reduction process of air or oxygen). A catalyst at the anode (usually based upon platinum-family elements) causes hydrogen atoms to give up their negatively charged electrons, leaving positively charged protons.

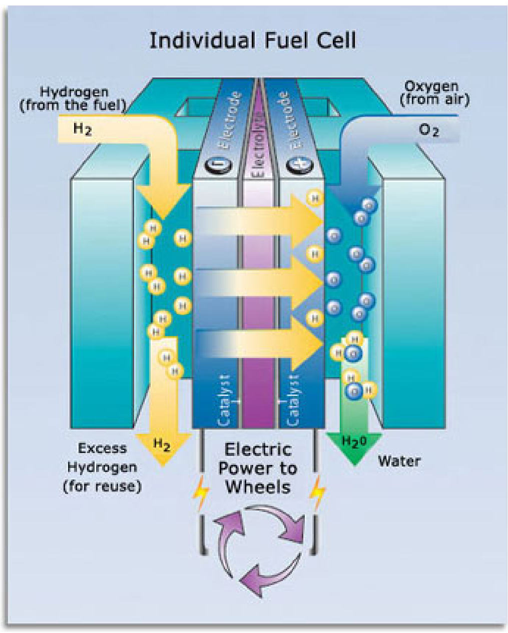


Figure 8: Fuel cell principle [10].

Negatively charge oxygen ions (from ionized oxygen gas) at the cathode side attract the hydrogen protons. As the protons pass selectively through a semi-permeable solid electrolyte membrane (in the most common fuel cell type), the remaining electrons are redirected to the cathode by way of an external circuit, thus producing current that power an electric motor or charges a battery. The electrons combine with the hydrogen protons and oxygen ions at the cathode forming the fuel cell's major byproduct, water. The other principal end product is heat, which can be captured and reused, or released.

Individual fuel cells produce approximately 0.6 volt and are combined in stacks to provide the right amount of electrical power. The major fuel cell configurations are identified by the type of electrolyte used in each, which in turn determines the mobile ion species responsible for the cell reaction mechanism.

Table 1 presents different kinds of fuel cells and their applications.

Hydrogen as a fuel

Hydrogen gas is very diffuse, requiring more volume than gasoline or natural gas to store a given quantity of energy. Indeed, hydrogen density is very low (18 kg/m^3 instead of 749 kg/m^3 for gasoline or 835 kg/m^3 for diesel).

Fuel cell type	Mobile Ion	Temperature	Applications
Alkaline	OH^-	50-200 °C	Space (300W to 5kW).
Proton Exchange Membrane (PEFC)	H^+	50-100 °C	Automotive (because of its quick startup). Range from 1 to 250kW.
Phosphoric Acid (PAFC)	H^+	~ 220 °C	Large vehicles (buses, Loco) or small stationary power generation. Output up to 200Kw.
Molten carbonate	CO_3^{2-}	~ 650 °C	Large stationary application (from 10kW to 2MW).
Solid Oxide (SOFC)	O^{2-}	500-1000 °C	Big, high power applications (central electricity generating stations).

Table 1: Fuel Cell Types.

The best option today is to compress hydrogen to at least 5,000 psi (340 atmospheres or 34.5 MPa) and store the hydrogen in carbon fiber-wrapped composite tanks. The carbon fiber provides extraordinary strength. Even with compression to 5,000 psi, a compressed hydrogen tank would require approximately 9.6 times as much volume as a gasoline tank for the same quantity of energy. Fortunately, the fuel cell does not need as much energy as a gasoline ICE. Indeed, hydrogen Lower Heating Value (LHV) is of the order of 120 MJ/kg compared to 43 MJ/kg for gasoline and 42.5 MJ/kg for diesel.

It should be noted that just comparing fuel storage volumes does not provide the full picture. A Fuel Cell Vehicle (FCV) would replace the internal combustion engine, catalytic converter system, transmission, fuel tank and related components of a conventional car with electric motors, the fuel cell stack, hydrogen tanks, inverter and power control electronics and related components for humidification and air pressurization. The appropriate question is whether all of these FCV components can be placed in a motor vehicle without encroaching into the passenger or trunk space.

Direct hydrogen fuel cell vehicles are true ZEVs, producing no local emissions, but the total well-to-wheels greenhouse gas (GHG) emissions depend on the source of the hydrogen. Indeed, hydrogen is rarely at its natural state, and thus it has to be produced from another energy source. Several sources can generate hydrogen, namely:

- Renewable sources such as wind, sun, biomass or hydroelectricity
- Natural gas, and
- Electric power stations (nuclear, coil, oil…).

Greenhouse gases can be virtually eliminated if the hydrogen were generated by renewable sources. This is the ultimate goal of the hydrogen economy.

Fuel cell vehicles

Only two families of fuel cell vehicles exist: vehicles propelled by the fuel cell only, and hybrid fuel cell vehicles (fuel cell and energy storage). A fuel cell only vehicle is in fact an electric vehicle where the energy storage is replaced by a fuel cell.

In hybrid fuel cell vehicles (Figure 9), fuel cell and batteries are connected in parallel to provide electricity to the motor. The advantage of this solution, in comparison to the fuel cell only vehicle, is the ability to recuperate braking kinetic energy. During deceleration, the energy storage is recharged and as a consequence, it can provide power when the fuel cell is warming up or when it is not able to give the desired power (high transients).

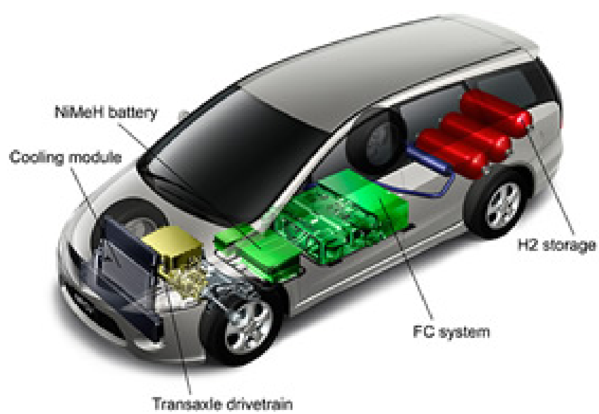


Figure 9: Hybrid fuel cell vehicle [11].

1.4 Study Objectives

The main objective of this study was to evaluate the impact of advanced technologies on the fuel economy under various driving cycles. Such technologies include conventional vehicle configurations with hydrogen ICE; power split with Otto and Atkinson cycles; fuel cell only, and fuel cell hybrid configurations. Driving cycles considered include US06, FHDS, FUDS, and combined cycles. The purpose of the analysis is to compare the various options and identify those that demonstrate the best potential for future implementation.

Moreover, a parametric analysis is performed to evaluate the impact of vehicle characteristics on the performance of a hydrogen-fueled internal combustion engine (ICE) vehicle in terms of fuel efficiency and engine efficiency for various driving cycles. The results of the analysis are used to determine the parameter values that yield the best results.

Simulation modeling is used in order to perform the analysis. A review of available vehicle simulation software packages was performed to determine appropriate tools for addressing the research objectives and summarized next.

1.5 Review of Available Vehicle Simulation Software

1.5.1 Advanced Vehicle Simulator (ADVISOR)

The Advanced Vehicle Simulator (ADVISOR) developed by AVL is a hybrid electric vehicle (HEV) simulation model written in a widely used software environment called Matlab/Simulink. This tool tests the impact of changes in vehicle components, such as climate control systems, alternative fuels, or other modifications, that might impact fuel economy. The user can alter simulation results by selecting vehicle component types, sizes, and parameters.

Currently, ADVISOR is being used successfully by many organizations, is continuously fed up-to-date component test data through users and university validation efforts, and has the flexibility to model specific components and vehicle configurations. The simulation tool can be used for conventional, advanced, light, and heavy vehicles. The capability to quickly perform parametric and sensitivity studies for specific vehicles is an important feature of ADVISOR [12].

1.5.2 Texas A&M University, V-Elph 2.01

This simulation and modeling package developed at Texas A&M University facilitates in-depth studies of electric vehicle and hybrid electric vehicle configurations or energy management strategies through visual programming by creating components as hierarchical subsystems that can be used interchangeably as embedded systems. V-Elph is composed of detailed models of three major types of components: electric motors, internal combustion engines, and batteries. Moreover, it models support components that can be integrated to model and simulate drive rains having all electric, series hybrid, and parallel hybrid configurations. V-Elph was written in the Matlab/Simulink language [13].

1.5.3 Lawrence Livermore National Laboratory (LLNL)

LLNL used its experience in computer code development, cost/benefit and decision analysis, and testing to develop a hybrid vehicle evaluation code. The model can be used to simulate a variety of vehicle types and components. The code can predict fuel economy and emissions for the Environmental Protection Agency (EPA) Urban and Highway driving schedules, as well as hill climbing ability and acceleration times.

The model can simulate pure electric or series hybrid vehicles. In a series hybrid vehicle, the chemical energy of the fuel is first converted to electrical energy. The electrical energy is then either stored or transferred as needed to the electric drive motor. Different engine-generator units or fuel cells can be specified for generating electricity from various fuels. Batteries, flywheels, or ultra capacitors can be specified to store the electrical energy. An electric propulsion motor can be selected from the different types available. Experimental components can also be incorporated to the code if an engineering model is supplied.

The code estimates weight and volume for power train components, mileage on the EPA Federal Urban and Highway Driving Cycles, acceleration and hill climbing performance, and emissions. The model includes regenerative braking and is useful for sensitivity analysis on components performance. The code has been applied to many vehicles, including electric vehicle prototypes, a hydrogen concept car, electric buses, hybrid trains, and a natural gas vehicle. The code has also been used to optimize vehicles for high fuel economy and low emissions.

Applications of the LLNL code include battery electric vehicles, flywheel vehicles, battery-Flywheel hybrid vehicles, Engine-Generator-Flywheel vehicles, Engine-Generator-Battery hybrid vehicles, Fuel Cell-Flywheel hybrid vehicles, Fuel Cell-Battery hybrid vehicles, and Fuel Cell vehicles [14].

1.5.4 AirCRED

AirCRED was developed by Argonne National Laboratory (ANL) and is a graphical user interface-based calculation model. It is designed to provide an easy, straightforward way to sum the values of ozone precursor emission reduction credits with Voluntary Mobile Source Emission Reduction Program (VMEP) credits. The latter are given for other local voluntary strategies and programs earned pursuant to the U.S. Environmental Protection Agency's (EPA's) October 1997 guidance about VMEP initiatives. AirCred is based on EPA's MOBILE5b model, in combination with emission test certification data for new vehicles and their gasoline- or diesel-fueled counterparts.

The model starts with the MOBILE5b-computed emission factor (by vehicle type) appropriate to midsummer, ozone-season conditions in each major city (about 60 different values are available). The "clean gap" between the certification test emissions by alternative fuel vehicles (AFVs) and their conventional counterparts of non-methane hydrocarbon (NMHC), carbon monoxide (CO), and nitrogen oxides (NO_x) determines the magnitude of the credit (in grams per mile [g/mi]) that can be taken for AFV driving in each city, relative to MOBILE5b's emission rates [15].

1.5.5 Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET)

The Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET) is a fuel-cycle model that allows researchers to evaluate various engine and fuel combinations on a consistent fuel-cycle basis. To address technology improvements over time, GREET separates fuels and vehicle technologies into near- and long-term options. The latter are assumed to have improved energy and emission performance compared with the former. GREET was developed as a multidimensional spreadsheet model in Microsoft Excel by ANL.

More than 100 organizations are using GREET, including government agencies, the auto industry, the energy industry, research institutes, universities, and public interest groups. GREET users reside in North America, Europe, and Asia [16].

1.5.6 MARVEL

MARVEL performs least-life-cycle-cost analyses of battery/heat engine/hybrid vehicle systems to determine the combination of battery and heat engine characteristics for different vehicle types and missions. Simplified models are used for the transmission, motor/generator, controller, and other vehicle components, while a rather comprehensive model is used for the battery. Battery relationships available include the Ragone curve, peak power versus specific energy and depth-of-discharge (DOD), cycle life versus DOD, effects of battery scale, and capacity recuperation due to intermittent driving patterns. Energy management in the operation of the vehicle is based on the specified mission requirements, type and size of the battery, allowable DOD, size of the heat engine, and the management strategy employed. Several optional management strategies are available in MARVEL.

The program can be used to analyze a pure electric vehicle, a pure heat engine vehicle, or a hybrid vehicle that employs batteries as well as a heat engine. Cost comparisons for these vehicles can be made on the same basis. Input data for MARVEL are contained in three files generated by the user using three preprocessors which are included. MVDATA processes vehicle specification and mission requirements information, while MBDATA creates a file containing specific peak power as a function of specific energy and DOD, and MPDATA produces the file containing vehicle velocity specification data based on driving cycle information [17].

1.5.7 Powertrain System Analysis Toolkit (PSAT)

PSAT is a vehicle simulation model developed by Argonne National Laboratory (ANL) and written in Matlab/Simulink. The software allows the user to simulate a variety of vehicular models, including conventional vehicles, battery electric vehicles, fuel cell electric vehicles, parallel hybrid vehicles, series hybrid vehicles (engine and fuel cell), and power split vehicles. PSAT allows users to simulate an unrivaled number of predefined configurations. PSAT, is a forward-looking model, that can be used for several purposes including the calculation of fuel consumption and vehicle performance such as maximum acceleration, time to accelerate from 0-60 mph, 0-85 mph , 40-60 mph, maximum launch grade, and maximum grade sustainability at 55 mph.

Moreover, PSAT offers the possibility to build the drive train models and choose each component model to be used. This allows the users to easily implement their own detailed component models to study more precisely the behavior of this component within the system. The same logic can be followed concerning control strategies or shifting logic. More specifically, PSAT allows users to:

- Select the best drive train configuration for specific customers expectations;
- Develop advanced control strategies that can later be implemented in a vehicle;
- Optimize the system as far as component sizes and control;
- Integrate advanced transient component models; and
- Run parametric studies by changing component parameters or cycle choices.

PSAT is flexible and reusable. The drive train configurations in PSAT are built leading to unrivaled number of predefined configurations. Each component model is composed of 3 inputs and 3 outputs allowing users to choose different level of modeling depending upon the simulation to be realized. The power train controller is composed of 3 blocks. Users have the possibility to compare different control and shifting algorithms within the same model. Each simulation is saved and users have the possibility to rerun the exact simulation. Component parameters, models, and files are named following a defined nomenclature. PSAT also provides an easy to use Graphical User Interface [18].

1.6 Simulation Model Selection

A fuel cell vehicle model has to be physically and mathematically sound. All relevant physical effects have to be considered and the model should stand on solid mathematical ground. Unless these two conditions are fulfilled one cannot rely on the results. In addition to soundness, the scope of the model should also be complete. Complete in this context means that it should enable the simulation of different types of vehicles (hybrids, non hybrids, and different forms of hybrids) and fuel cell systems for different fuels. The resolution of the modeling effort should also be high enough to capture all the effects of interest. Also a fuel cell vehicle model has to be flexible enough to incorporate new trends and technologies without the need to start from the beginning. From a practical point of view, the necessary input data have to be available, the validation of the model should be possible, and the model should support its use as well as the issue of program maintenance.

Close consideration of these requirements and available vehicle simulation software capabilities led to the selection of PSAT as the best candidate for the analysis to be performed in this study. PSAT allows the users to modify the existing strategies or implement new ones, and develop and compare various control strategies. Moreover, when considering the impact of control on HEV, this capability is vital and allowed by the forward-looking philosophy. Forward modeling (driver-to-wheels) more realistically predicts system dynamics, transient component behavior, and vehicle response.

Because PSAT allows realistic control strategy development, the controls can be later implemented in a microcontroller and used to control real components on a bench or in a vehicle. Finally, PSAT also allows parametric study as users can change the value of any parameter or any cycle.

2 PSAT Description

2.1 Forward-looking model software

The Powertrain System Analysis Toolkit (PSAT) is an advanced vehicle powertrain simulation software. PSAT was initiated by the United States Council for Automotive Research (USCAR) in 1995. It was formed by three companies namely, DaimlerChrysler, Ford, and General Motors (GM). In 1999, it was redesigned by ANL to meet the needs of DOE's integrated analysis, hardware-in-the-loop and validation activities. The software builds a complete vehicle model using generic component models including motor, engine, transmission or battery.

The vehicle model architecture is "forward-looking", meaning that component interactions are "real world". The speed and torque calculations are done from the driver to the wheels. PSAT is called a command-based model. The user estimates the necessary torque to be at the desired speed by sending real commands to the components such as throttle for engine, displacement for clutch, gear number for transmission or mechanical braking to the wheel model. In a way, the user can model a driver who follows a pre-defined speed cycle. Moreover, as components react as in reality to the commands, one can implement advanced component models, take into account transient effects or develop realistic control strategies.

On the other hand, in a backward looking model, components cannot be controlled as in reality. The desired vehicle speed goes from the vehicle model to the other components to finally find out how each component should be used to follow the speed cycle. Because of this model organization, one can only use quasi-steady models (transient effects such as engine starting, clutch engagement/disengagement, or shifting can not be taken into account). No accurate control application is then possible with a backward looking model.

To be able to study transient effects and interaction between components with accurate control commands, ANL has developed PSAT as a forward-looking model.

2.2 Component models organization

All the component models used by PSAT are stored in libraries. To easily exchange the models and implement new ones, a common format, based on Bond Graph, is used between the input/output of the power ports, as shown in Figure 10.

The first ports are used for the information:

- Input: components commands (on/off engine, gear number, etc.)
- Output (sensors): simulated measures (torque, rotational speed, current, voltage, etc.)

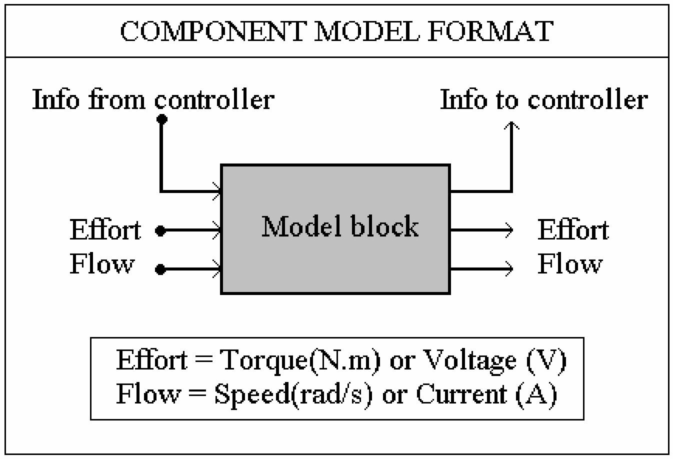


Figure 10: Formalism of the models I/O using Bond Graph.

The second ports carry the effort (i.e., voltage, torque) and the last ones, the flow (i.e., current, speed).

When configuration models and initialization files are selected, the user first opens the model libraries, then imports the component and finally builds the complete powertrain by linking the components accordingly to user's choice.

As an example, it is interesting to look at a PSAT parallel configuration model to understand the interest of the use of a library and standard format (Figure 11).

The driver sends an accelerator or brake pedal command to the vehicle powertrain controller, which is in fact the brain of the vehicle as it sends commands to the rest of the drivetrain and decides what is the best blending between the engine and the motor, when and how do we start the engine, etc.

Indeed, the powertrain controller will ask for some torque to the electric motor, a throttle command to the engine, a displacement command to the clutch, a gear number to the transmission and a mechanical brake command to the wheels.

Then, the mechanical power from the engine and the electrical power from the motor via the battery are summed. In fact, both of those powers, mechanical and electrical are used to propel the vehicle.

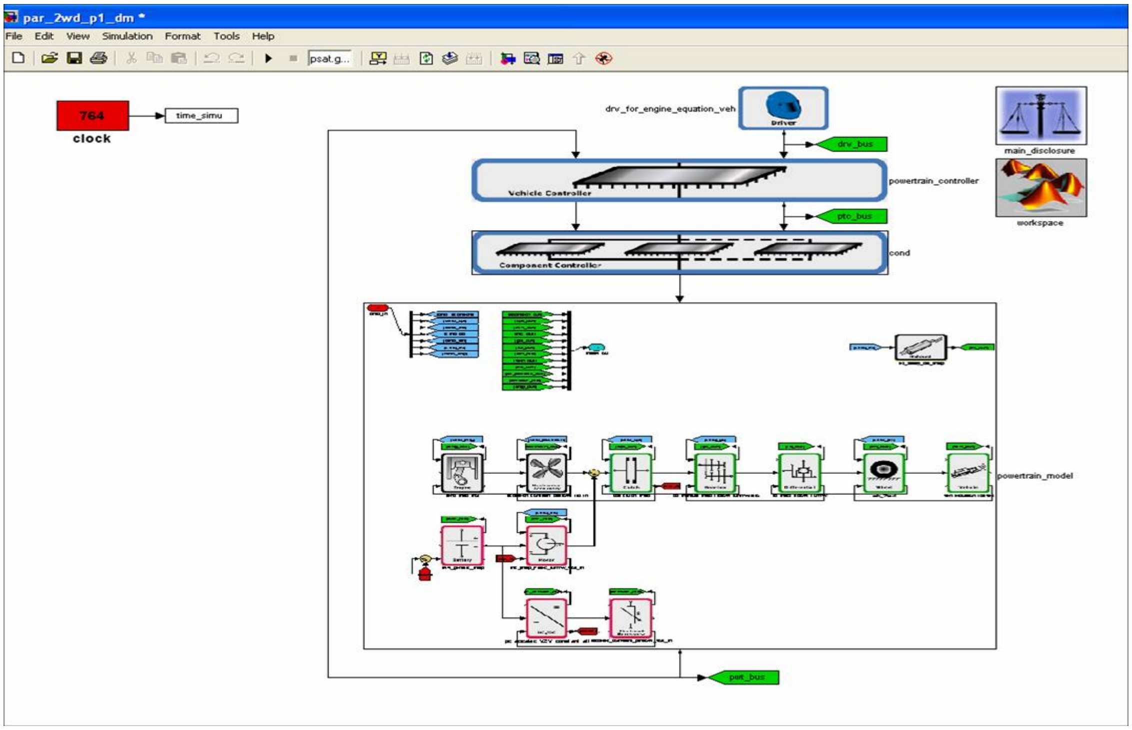


Figure 11: Starter-alternator parallel configuration in PSAT.

2.3 Control strategy organization

PSAT powertrain controllers, in charge of commanding the different components, have a generic structure common to all configurations, as shown in Figure 12 below:

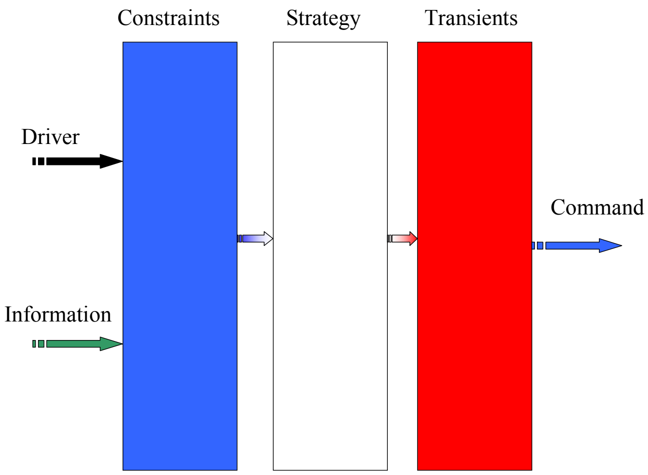


Figure 12: PSAT controller architecture.

- Constraints block: By using the accelerator pedal and the information (sensors) coming from the component models, the constraints of the system such as the maximum available torque of the engine can be evaluated.
- Strategy block: Then those limits are used to define the optimized control strategy, which decides the best way to command the components of the powertrain to minimize fuel consumption and emissions.
- Transient block: Finally, the transients are taken into account by defining the actions to do in order to satisfy the control strategy demands. For instance, if the control strategy decided to shift gear with a manual transmission, one would have to cut off the engine ignition, declutch, engage the neutral gear, engage the new gear, clutch and inject once again. These steps have to happen successively and lead to a modification of the command previously sent by the control strategy.

The outputs of the transient block (powertrain controller outputs) go to a conditioning block (component control unit), which calculates the commands that will be sent to the components.

2.4 Graphical User Interface (GUI)

PSAT includes more than 300 predefined configurations, including conventional vehicles, parallel hybrids, series hybrids, fuel cell hybrids, power split hybrids and series-parallel hybrids. The wide range of configurations proposed in PSAT allows users to choose the most appropriate configuration related to their requirements.

In PSAT, different steps are necessary to perform a simulation. The steps are described next.

- Define the powertrain

This tab allows the user to build his vehicle. First, he/she chooses the configuration among conventional, parallel, series, fuel cell hybrids vehicles, then the components and their characteristics. For each component, there are:

  - Several versions, which correspond to different technologies such as automatic or manual gearbox for the transmission
  - Several types such as spark ignition and compressed ignition for the engine, and
  - Several initialization files

For a particular version and type, many initialization files can be available to give a choice for the component size. Even if the size expected is not available in the list, one can scale the components.

Once the vehicle is defined, it is possible to modify some parameters, such as the vehicle mass, or the initial battery state of charge.

- Select the type of simulation

The interface also allows the user to select his control strategy and its parameters. He can choose between a performance test, a standard cycle, a combination of cycles or a parametric study. When the selection is done, the simulation can start.

- Analyze the results

This tab contains the results of the simulation. All the data calculated either in the models or in the strategy are accessible. They can be plotted, analyzed and compared. The fuel economy is also determined from the fuel rate, the initial and final states of charge are given as well as component efficiencies. It is even possible to replay the simulation in order to better understand one part of the cycle or to compare simulation with test data for example.

A picture of the interface is provided in Figure 13 below.

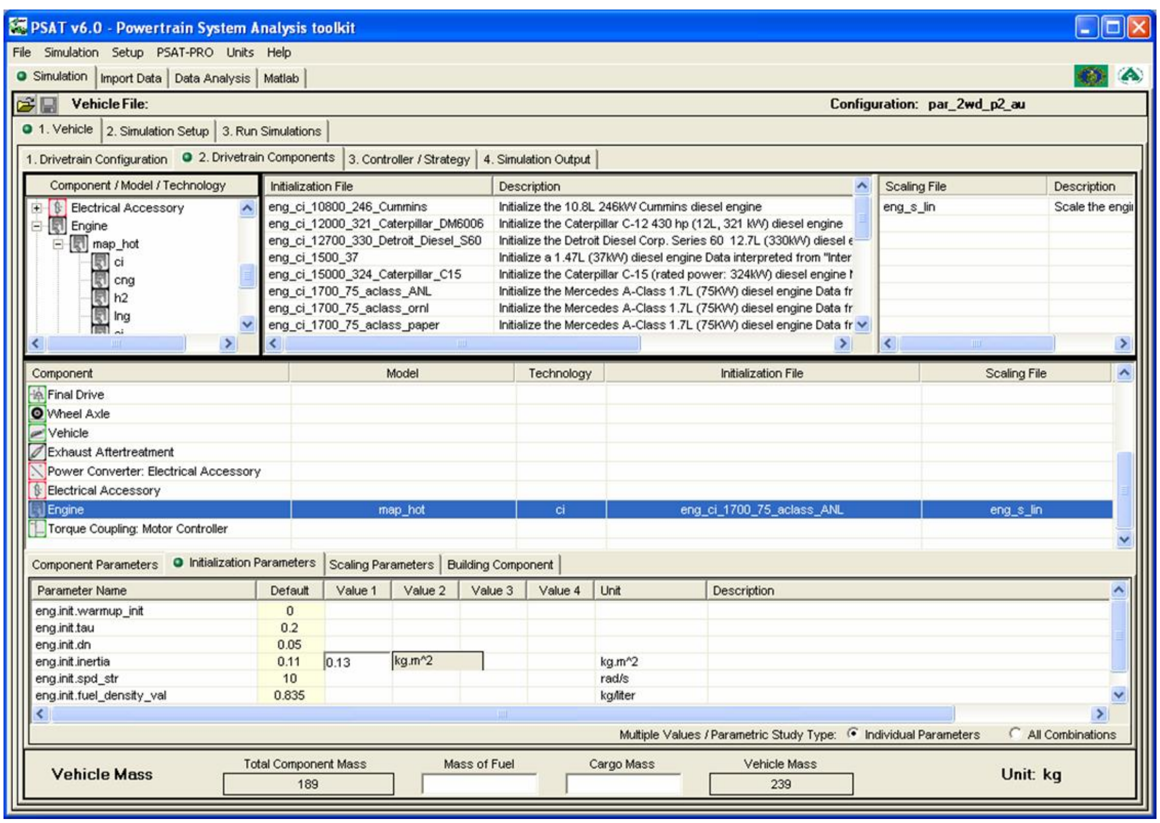


Figure 13: PSAT GUI - Component selection.

3 Simulation Analysis

3.1 Description

This study analyzed candidate hydrogen-fueled vehicles for near and long-term use in terms of their efficiency, performance, and emissions. Various types of hydrogen-fueled vehicles were assessed, from currently available technology to technologically feasible future vehicle technologies. These technologies include: hythane- and hydrogen-fueled internal combustion engines (ICEs); hydrogen-fueled hybrid electric propulsion, and direct hydrogen fuel cells.

The hydrogen-fueled ICE, hybrid and fuel cell vehicles were modeled and simulated using Argonne's vehicle simulation model PSAT. Vehicle sizes and configurations consistent with the available component models/data were simulated to compare efficiency and emissions with baseline conventional vehicles. The simulations provided detailed results on the vehicle characteristics, performance, efficiency, and emissions profiles as functions of operating conditions on standard driving cycles.

3.1.1 Hypothesis

A compact vehicle platform was selected for the study. The reference vehicle characteristics are described in Table 2:

Component	Parameter	Value
Gasoline Engine	Power (kW)	107
	Peak efficiency (%)	0.34
Automatic Transmission	Ratios	2.8,1.5,1,0.7
Tire	Radius (m)	0.31
Vehicle	Frontal Area (m^2)	2.06
	Drag Coefficient	0.31
	Test Mass (kg)	1371

Table 2: Reference Vehicle Characteristics.

Several additional powertrain configurations have been developed to study the impact of advanced technologies on the fuel economy, including

- Conventional with hydrogen ICE
- Power split with Otto and Atkinson cycles
- Fuel cell only, and
- Fuel cell hybrid

Each configuration details are provided in Appendix 1.

3.2 Methodology Assumptions

Several studies 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 s +/-0.2 s and maximum speed >100 mph). Other studies [19] took the approach of keeping a constant powertrain-specific power, but this does not adequately consider the different torque characteristics of each component technology.
- The results for a powertrain configuration or technology are dependent on the driving schedule; each of the 6 options have been simulated on the Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Driving Schedule (FHDS) and the US06.
- Powertrain efficiencies have been provided to remove the influence of powertrain, vehicle weight, and body structures.
- 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.
- Each cycle is run with a State-Of-Charge (SOC) Correction algorithm for the hybridized vehicles to ensure a charge sustaining control.

3.3 Parametric Analysis

3.3.1 Methodology

The purpose of this analysis is to determine the impact of vehicle design characteristics on the performance of a hydrogen fueled vehicle to evaluate the uncertainties related to future technologies. The simulations were performed using a conventional vehicle. A parametric study was performed on the following parameters:

- Vehicle mass : 1800, 2000, 2200, 2400, 2500, 2600, 2800, and 3000 (kg)
- Drag coefficient varied from 0.45 to 0.54 with 0.03 increments
- Wheel radius varied from 0.36 m to 0.40 m with 0.01 increments
- Final drive ratio varied between 3.5 and 4.1 with 0.1 increments.

The simulations were performed on automotive industry standard drive cycles. They included the US06, FHDS, FUDS, and performance driving cycles. The US06 driving cycle represents an aggressive driving cycle with high speeds and quick acceleration. The FHDS driving cycle is used to simulate typical highway driving conditions, whereas the FUDS cycle represents driving conditions at an urban rate. In this research, the FTP75, which is based on a combination of FUDS and FHDS, is also considered.

The simulation is performed in 3 steps. First the reference vehicle characteristics are loaded, then the driving cycles are selected, and finally the parameters used for the parametric study are selected. The results from each simulation run were tabulated into a summary spreadsheet. PSAT allows users to automatically export the simulation results from Matlab to EXCEL. A total of 81 simulation runs were performed. Table 3 summarizes the number of simulations for each parameter.

PSAT offers the possibility to access the results graphically (GUI) and in text format with a Matlab command prompt. The simulation outputs are categorized by simulation type (e.g., fuel economy, performance…) and component (e.g., vehicle, engine, energy storage…). This study focused on the impact of hydrogen-fueled vehicle parameter values on fuel economy and engine efficiency. The next section summarizes the results from the parametric analysis.

Parameter	No. of Increments (a)	No. of Driving Cycles (c)	Total No. of Simulations (a x b x c)
Mass Of Vehicle	8	3	24
Frontal Area	4	3	12
Drag Coefficient	4	3	12
Wheel Radius	5	3	15
Final Drive	6	3	18
		Total	**81**

Table 3: Total Number of Simulations

3.3.2 Results

3.3.2.1 Impact on Fuel Economy

The simulation results are presented in the following section. The fuel economy is provided in miles per gallon gasoline equivalent (mpgge). The impact of vehicle mass (increment of 200 kg) is presented in Table 4. As expected, an increase in mass lead to a decrease in fuel economy, independently of the driving cycle. It is interesting to notice an increase in average engine efficiency during the same time, which is not sufficient to overcome the increase in vehicle losses.

Mass / Cycle	1800	2000	2200	2400	2600	2800	3000
FUDS	16.46	15.92	15.36	14.88	14.42	14.01	13.60
FHDS	23.83	23.21	22.63	22.07	21.53	20.99	20.47
Combined	19.13	18.55	17.96	17.44	16.94	16.48	16.03
US06	19.00	18.32	17.69	17.131	16.55	16.10	15.65

Table 4: Fuel Efficiency (miles/gal) vs. Mass of Vehicle (kg).

The results were plotted in Figure 14 and show that the fuel efficiency decreases linearly in all the cycles and there is uniform variation with almost equal slope. This is not surprising because lighter vehicle typically need less fuel to move around. For the same vehicle mass, the FHDS cycle gives the best fuel efficiency, whereas the FUDS demonstrates the poorest fuel efficiency compared to all other driving cycles tested.

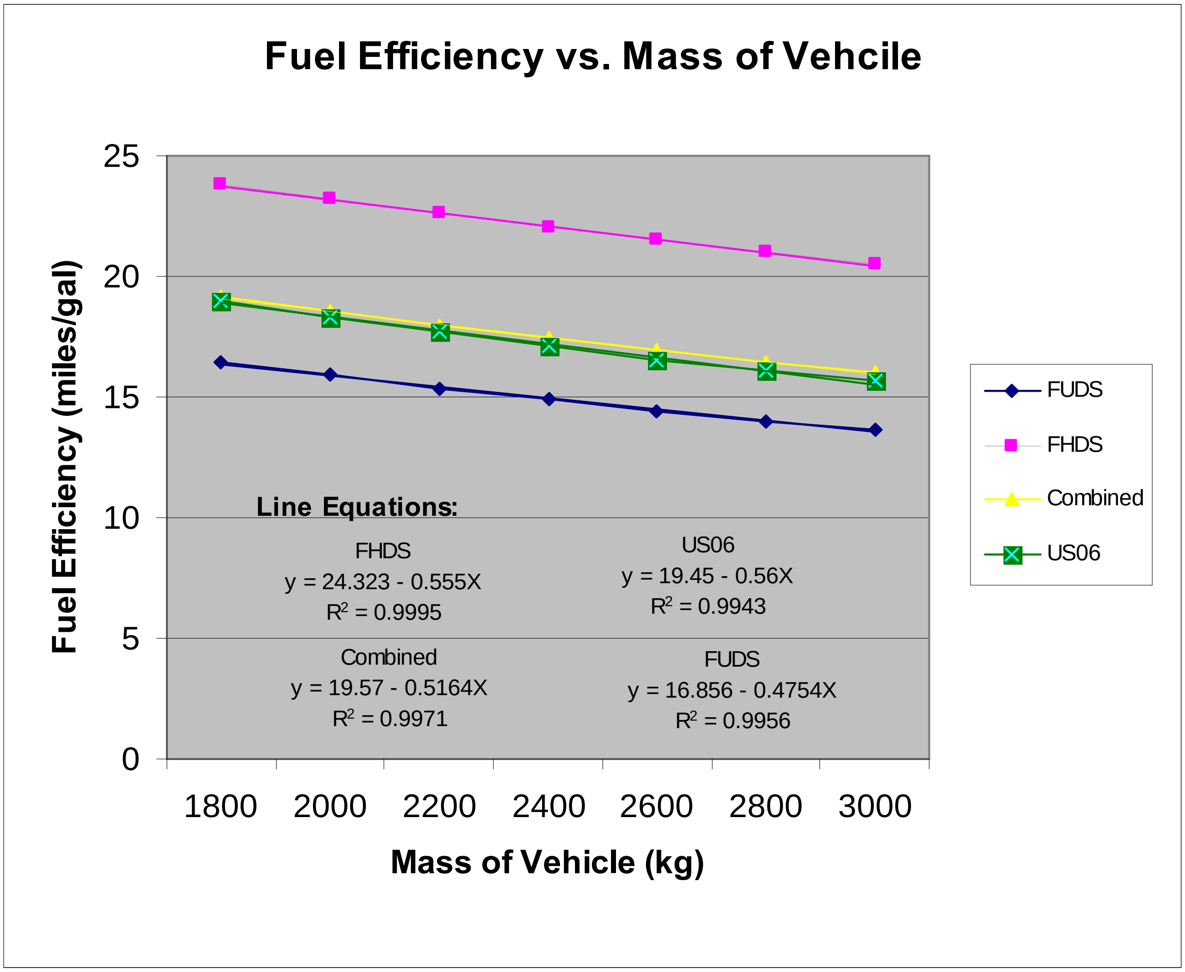


Figure 14: Fuel Efficiency vs. Mass of Vehicle.

Table 5 and Figure 15 summarize the relationship between vehicle wheel radius and fuel efficiency of a hydrogen fueled vehicles. When the vehicle wheel radius is varied between 0.36 and 0.41 in 0.01 increments, it was observed that the fuel efficiency increases. This was true for all the driving cycles tested in the simulation experiments.

Cycle \ Wheel Radius	0.36	0.37	0.38	0.39	0.40
FUDS	14.23	14.42	14.60	14.75	14.91
FHDS	21.20	21.47	21.72	21.97	22.17
Combined	16.70	16.92	17.13	17.31	17.50
US06	16.45	16.65	16.83	16.93	17.08

Table 5: Fuel Efficiency (miles/gal) vs. Mass of Vehicle (kg).

Figure 15 clearly shows that there is a uniform variation for all the driving cycles tested and the rate of increase (slope) is almost equal for all cycles. However, it should be noted

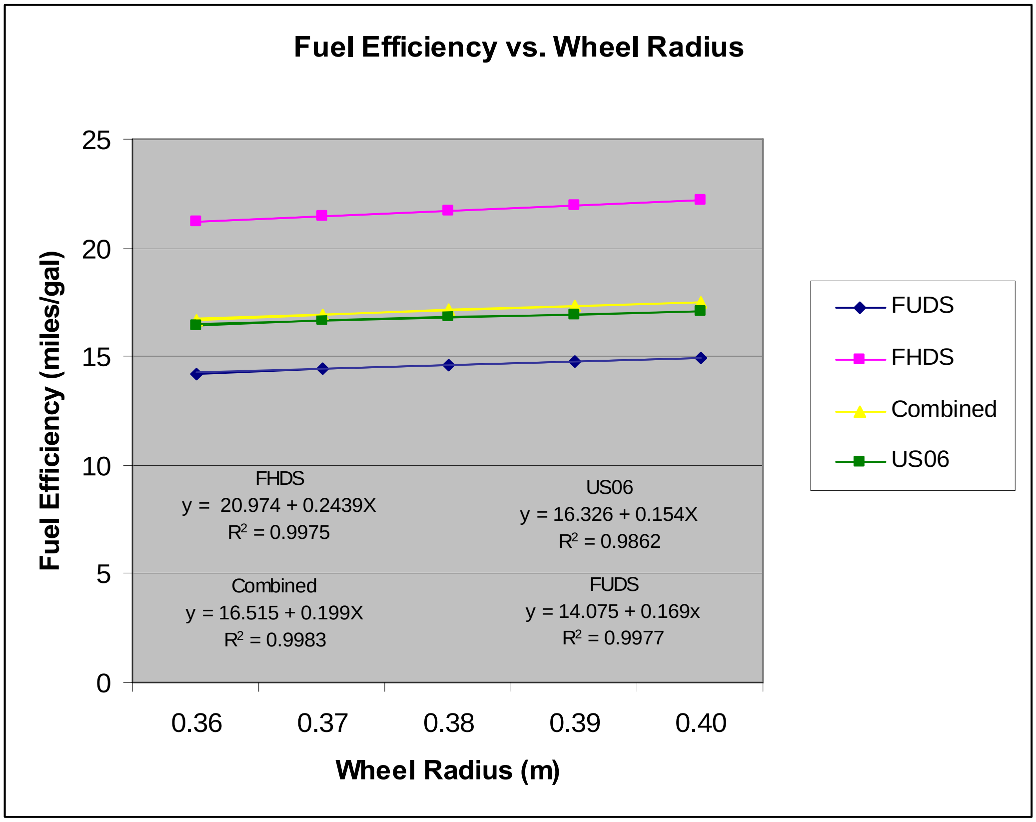


Figure 15: Fuel Efficiency vs. Wheel Radius.

that there was an increase in fuel economy, although not a significant one, as was also the case of the vehicle mass above.

Simulations were performed to analyze the impact of the drag coefficient on fuel efficiency for a hydrogen-fueled vehicle. The results are tabulated in Table 6 and are plotted in Figure 16.

Drag Co-eff. / Cycle	0.45	0.48	0.51	0.54
FUDS	14.63	14.55	14.48	14.41
FHDS	21.66	21.26	20.88	20.51
Combined	17.13	16.97	16.80	16.64
US06	16.76	16.46	16.18	15.91

Table 6: Fuel Efficiency (miles/gal) with Change in Drag Coefficient.

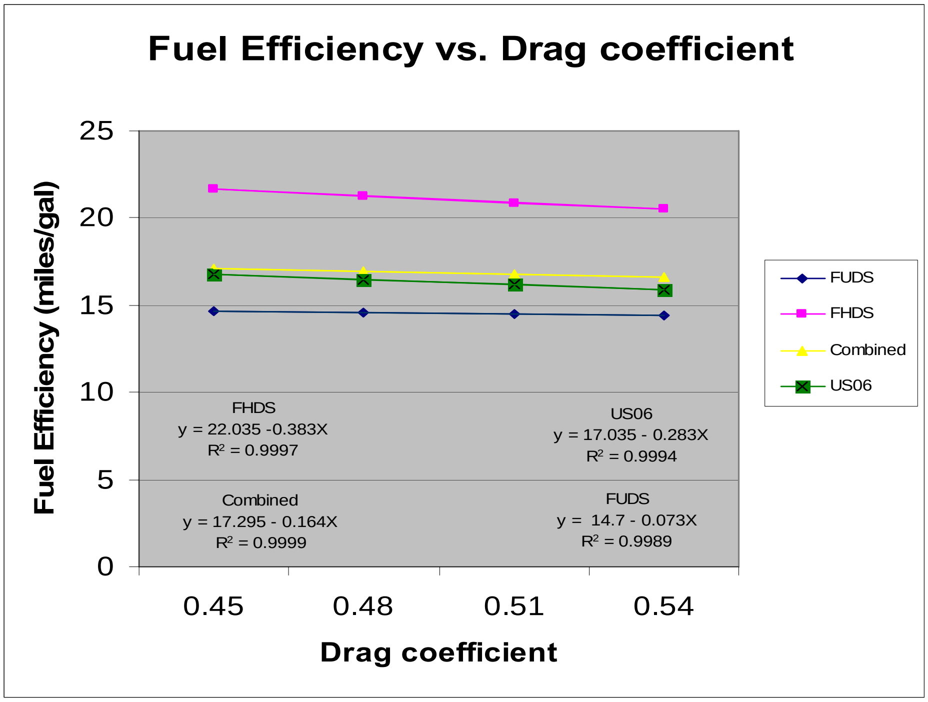


Figure 16: Fuel Efficiency vs. Drag Coefficient.

When the drag coefficient is varied between 0.45 and 0.54 at 0.03 intervals, the fuel efficiency decreased. For the FUDS and Combined cycles the variation was small (less than one mile per gallon) and for FHDS and US06 cycles, the variation was slightly higher (over a mile per gallon).

The results from simulation runs where final drive varied between 3.5 and 4.1 at an increment of 0.1 are summarized in Table 7 and Figure 17. It was found that the fuel efficiency decreased linearly. The behavior was consistent with all driving cycles tested and the decrease was considerable as compared to other parameter variation.

Final Drive / Cycle	3.5	3.6	3.7	3.8	3.9	4.1
FUDS	15.05	14.83	14.63	14.42	14.20	13.97
FHDS	22.34	22.06	21.77	21.47	21.16	20.84
Combined	17.64	17.40	17.17	16.92	16.67	16.41
US06	17.30	17.05	16.86	16.64	16.44	16.22

Table 7: Fuel Efficiency (miles/gal) with Change in Final Drive

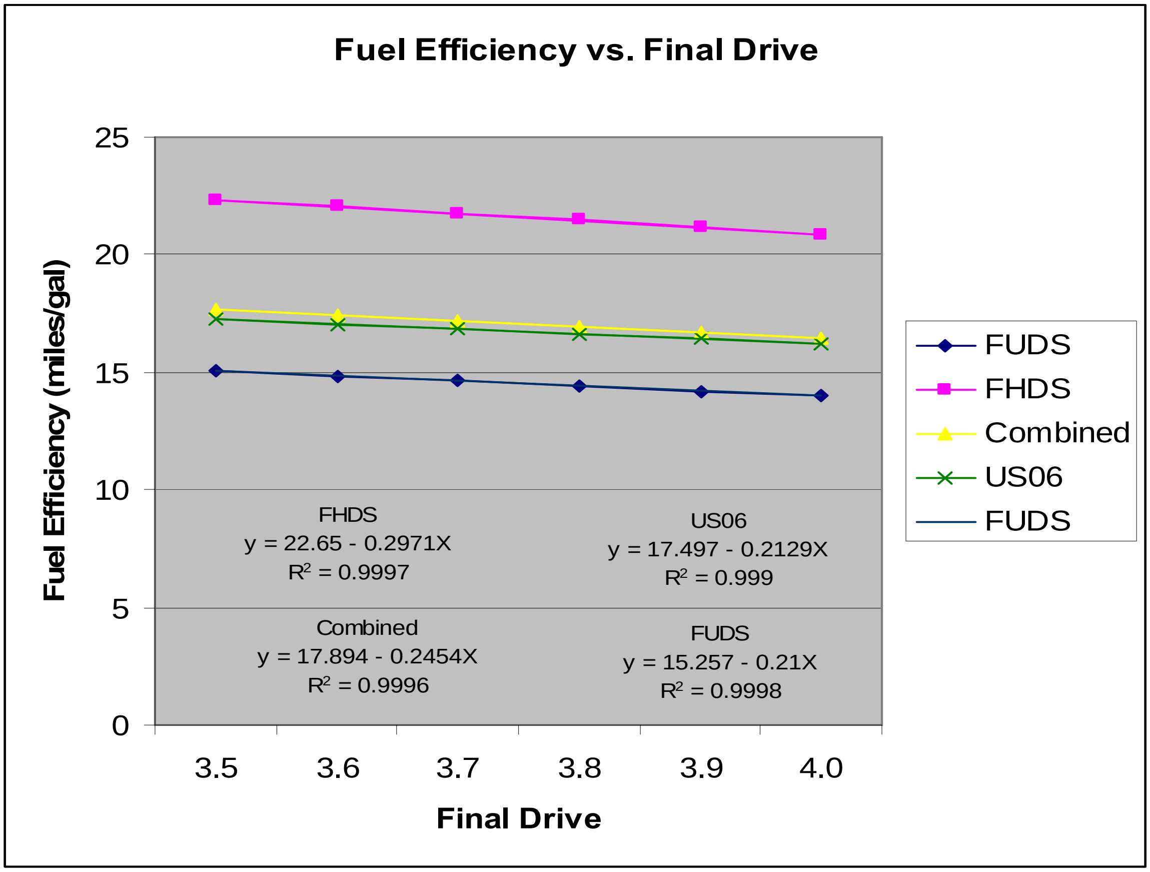


Figure 17: Fuel Efficiency vs. Final Drive

3.3.2.2 Impact on engine efficiency

The effect of variation of the parameters was also tested on the engine efficiency. Engine efficiency is the amount of power developed as compared to the energy input which is measured by the heating value of the fuel consumed. Ever since the invention of the internal combustion engine, scientists and engineers have worked to increase its efficiency. As it stands now, the average internal combustion automobile engine only converts roughly 20% of its energy into useful motivational power. Most of the rest is expended through heat loss in various locations.

The results from the simulation runs that show the correlation between hydrogen vehicle mass and engine efficiency are summarized in Table 8 and Figure 18. It can be observed that when the mass of the vehicle is varied from 1800 to 3000 kg, the engine efficiency increased linearly. The behavior is the same in all the driving cycles tested. The US 06 cycles gave the maximum efficiency of 31.89% for 3000 kg mass.

Analysis of the impact of wheel radius on engine efficiency demonstrates that when wheel radius is varied between 0.36 and 0.40m, the engine efficiency increases linearly

Mass / Cycle	1800	2000	2200	2400	2600	2800	3000
FUDS	19.89	20.52	21.06	21.63	22.13	22.67	23.13
FHDS	26.44	26.89	27.31	27.72	28.10	28.83	28.74
Combined	23.17	23.71	24.19	24.68	25.12	25.75	25.94
US06	30.56	30.91	31.20	31.47	31.55	31.77	31.89

Table 8: Engine Efficiency (%) with Change in Mass of Vehicle (kg).

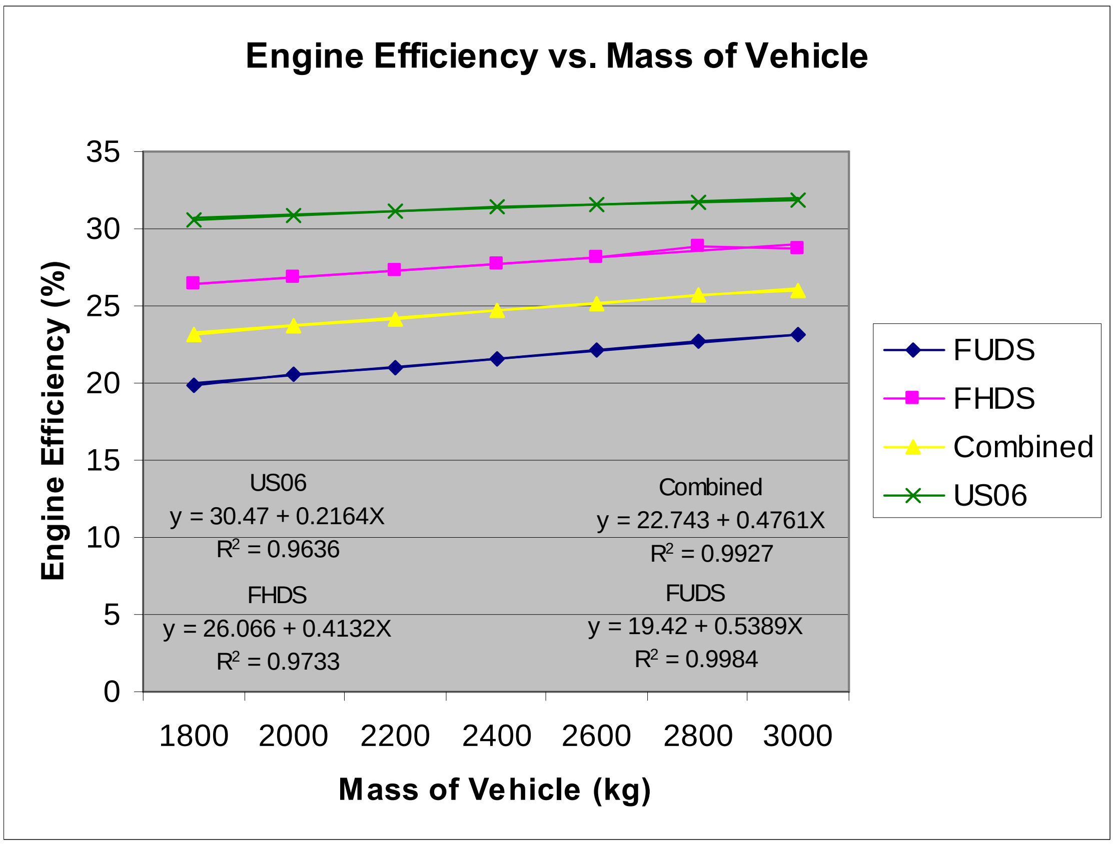


Figure 18: Engine Efficiency vs. Mass of Vehicle.

for all the driving cycles tested. As Table 9 and Figure 19 demonstrate, the US06 cycle gave a maximum efficiency of 31.77% for a 0.40 m wheel radius.

Wheel Radius / Cycle	0.36	0.37	0.38	0.39	0.40
FUDS	21.29	21.66	21.82	22.04	22.28
FHDS	27.18	27.51	27.83	28.12	28.39
Combined	24.24	24.59	24.83	25.08	25.34
US06	31.10	31.31	31.53	31.62	31.77

Table 9: Engine Efficiency (%) with Change in Wheel Radius (m).

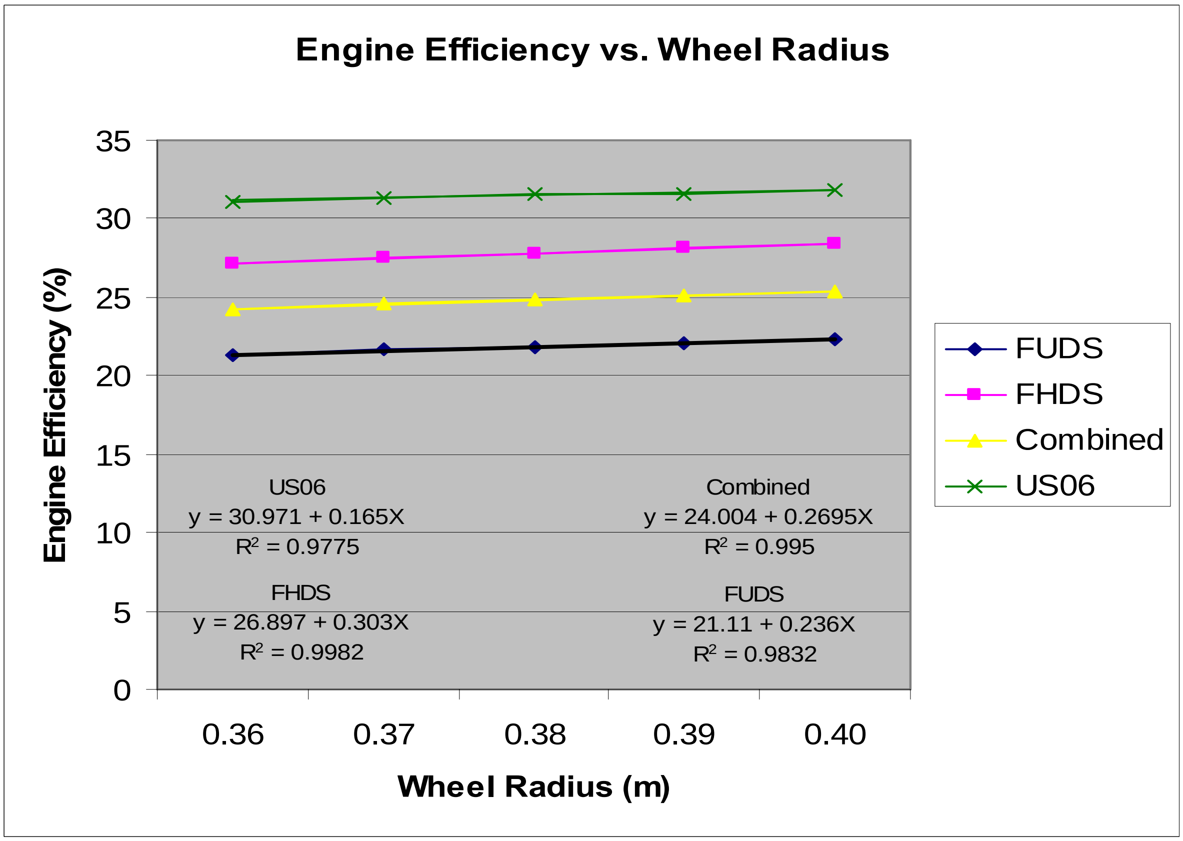


Figure 19: Engine Efficiency vs. Wheel Radius.

When the drag coefficient is varied between 0.45 and 0.54, the engine efficiency increased linearly for all the cycles, with the US 06 cycle giving a maximum efficiency of 32.27% for a drag coefficient of 0.54. The results of the analysis are shown in Table 10 and Figure 20, and confirm that the impact of drag coefficient on engine efficiency is small, compared to the impact of other parameters such as the vehicle mass.

Cycle \ Drag Co-eff.	0.45	0.48	0.51	0.54
FUDS	21.93	22.04	22.15	22.25
FHDS	28.02	28.33	28.62	28.91
Combined	24.98	25.19	25.39	25.58
US06	31.64	31.86	32.06	32.27

Table 10: Engine Efficiency (%) with Change in Drag Coefficient.

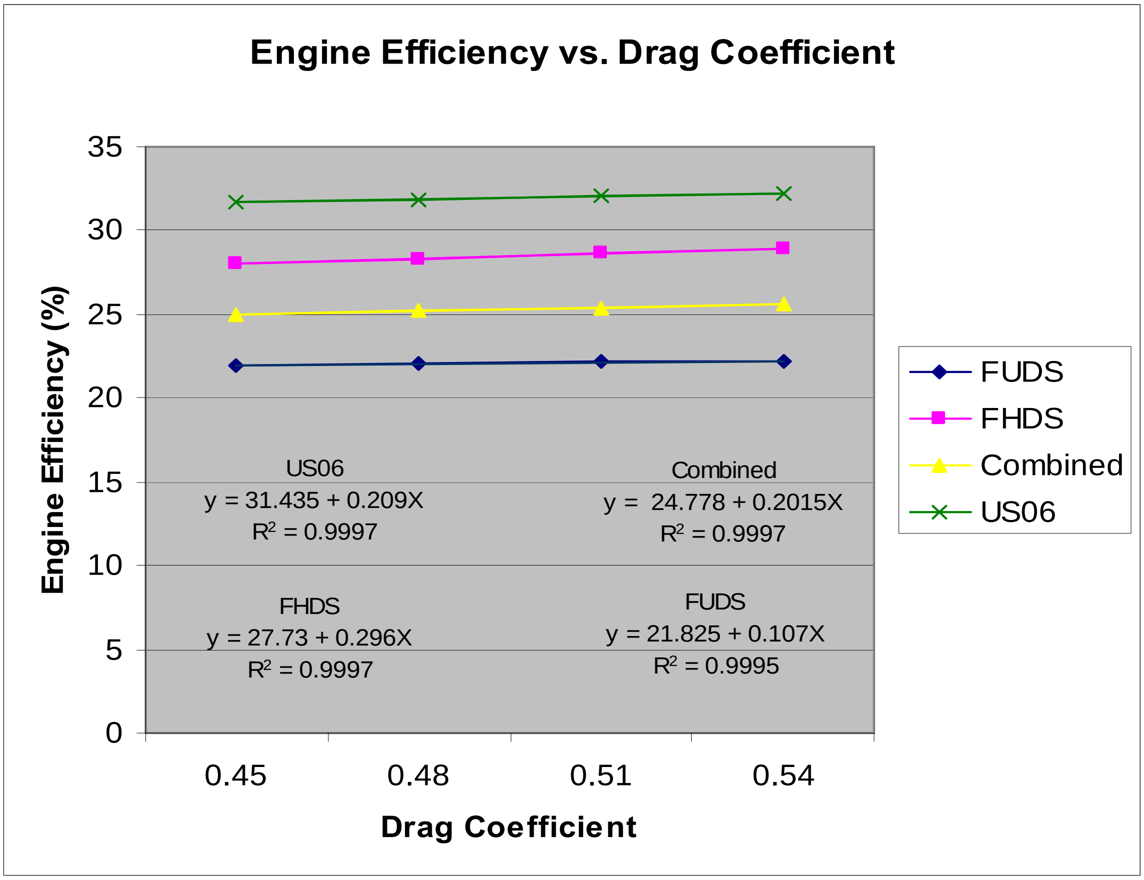


Figure 20: Engine Efficiency vs. Drag Coefficient.

Further analysis was performed to study the impact of the final drive ratio on engine efficiency. The results are shown in Table 11 and Figure 21. When the final drive ratio was varied from 3.5 to 4.0 the efficiency of the engine decreased. This was consistent in all the driving cycles tested. The US 06 driving cycle still gave the highest efficiency of 32.04% at a 3.5 final drive ratio.

Cycle \ FD Ratio	3.50	3.60	3.70	3.80	3.90	4.00
FUDS	22.48	22.16	21.87	21.55	21.24	20.92
FHDS	28.60	28.24	27.89	27.51	27.14	26.77
Combined	25.54	25.20	24.88	24.53	24.19	23.85
US06	32.04	31.78	31.56	31.29	31.03	30.72

Table 11: Engine Efficiency with Change in Final Drive.

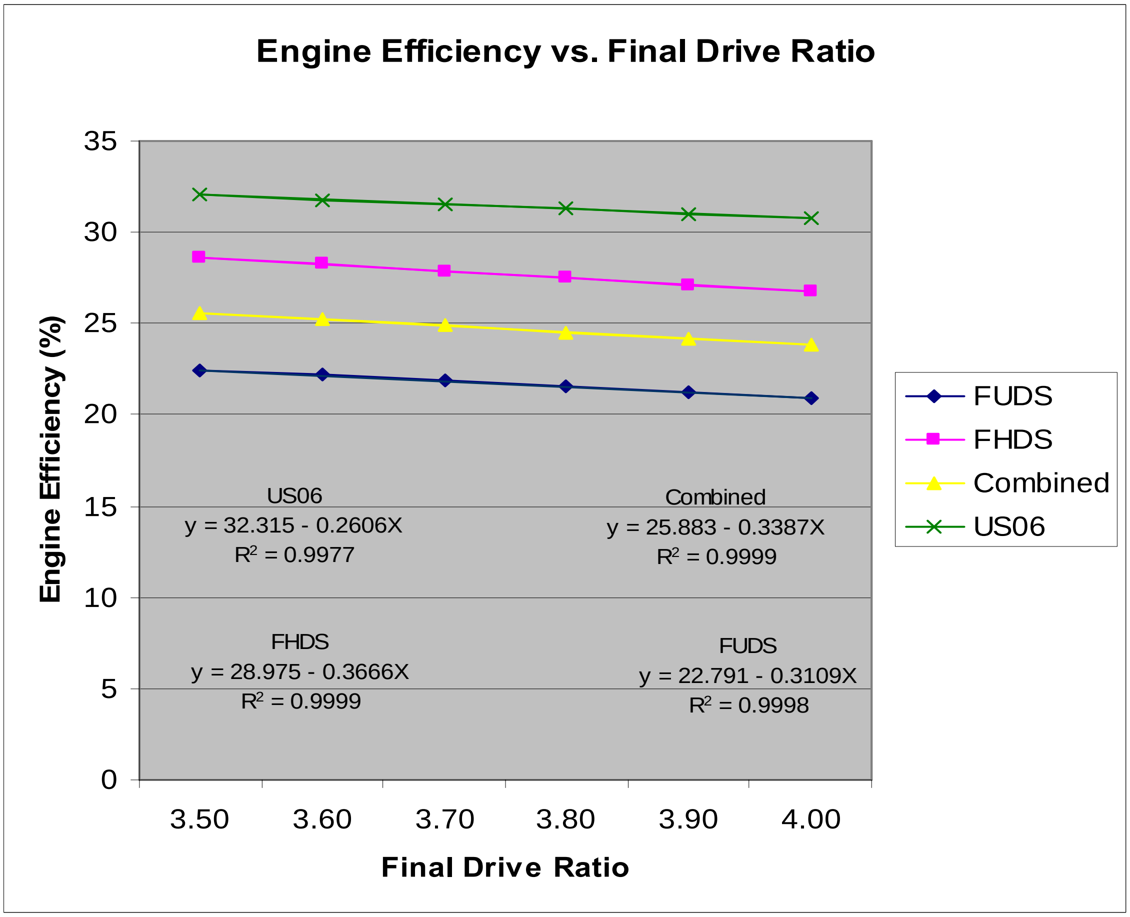


Figure 21: Engine Efficiency vs. Final Drive Ratio.

From this study it can be concluded that hydrogen vehicles are good alternative fuel engines and they perform very well. The performance of the hydrogen vehicles is better than the regular internal combustion engines based on the engine efficiency results. Standard internal combustion engines convert only 20% of their energy into useful power. In case of hydrogen vehicles, the engine efficiency is always greater than that mark, registering above 30% for the US06 driving cycle. The summary of the simulation results from the parametric analysis are shown in Tables 12 and 13.

Effected Investigation	Driving Cycle	Linear Trend Line	Correlation Coefficient
Fuel Efficiency vs. Mass of Vehicle	FUDS	y = 16.856 - 0.4754X	0.9956
	FHDS	y = 24.323 - 0.555X	0.9995
	Combined	y = 19.57 - 0.5164X	0.9971
	US06	y = 19.45 - 0.56X	0.9943
Fuel Efficiency vs. Wheel Radius	FUDS	y = 14.075 + 0.169X	0.9977
	FHDS	y = 20.974 + 0.2439X	0.9975
	Combined	y = 16.515 + 0.199X	0.9983
	US06	y = 16.326 + 0.154X	0.9862
Fuel Efficiency vs. Drag Coefficient	FUDS	y = 14.7 - 0.073X	0.9989
	FHDS	y = 22.035 -0.383X	0.9997
	Combined	y = 17.295 - 0.164X	0.9999
	US06	y = 17.035 - 0.283X	0.9994
Fuel Efficiency vs. Final Drive Ratio	FUDS	y = 15.257 - 0.21X	0.9998
	FHDS	y = 22.65 - 0.2971X	0.9997
	Combined	y = 17.894 - 0.2454X	0.9996
	US06	y = 17.497 - 0.2129X	0.999

Table 12: Summary of Simulation Results - Fuel Efficiency Analysis

Effected Investigation	Driving Cycle	Linear Trend Line	Correlation Coefficient
Engine Efficiency vs. Mass of Vehicle	FUDS	y = 19.42 + 0.5389X	0.9984
	FHDS	y = 26.066 + 0.4132X	0.9733
	Combined	y = 22.743 + 0.4761X	0.9927
	US06	y = 30.47 + 0.2164X	0.9636
Engine Efficiency vs. Wheel Radius	FUDS	y = 21.11 + 0.236X	0.9832
	FHDS	y = 26.897 + 0.303X	0.9982
	Combined	y = 24.004 + 0.2695X	0.995
	US06	y = 30.971 + 0.165X	0.9775
Engine Efficiency vs. Drag Coefficient	FUDS	y = 21.825 + 0.107X	0.9995
	FHDS	y = 27.73 + 0.296X	0.9997
	Combined	y = 24.778 + 0.2015X	0.9997
	US06	y = 31.435 + 0.209X	0.9997
Engine Efficiency vs. Final Drive Ratio	FUDS	y = 22.791 - 0.3109X	0.9998
	FHDS	y = 28.975 - 0.3666X	0.9999
	Combined	y = 25.883 - 0.3387X	0.9999
	US06	y = 32.315 - 0.2606X	0.9977

Table 13: Summary of Simulation Results – Engine Efficiency Analysis.

Statistical analysis, using t-test was performed to evaluate if the driving cycle had an impact on the fuel economy and engine efficiency as the vehicle mass, wheel radius, drag coefficient, frontal area, and final drive ratio changed. The test was performed using two hypotheses. Hypotheses H_0 states that the means from each pair of driving cycles is not equal which implies that the parametric variation has an influence on the fuel efficiency and engine efficiency. Alternate hypothesis H_1 states that the means from each pair of driving cycles is equal, which implies that the parametric variation has no influence on the fuel and engine efficiency.

The probability of the mean being constant for a pair of driving cycles was measured using α, where the α value determined if the means of the pair of driving cycles were the same or not. A t-value for 95% confidence level (α = .05) is compared with the calculated t-value. If the calculated t-value is greater than the 95% confidence level value (t-table), the hypothesis is accepted. The summary of the t-test results is shown in Tables 14 and 15 for fuel efficiency and engine efficiency respectively. In most cases, H_0 was accepted,

Simulation	Comparison	x1	x2	t (calculated)	t (table for α = .05)	Accept / Reject
Fuel Efficiency vs. Mass of Vehicle	FUDS vs. FHDS	14.95	22.10	11.90	1.94	Accept
	FUDS vs. Combined	14.95	17.50	4.40	1.94	Accept
	FUDS vs. US06	14.95	17.21	3.75	1.94	Accept
	FHDS vs. Combined	22.10	17.50	7.42	1.94	Accept
	FHDS vs. US06	22.10	17.21	7.59	1.94	Accept
	US06 vs. Combined	17.21	17.50	7.23	1.94	Accept
Fuel Efficiency vs. Wheel Radius	FUDS vs. FHDS	14.58	21.71	33.90	2.13	Accept
	FUDS vs. Combined	14.58	17.11	13.69	2.13	Accept
	FUDS vs. US06	14.58	16.78	13.59	2.13	Accept
	FHDS vs. Combined	21.71	17.11	24.04	2.13	Accept
	FHDS vs. US06	21.71	16.78	20.61	2.13	Accept
	US06 vs. Combined	***16.78***	***17.11***	***1.81***	***2.13***	***Reject***
Fuel Efficiency vs. Drag Co-Efficient	FUDS vs. FHDS	14.51	21.07	26.06	2.13	Accept
	FUDS vs. Combined	14.51	16.88	20.42	2.13	Accept
	FUDS vs. US06	14.51	16.32	9.59	2.13	Accept
	FHDS vs. Combined	21.07	16.88	15.58	2.13	Accept
	FHDS vs. US06	21.07	16.32	15.44	2.13	Accept
	US06 vs. Combined	16.32	16.88	2.60	2.13	Accept
Fuel Efficiency vs. Final Drive	FUDS vs. FHDS	14.52	21.60	25.17	1.81	Accept
	FUDS vs. Combined	14.52	17.03	10.12	1.81	Accept
	FUDS vs. US06	14.52	16.75	9.68	1.81	Accept
	FHDS vs. Combined	21.60	17.03	15.44	1.81	Accept
	FHDS vs. US06	21.60	16.75	17.27	1.81	Accept
	US06 vs. Combined	***16.75***	***17.03***	***1.14***	***1.81***	***Reject***

Table 14: Summary of Simulation Results – Fuel Efficiency Statistical Analysis.

Simulation	Comparison	x1	x2	t (calculated)	t (table for α = .05)	Accept / Reject
Engine Efficiency vs. Mass of Vehicle	FUDS vs. FHDS	21.57	27.72	11.01	1.94	Accept
	FUDS vs. Combined	21.57	24.65	5.23	1.94	Accept
	FUDS vs. US06	21.57	31.33	20.50	1.94	Accept
	FHDS vs. Combined	27.72	24.65	5.92	1.94	Accept
	FHDS vs. US06	27.72	31.33	9.36	1.94	Accept
	US06 vs. Combined	31.33	24.65	2.02	1.94	Accept
Engine Efficiency vs. Wheel Radius	FUDS vs. FHDS	21.82	27.81	21.96	2.13	Accept
	FUDS vs. Combined	21.82	24.82	11.78	2.13	Accept
	FUDS vs. US06	21.82	31.46	4.69	2.13	Accept
	FHDS vs. Combined	27.81	24.82	10.42	2.13	Accept
	FHDS vs. US06	27.81	31.46	14.95	2.13	Accept
	US06 vs. Combined	31.46	24.82	29.65	2.13	Accept
Engine Efficiency vs. Drag Coefficient	FUDS vs. FHDS	22.09	28.47	31.38	2.13	Accept
	FUDS vs. Combined	22.09	25.28	21.79	2.13	Accept
	FUDS vs. US06	22.09	31.95	65.07	2.13	Accept
	FHDS vs. Combined	28.47	25.28	12.05	2.13	Accept
	FHDS vs. US06	28.47	31.95	14.34	2.13	Accept
	US06 vs. Combined	31.95	25.28	32.58	2.13	Accept
Engine Efficiency vs. Final Drive	FUDS vs. FHDS	21.69	27.68	16.32	1.81	Accept
	FUDS vs. Combined	21.69	24.69	8.52	1.81	Accept
	FUDS vs. US06	21.69	31.40	31.15	1.81	Accept
	FHDS vs. Combined	27.68	24.69	7.86	1.81	Accept
	FHDS vs. US06	27.68	31.40	10.80	1.81	Accept
	US06 vs. Combined	31.40	24.69	20.56	1.81	Accept

Table 15: Summary of Simulation Results – Engine Efficiency Statistical Analysis

indicating that the driving cycle has an impact on fuel efficiency and engine efficiency. The tests where the alternative hypothesis is accepted are identified in bold italics. From all parameters tested, vehicle mass appears to have the greater impact on fuel efficiency and engine efficiency.

It should be noted that validation of the simulation model with field data was desirable but not feasible due to lack of field data availability. Still the findings of this study are of value as the PSAT model has been previously tested and validated successfully and is extensively used for simulation analyses by the automobile industry. Some examples of validation are [20]:

- Ford Taurus 97 3.0L V6 has been validated within limits of test capabilities (1% fuel efficiency, 10% emissions).

- Japan Prius and Honda Insight fuel economy and SOC validated within 5% for several driving cycles.
- Ford P2000 validated within 5% for fuel economy and SOC.
- Japan Prius, Honda Insight and Ford P2000 validations have been realized with the Advanced Powertrain Research Facility (APRF) Data.

With these factors in view, the results obtained from this research can be trusted and may be used for future comparisons between the performance of hydrogen vehicles and other vehicles (conventional, fuel cell, hybrid etc.) based on simulation and field studies.

3.4 Fuel Economy Results

3.4.1 Powertrain Comparison

Figure 22 details the fuel economies for the different configurations on the combined cycle (including UDDS and FHDS). Note that substantial gains can be achieved through hybridization both for conventional and fuel cell vehicles. The hybrid fuel cell configuration combines high fuel-cell-system efficiency and regenerative braking to achieve the highest fuel economy (62.8 mpg). However, it is important to note that, based on current technologies, ICE HEVs achieve higher fuel economy than fuel cell configurations. Comparable results are obtained with fuel cell HEV. This is primarily due to the high power density of fuel cell systems.

In addition, it can be seen that current hydrogen ICE technology would require hybridization to be competitive with gasoline ICE due to a lower power density. Indeed, for conventional vehicles, hydrogen ICEs achieve not only lower fuel economy, but also slower acceleration. When hybridized, hydrogen ICE configurations achieve comparable fuel economy than their gasoline counterparts. Consequently, they can be considered as a bridge to achieve hydrogen economy.

The detailed results are provided in Appendices 2 and 3.

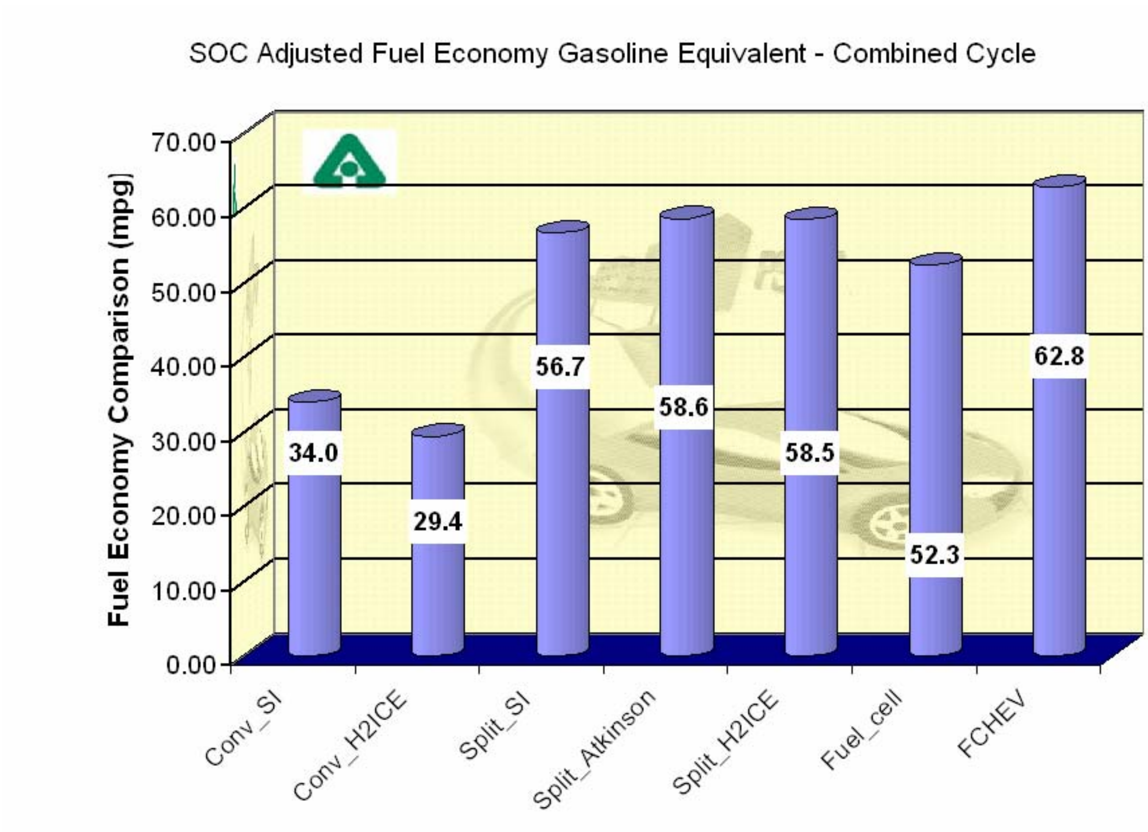


Figure 22: Fuel Economy - Combined Cycle.

Figure 23 illustrates the energy loss repartition per component for the FUDS cycle. Notably, for ICE configuration, the losses are mostly due to the engine (up to 78% for conventional configurations). Consequently, it is natural to see an increase in fuel economy when (a) the engine is less used as it is the case for HEVs or (b) it is replaced by a more efficient component such as fuel cells.

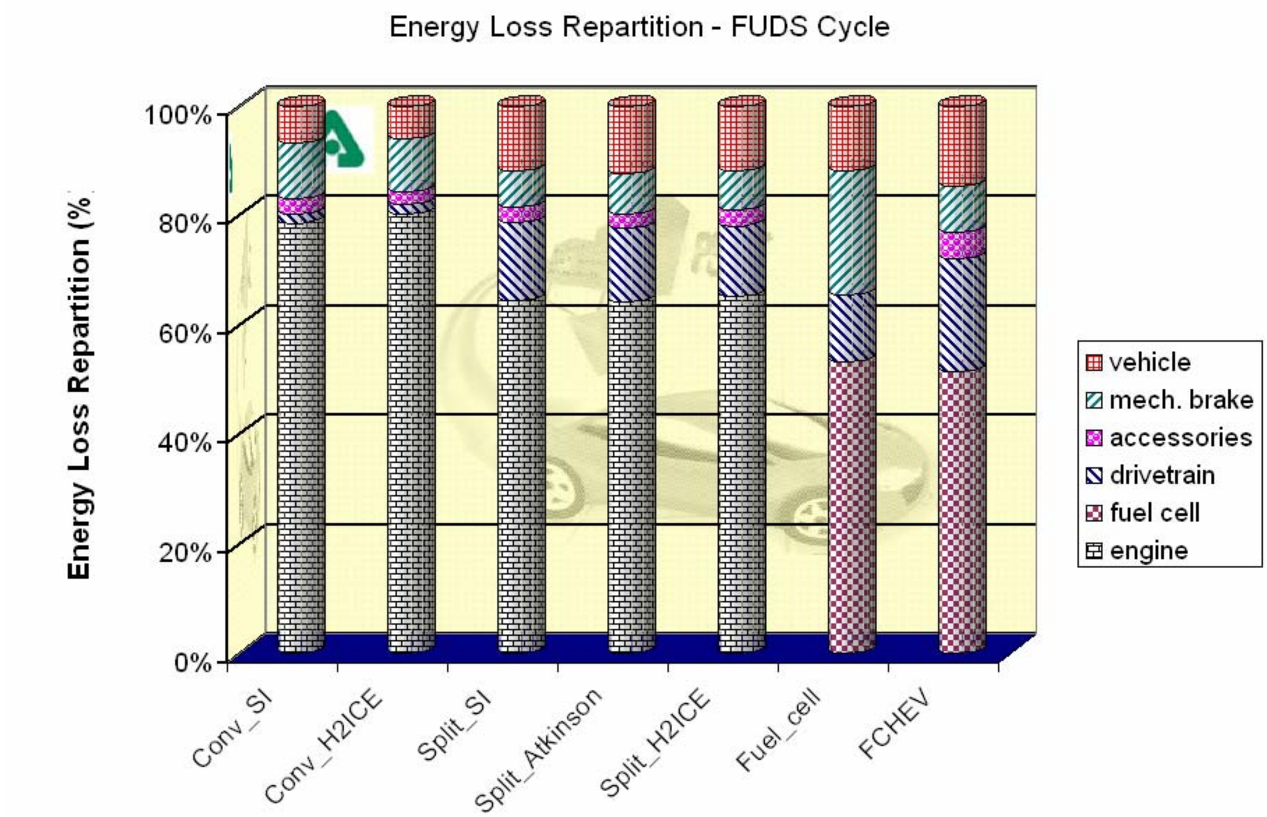


Figure 23: Energy Loss Repartition - FUDS Cycle.

3.4.2 Drive Cycle Influence

The results differ as a function of the driving schedule. Figure 24 compares the efficiency results of the power split Atkinson ICE hybrid and the reference vehicle for various cycles. The cycles with low power demand (low speed or steady-state operations) appear to be the best 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. Therefore, the hybrid's fuel economy gains on the Highway or US06 cycle are less than for the Urban.

Studies by Santini [21] pointed out that on a fixed time budget, vehicle miles traveled by vehicle vary inversely 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 25 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). The difference between drive cycles is not of great importance anymore. By analyzing the results of each cycle, 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.

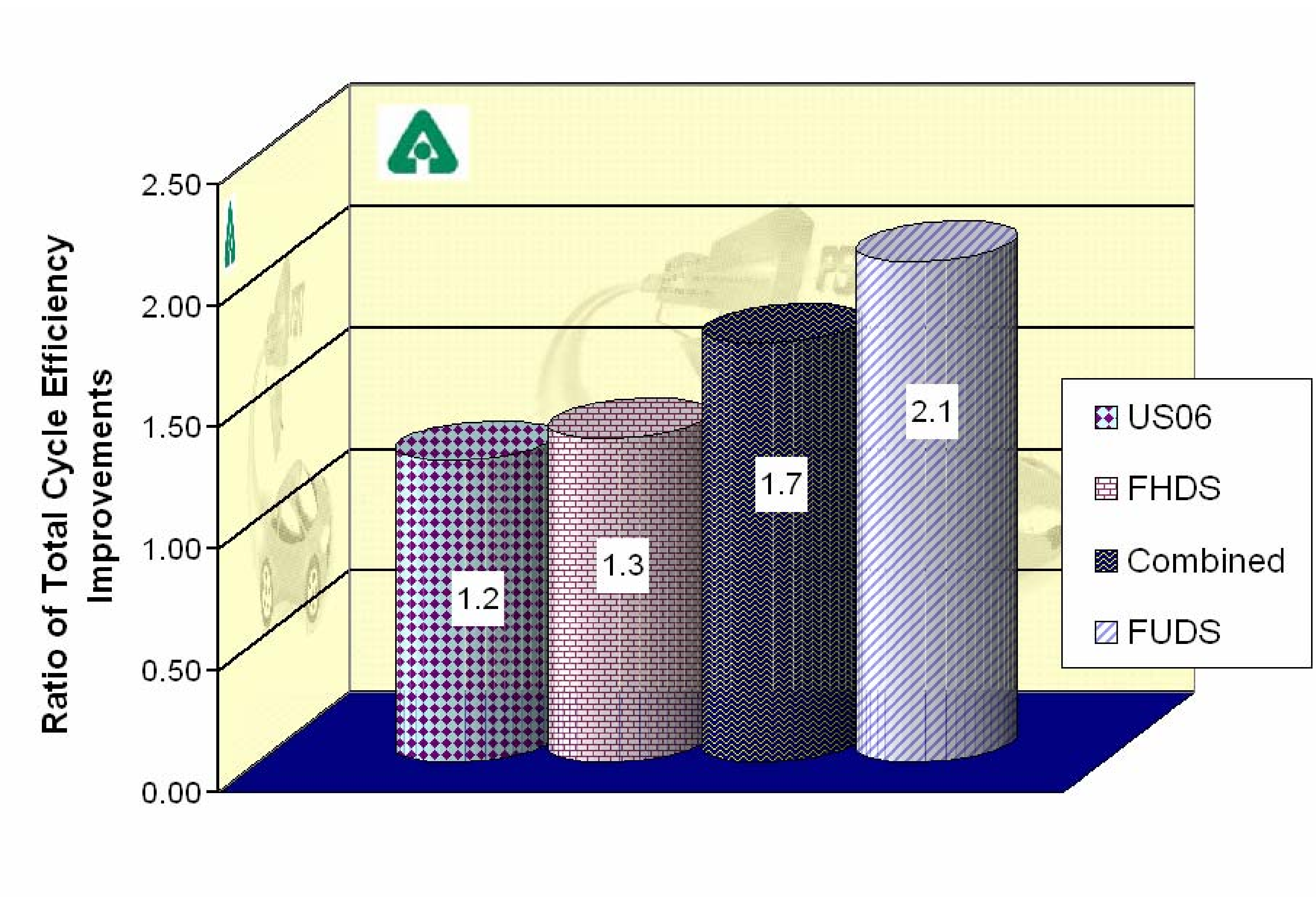


Figure 24: Fuel Economy Ratio - All Cycles.

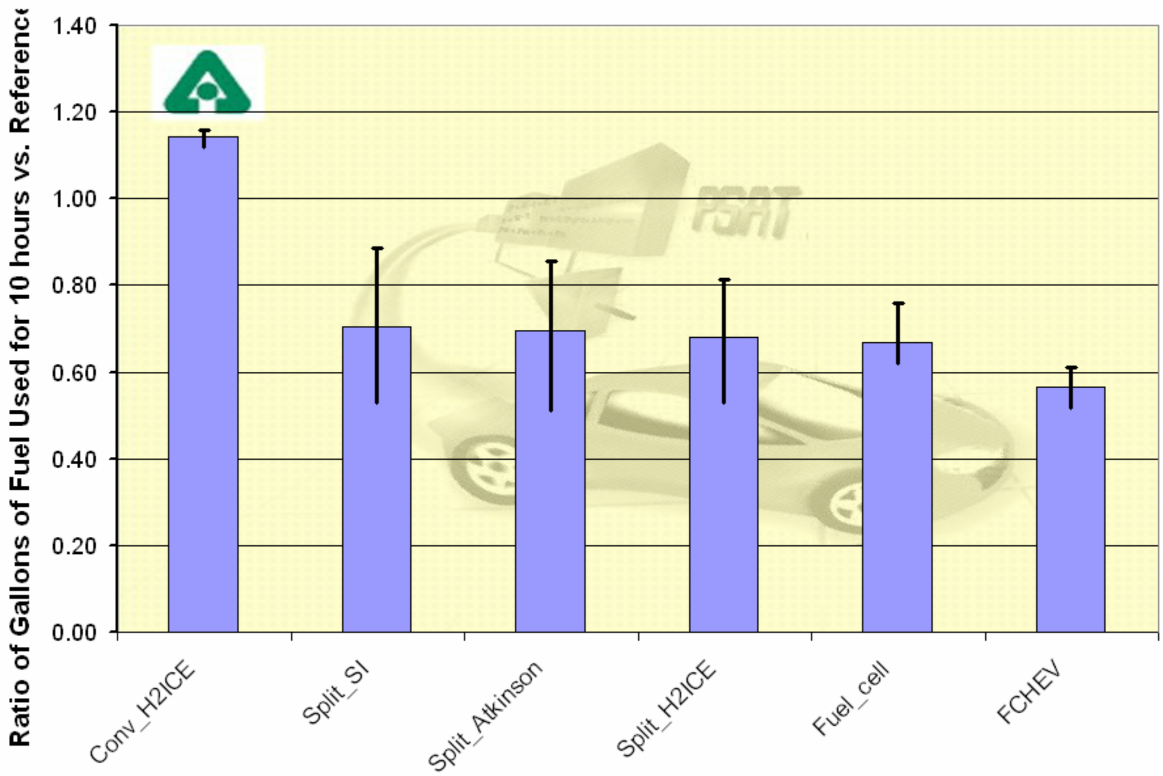


Figure 25: Ratio of gallons of fuel used for 10 hours driving.

3.5 Potential Technology Evolution

On January 9, 2002, the Secretary of the U.S Department of Energy and senior executives of DaimlerChrysler, Ford, and General Motors announced the FreedomCAR Partnership. This plan replaces the PNGV partnership. The CAR in FreedomCAR stands for Cooperative Automotive Research, and the "Freedom" principle is framed by:

- Freedom from petroleum dependence
- Freedom from pollutant emissions
- Freedom for Americans to choose the kind of vehicle they want to drive, and to drive where they want
- Freedom to obtain fuel affordably and conveniently

The vision of the FreedomCAR Partnership is the achievement of vehicles and fuels that lead to a clean and sustainable energy future. Fuel cell vehicles running on hydrogen made from clean, renewable sources of energy offer a promising pathway toward achieving this vision and could more than double the energy efficiency of today's vehicles while emitting only water at the tailpipe.

A major thrust of the partnership is to develop and validate the technologies necessary to enable mass production of affordable hydrogen-fueled fuel cell vehicles. Additionally, FreedomCAR will address technology barriers that hinder the commercialization of hybrid electric vehicles, which also offer the potential to reduce significantly the nation's dependence upon foreign oil. To achieve this goal, the FreedomCAR Partners have developed the following strategic approach:

- Develop technologies to enable mass production of affordable hydrogen-powered fuel cell vehicles
- Coordinate with public and private entities supporting technology development to enable the national infrastructure necessary for the viability of fuel cell vehicles
- Support other technologies to significantly reduce oil consumption and environmental impacts in the nearer term
- Develop component technologies applicable across a wide range of passenger vehicles

Because of the FreedomCAR Partnership, fuel cell technology is expected to significantly improve in the next few years, especially from a power density point of view with a goal of 3.1 kg/kW.

Based on the assumption that the goals will be reached, both fuel cell and HEV technologies improvement will lead to a faster introduction of advanced vehicles in the market.

4 Conclusion

Current technology capabilities have been compared and their potential from a fuel economy perspective has been evaluated by using the simulation model PSAT. The parametric study allowed to evaluate the fuel economy uncertainties related to vehicle mass, wheel radius, final drive ratio, drag coefficient and rolling resistance. Based on FreedomCAR activities, fuel cell hybrid vehicles are expected to provide even greater fuel economy reduction than their internal combustion engine counterparts. However, because of lack of hydrogen infrastructure, hydrogen ICE should be considered as an intermediate step toward hydrogen economy.

5 References

[1] http://www.eere.energy.gov/vehiclesandfuels/facts/2003/fcvt_fotw281.shtml

[2] http://www.theaustralian.news.com.au/common/story_page/0,5744,3945362%255E13232,00.html

[3] U.S. Office of Transportation Technology Technical Team

[4] http:// www.eia.doe.gov

[5] U.S. DOE / EIA

[6] http://www.epa.gov

[7] http://world.honda.com/news/2000/c001030.html

[8] http://www2.naias.com/main.asp?sectionID=247

[9] http://www.etvi.org/

[10] http://www.ott.doe.gov/images/ fuel_cell_diagram.jpg

[11] http://media.mitsubishi-motors.com/pressrelease/e/corporate/detail32.html

[12] National Renewable Energy Laboratory, *ADVISOR Reference Manual, Version 2002*. 2002.

[13] Ehsani M. *Introduction to ELPH: A parallel Hybrid Vehicle Concept,* Proceedings of ELPH Conference, University of Texas A&M, College Station, TX, Oct. 1994.

[14] USDOE. Available online at http://ww.llnl.gov/IPandC/profile/transportation/Hybr-idVehcileEvaluationCode.php. Accessed on 26th March 2004.

[15] Argonne National Laboratory, *AirCRED Users Guide, Version 1.3,* 2000.

[16] Wang M.Q., ANL/ESD-39, Vol.1, Center for Transportation Research, Argonne National Laboratory, *GREET 1.5 — Transportation Fuel-Cycle Model: Methodology, Use, and Results,* Aug. 1999.

[17] Campbell A., Rengan A., and Steffey J., *The Simulation of 42-Volt Hybrid Electric Vehicles*, available online at: www.mth.msu.edu/Graduate/msim/MSIMProjectReports/MCP2.May.2001.report.doc

[18] Argonne National Laboratory, *PSAT Reference Manual, Version 5.2,* 2004.

[19] Heywood, J., *Comparative Assessment of Fuel Cell Cars,* MIT Report LFEE 2003-001 RP, Massachusetts Institute of Technology, Cambridge, MA, February 2003.

[20] Triger L., Paterson J., and Drozdz P., ORTECH International, *Hybrid Vehicle Engine Size Optimization,* 2000.

[21] Plotkin, S., Santini, D., Vyas, A., Anderson, J., Wang, M., He, J., and Bharathan, D., Hybrid Electric Vehicle Technology Assessment: Methodology, Analytical Issues, and Interim Results.Rep. No. ESD/02-2, Argonne National Laboratory, Argonne, IL, October 2001.

APPENDIX 1 – VEHICLE CHARACTERISTICS

		Conv_SI	Conv H2ICE	Split_SI	Split_Atkinson	Split H2ICE	Fuel cell	FCHEV
PSAT Vehicle File (gui_*_in)		gui_conv_compact_focus_107k	gui_conv_compact_focus	gui_split_compact_focus	gui_split_compact_focus_SI_atkin	gui_split_compact_focu	gui_compact_fconly_focus	ESSFC_focus_in
Power								
IC Engine	**kW**	107.42	120	51.32	51.32	51.32	0	0
Fuel Cell	**kW**	0	0	0	0	0	130	105
Electric Motor #1 : Peak Power	**kW**	0	0	45.1	45.1	45.1	105	98
Electric Motor #1: Cont. Power	**kW**	0	0	32	32	32	45	45
Electric Motor #2 : Peak Power	**kW**	0	0	27.06	27.06	27.06	0	0
Starter	**kW**	2	2	0	0	0	0	0
12V Battery	**kW**	1.24	1.24	1.24	1.24	1.24	1.24	1.24
High Power Energy Storage #1	**kW**	0	0	18.9592	18.9592	18.9592	0	23.3344
Transmission								
Transmission Type		4- au	4- au				NA	NA
Transmission Ratios		2.8,1.5,1,0.7	2.8,1.5,1,0.7				NA	NA
Fixed Ratio							1.2	1.2
Final Drive Ratio		3.73	3.73	3.73	3.73	3.73	3.55	3.55
Battery Pack - 12V								
Type		Pb	Pb	Pb	Pb	Pb	PbA	PbA
Number of Cells		6	6	6	6	6	6	6
Cell Capacity (C/3)	**Ah**	66	66	66	66	66	66	66
High Power Energy Storage #1								
Type				Lion	Lion	Lion		Lion
Number of Cells				65	65	65		80
Cell Capacity (C/3)	**Ah**			6	6	6		6
Nominal Cell Voltage	**V**			3.6	3.6	3.6		3.6
Cell Peak Power (discharge)	**W**			291.68	291.68	291.68		291.68
Cell Mass	**kg**			0.4861	0.4861	0.4861		0.4861
Cell Power Density	**W/kg**			600.04	600.04	600.04		600.04
Cell Energy (C/3)	**Wh**			21.6	21.6	21.6		21.6
Cell Energy Density	**Wh/kg**			44.44	44.44	44.44		44.44
Power / Energy Ratio	**W/Wh**			13.50	13.50	13.50		13.50
Weights								
Glider (Body & Chassis)	**kg**	791	791	791.00	791.00	791.00	791	791
ICE	**kg**	130.00	200	64.27	64.27	64.27	0	0
Exhaust	**kg**	30	30	23.88	23.88	23.88	0	0
FC System	**kg**	0	0	0.00	0.00	0.00	550	425
Mass of fuel tank	**kg**	20	100	20.00	20.00	20.00	100	100
Mass of fuel	**kg**	50	4	50.00	50.00	50.00	4	4
Total Mass Used In Simulation	**kg**	1371	1475.00	1327.00	1327.00	1327.00	1920	1860
Vehicle								
Frontal Area	**m2**	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Coefficient Drag	**/**	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Rolling Resistance	**/**	0.0863	0.0863	0.0863	0.0863	0.0863	0.0863	0.0863
Wheel Radius	**m**	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Peak Efficiencies (0-100)								
IC Engine	**%**	0.33546		0.3345	0.3345	0.3345		
Transmission	**%**	97	97	97	97	97	97	97
Final Drive #1	**%**	93	93	93	93	93	93	93
Accessory Power								
Mechanical	**W**	300	300	300	300	300	0	0
Electrical	**W**	200	200	200	200	200	600	600
Simulation Results - Performance								
0-60 mph	**sec**	9.9	15.7	10	10	10	9.5	9.9

APPENDIX 2 – FUEL ECONOMY RESULTS

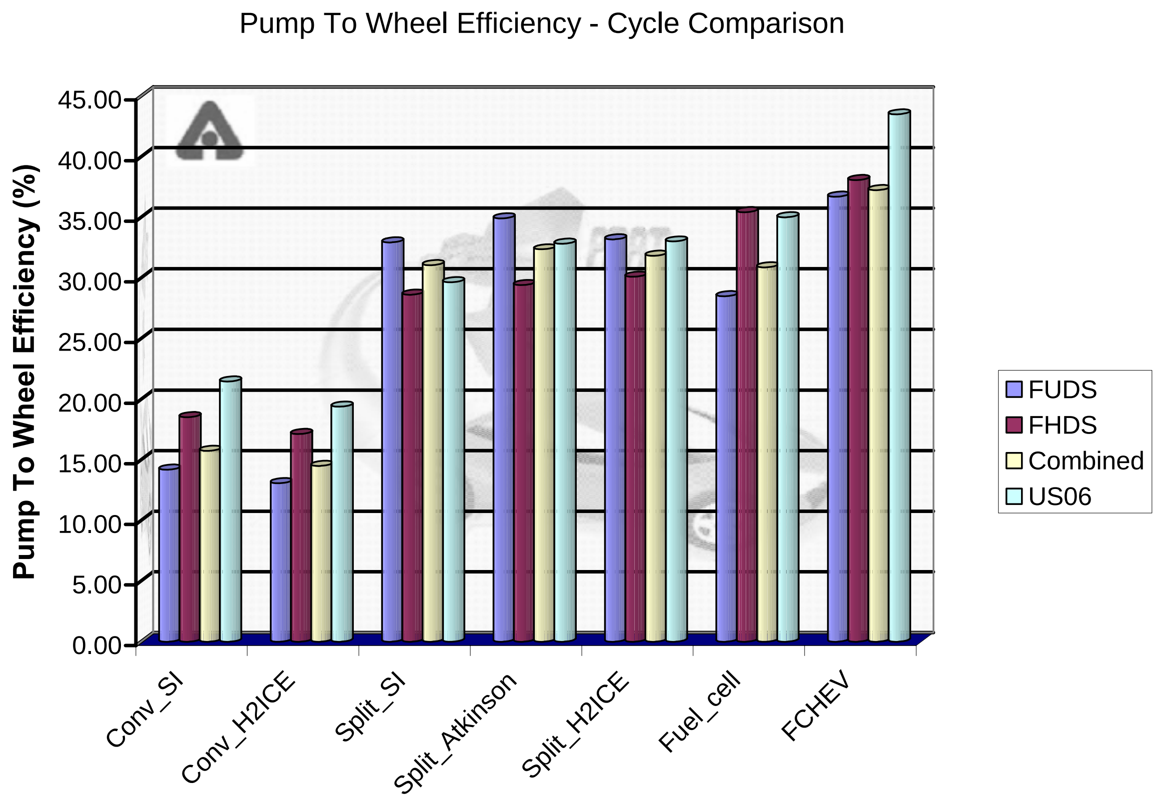
		Conv_SI	Conv H2ICE	Split_SI	Split_Atkinson	Split H2ICE	Fuel cell
Simulation Results - City							
Time	**sec**	1372	1372	1372	1372	1372	1372
Distance	**miles**	7.42	7.42	7.46	7.46	7.46	7.35
Fuel Economy	**mpg**	29.15	1.69	55.28	57.20	3.72	2939.97
FE Gasoline equivalent	**mpg**	29.15	24.92	55.28	57.20	55.41	43.84
SOC adjusted PSAT onboard	**mpg**	29.15	24.92	55.41	60.12	57.59	43.84
WSFC - gas equiv	**Gal/T/100miles**	2.50	2.72	1.36	1.32	1.36	1.19
ESS#1 - SOC init	**%**	70.00	70.00	69.05	69.18	69.07	70.00
ESS#1 - SOC final	**%**	63.61	63.51	69.05	69.19	69.07	70.00
Mass fuel consumed	**kg**	0.72	0.30	0.38	0.37	0.14	0.17
Equivalent gasoline fuel mass consumed	**kg**	0.72	0.84	0.38	0.37	0.38	0.48
Mass for 320 miles	**kg**	31.12	12.92	16.41	15.86	5.87	7.42
Regen braking energy recovered	**%**	0.00	0.00	68.66	68.97	72.61	0.00
Engine Energy Loss	**Wh**	6901.38	8160.98	3161.54	3043.05	3196.66	0.00
Fuel Cell Losses - SUM	**Wh**	0.00	0.00	0.00	0.00	0.00	3167.46
Motor#1 Energy Loss	**Wh**	0.00	0.00	317.32	300.69	293.14	681.98
Motor#2 Energy Loss	**Wh**	0.00	0.00	140.97	90.04	99.98	0.00
Generator Energy Loss	**Wh**	-11.37	11.23	0.00	0.00	0.00	0.00
ESS#1 Energy loss	**Wh**	2.91	2.96	77.79	89.53	75.11	0.00
Drivetrain Losses - SUM	**Wh**	153.96	188.36	691.42	642.54	623.46	732.12
Accessories Losses - SUM	**Wh**	228.54	228.56	136.32	121.47	138.23	4.57
Mechanical Braking Loss - SUM	**Wh**	904.48	981.86	327.12	357.04	350.47	1339.45
Aerodynamic Energy Loss	**Wh**	271.47	271.67	275.03	274.81	275.61	271.03
Tire Loss	**Wh**	312.24	335.93	303.74	303.56	303.78	432.97
Vehicle Energy loss - SUM	**Wh**	583.70	607.60	578.77	578.37	579.39	703.99
Total Energy Loss	**Wh**	8772.07	10167.35	4895.18	4742.47	4888.21	5947.60
Usable Energy at the vehicle	**Wh**	840.24	904.75	846.05	911.85	867.91	1157.34
Calculated Energy In	**Wh**	9612.31	11072.10	5741.23	5654.32	5756.13	7104.94
Fuel Energy Use	**Wh**	8635.11	9999.50	4573.59	4416.00	4561.40	5680.14
ESS#1 - Net Energy Use	**Wh**	52.79	53.67	39.41	34.58	32.79	0.00
Combined Energy Use - from simul	**Wh**	8687.90	10053.17	4613.00	4450.58	4594.19	5680.14
Total Energy In	**Wh**	8688.15	10053.46	5822.17	5706.31	5812.02	5680.14
Total Energy Out	**Wh**	1232.11	1314.31	1917.03	1991.56	1928.67	1618.47
Engine average cycle efficiency	**%**	20.08	18.39	30.87	31.09	29.92	0.00
Fuel cell average cycle efficiency	**%**	0.00	0.00	0.00	0.00	0.00	44.24
Motor #1 average cycle efficiency	**%**	0.00	0.00	-1166.60	78.18	78.77	71.67
Motor #2 average cycle efficiency	**%**	0.00	0.00	84.79	87.27	86.39	0.00
Generator average cycle efficiency	**%**	117.65	85.00	0.00	0.00	0.00	0.00
Transmission average cycle efficiency	**%**	91.34	90.94	87.21	94.88	94.99	0.00
PTW Efficiency (Total NRG in)	**%**	14.18	13.07	32.93	34.90	33.18	28.49

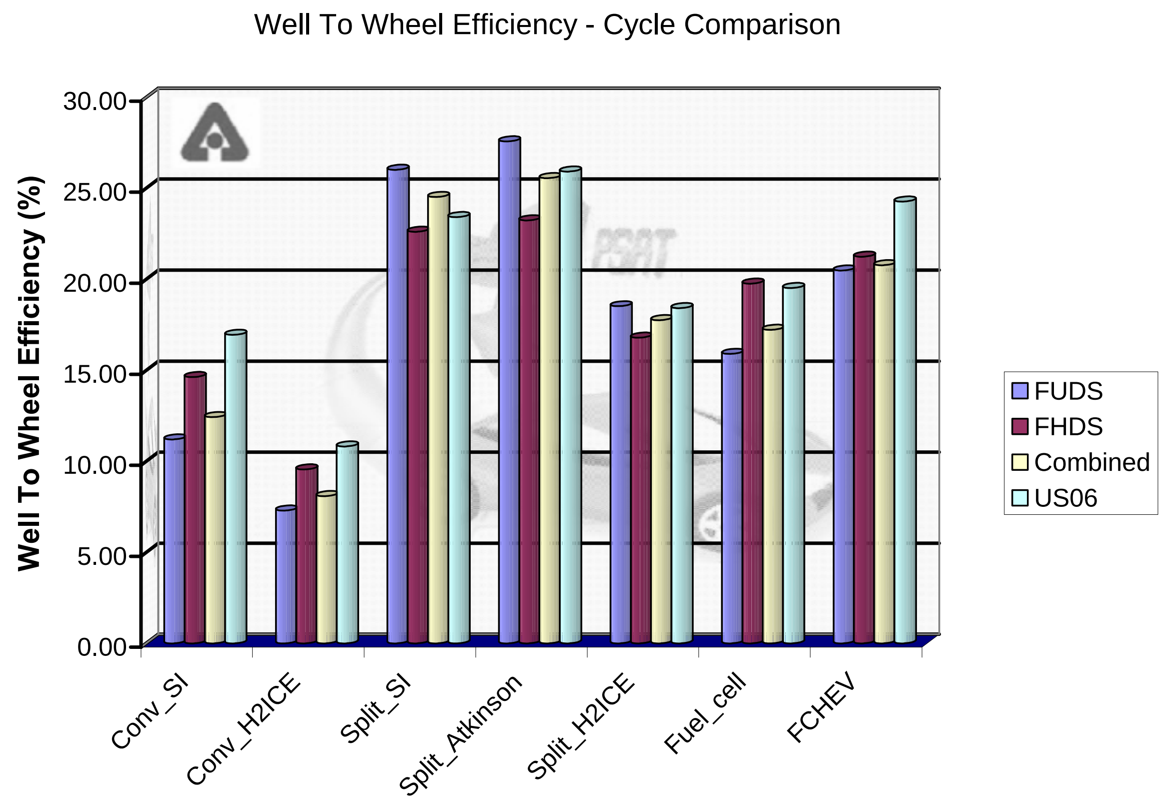
		Conv_SI	Conv H2ICE	Split_SI	Split_Atkinson	Split H2ICE	Fuel cell
Simulation Results - Highway							
Time	**sec**	765.00	765.00	765.00	765.00	765.00	765.00
Distance	**miles**	10.25	10.25	10.29	10.32	10.33	10.24
Fuel Economy	**mpg**	42.60	2.55	57.34	56.42	3.95	4599.95
FE Gasoline equivalent	**mpg**	42.60	37.69	57.34	56.42	58.95	68.59
SOC adjusted PSAT onboard	**mpg**	42.60	37.69	58.31	56.84	59.57	68.59
WSFC - gas equiv	**Gal/T/100miles**	1.71	1.80	1.31	1.34	1.28	0.76
ESS#1 - SOC init	**%**	70.00	70.00	64.27	54.50	51.59	70.00
ESS#1 - SOC final	**%**	68.28	68.24	64.29	54.10	52.02	70.00
Mass fuel consumed	**kg**	0.68	0.27	0.51	0.52	0.18	0.15
Equivalent gasoline fuel mass consumed	**kg**	0.68	0.76	0.51	0.52	0.50	0.42
Mass for 320 miles	**kg**	21.30	8.55	15.82	16.08	5.52	4.74
Prercent regen braking energy recovered	**%**	0.00	0.00	57.89	89.20	92.83	0.00
Engine Energy Loss	**Wh**	6313.49	7226.99	4143.18	4173.50	3925.01	0.00
Fuel Cell Losses - SUM	**Wh**	0.00	0.00	0.00	0.00	0.00	2878.07
Motor#1 Energy Loss	**Wh**	0.00	0.00	161.53	160.13	166.70	257.37
Motor#2 Energy Loss	**Wh**	0.00	0.00	151.21	224.22	200.91	0.00
Generator Energy Loss	**Wh**	-8.81	8.75	0.00	0.00	0.00	0.00
ESS#1 Energy loss	**Wh**	0.47	0.49	44.91	52.72	42.35	0.00
Drivetrain Losses - SUM	**Wh**	108.29	127.65	508.89	596.64	565.32	312.78
Accessories Losses - SUM	**Wh**	127.27	127.26	101.84	103.89	105.01	2.55
Mechanical Braking Loss - SUM	**Wh**	615.43	668.86	447.21	452.42	449.30	904.71
Aerodynamic Energy Loss	**Wh**	885.05	885.09	895.76	902.21	905.01	884.87
Tire Loss	**Wh**	431.37	464.12	419.20	420.42	420.88	603.80
Vehicle Energy loss - SUM	**Wh**	1316.42	1349.21	1314.97	1322.62	1325.89	1488.68
Total Energy Loss	**Wh**	8480.90	9499.97	6516.09	6649.08	6370.52	5586.79
Usable Energy at the vehicle	**Wh**	461.23	496.48	457.19	488.08	473.87	640.89
Calculated Energy In	**Wh**	8942.13	9996.45	6973.28	7137.16	6844.40	6227.68
Fuel Energy Use	**Wh**	8151.81	9125.86	6079.69	6195.28	5935.23	5058.35
ESS#1 - Net Energy Use	**Wh**	14.22	14.58	17.78	39.06	23.11	0.00
Combined Energy Use - from simul	**Wh**	8166.03	9140.44	6097.46	6234.34	5958.34	5058.35
Total Energy In	**Wh**	8165.57	9139.95	6594.74	6832.66	6513.99	5058.35
Total Energy Out	**Wh**	1511.74	1564.71	1887.11	2009.97	1960.60	1790.95
Engine average cycle efficiency	**%**	22.55	20.81	31.86	32.64	33.88	0.00
Fuel cell average cycle efficiency	**%**	0.00	0.00	0.00	0.00	0.00	43.10
Motor #1 average cycle efficiency	**%**	0.00	0.00	79.96	88.60	88.84	88.09
Motor #2 average cycle efficiency	**%**	0.00	0.00	84.53	86.38	87.20	0.00
Generator average cycle efficiency	**%**	117.65	85.00	0.00	0.00	0.00	0.00
Transmission average cycle efficiency	**%**	95.74	95.83	94.67	94.46	94.51	0.00
PTW Efficiency (Total NRG in)	**%**	18.51	17.12	28.62	29.42	30.10	35.41

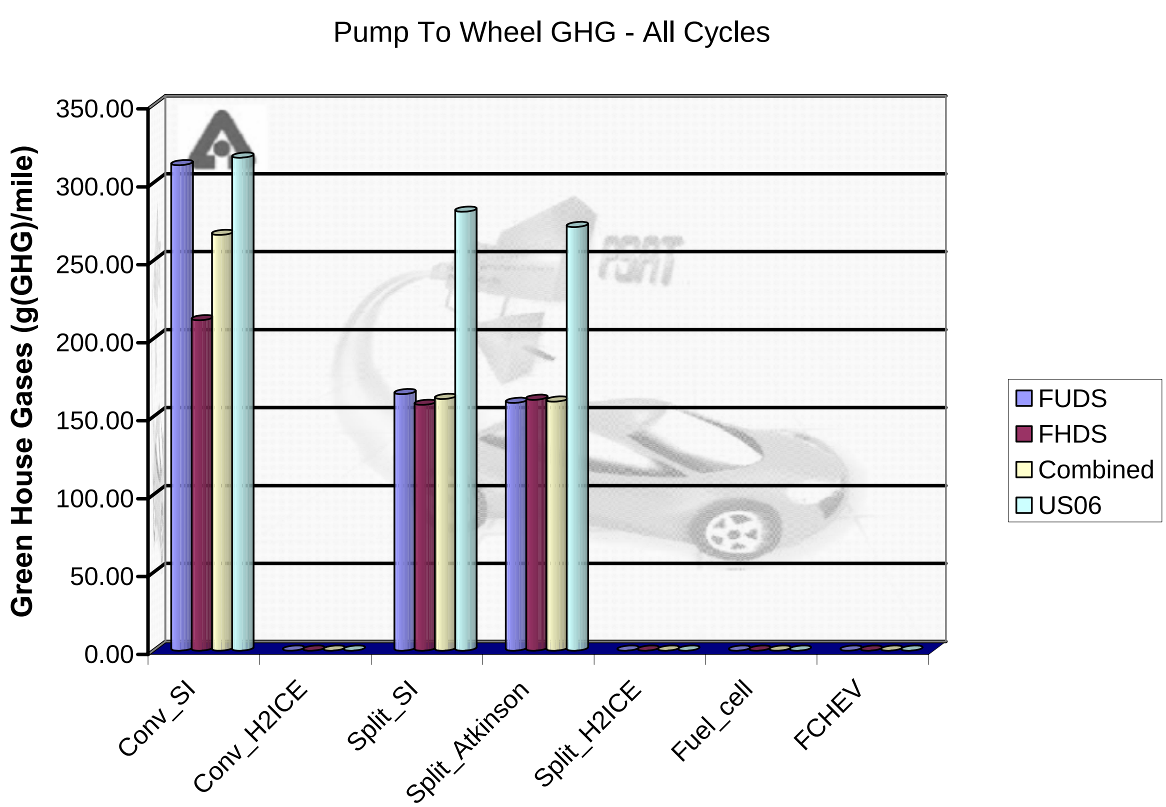
		Conv_SI	Conv H2ICE	Split_SI	Split_Atkinson	Split H2ICE	Fuel cell
Simulation Results - Combined							
Fuel Economy	**mpg**	33.98	2.96	56.19	56.85	6.43	148.19
FE Gasoline equivalent	**mpg**	33.98	29.41	56.19	56.85	56.95	52.34
SOC adjusted FE gasoline equivalent	**mpg**	33.98	29.41	56.68	58.60	58.46	52.34

		Conv_SI	Conv H2ICE	Split_SI	Split_Atkinson	Split H2ICE	Fuel cell
Simulation Results - US06							
Time	**sec**	600.00	600.00	600.00	600.00	600.00	600.00
Distance	**miles**	7.97	7.97	7.98	8.00	8.01	7.96
Fuel Economy	**mpg**	28.61	1.66	32.27	33.51	2.37	2527.82
FE Gasoline equivalent	**mpg**	28.61	24.45	32.27	33.51	35.33	37.69
SOC adjusted PSAT onboard	**mpg**	28.61	24.45	33.96	35.54	36.86	37.69
WSFC - gas equiv	**Gal/T/100miles**	2.55	2.77	2.33	2.25	2.13	1.38
ESS#1 - SOC init	**%**	70.00	70.00	60.37	54.50	53.83	70.00
ESS#1 - SOC final	**%**	67.66	67.62	60.33	54.94	53.72	70.00
Mass fuel consumed	**kg**	0.79	0.33	0.70	0.68	0.23	0.21
Equivalent gasoline fuel mass consumed	**kg**	0.79	0.92	0.70	0.68	0.64	0.60
Mass for 320 miles	**kg**	31.72	13.17	28.12	27.08	9.20	8.63
% Regen energy recovered	**%**	0.00	0.00	55.26	61.05	64.45	0.00
Engine Energy Loss	**Wh**	6906.21	8269.00	5828.99	5427.09	5107.76	0.00
Fuel Cell Losses - SUM	**Wh**	0.00	0.00	0.00	0.00	0.00	3784.22
Motor#1 Energy Loss	**Wh**	0.00	0.00	274.13	283.38	274.36	569.97
Motor#2 Energy Loss	**Wh**	0.00	0.00	197.93	265.95	257.69	0.00
Generator Energy Loss	**Wh**	-5.56	5.50	0.00	0.00	0.00	0.00
ESS#1 Energy loss	**Wh**	0.88	0.90	181.66	217.52	168.29	0.00
Drivetrain Losses - SUM	**Wh**	184.20	190.42	874.04	1003.45	914.11	647.42
Accessories Losses - SUM	**Wh**	99.93	99.92	75.97	73.02	77.44	2.00
Mechanical Braking Loss - SUM	**Wh**	973.78	1068.59	620.06	625.96	604.38	1475.01
Aerodynamic Energy Loss	**Wh**	1022.02	1023.71	1031.68	1037.10	1040.62	1024.95
Tire Loss	**Wh**	335.31	360.82	324.85	325.73	326.34	469.16
Vehicle Energy loss - SUM	**Wh**	1357.33	1384.53	1356.52	1362.83	1366.96	1494.11
Total Energy Loss	**Wh**	9521.46	11012.46	8755.58	8492.35	8070.65	7402.77
Usable Energy at the vehicle	**Wh**	1051.87	1140.73	1001.17	1075.80	1065.67	1456.94
Calculated Energy In	**Wh**	10573.33	12153.19	9756.75	9568.15	9136.32	8859.71
Fuel Energy Use	**Wh**	9450.04	10946.95	8371.35	8089.95	7686.27	7153.57
ESS#1 - Net Energy Use	**Wh**	19.36	19.72	64.74	75.42	69.77	0.00
Combined Energy Use - from simul	**Wh**	9469.40	10966.66	8436.09	8165.38	7756.04	7153.57
Total Energy In	**Wh**	9468.52	10965.77	9373.03	9353.47	8854.27	7153.57
Total Energy Out	**Wh**	2030.94	2124.99	2778.01	3068.87	2922.44	2503.19
Engine average cycle efficiency	**%**	26.92	24.46	30.40	32.92	33.55	0.00
Fuel cell average cycle efficiency	**%**	0.00	0.00	0.00	0.00	0.00	47.10
Motor #1 average cycle efficiency	**%**	0.00	0.00	81.94	83.46	83.45	82.36
Motor #2 average cycle efficiency	**%**	0.00	0.00	83.99	85.15	85.69	0.00
Generator average cycle efficiency	**%**	117.65	85.00	0.00	0.00	0.00	0.00
Transmission average cycle efficiency	**%**	94.41	95.39	94.52	94.56	95.09	0.00
PTW Efficiency (Total NRG in)	**%**	21.45	19.38	29.64	32.81	33.01	34.99

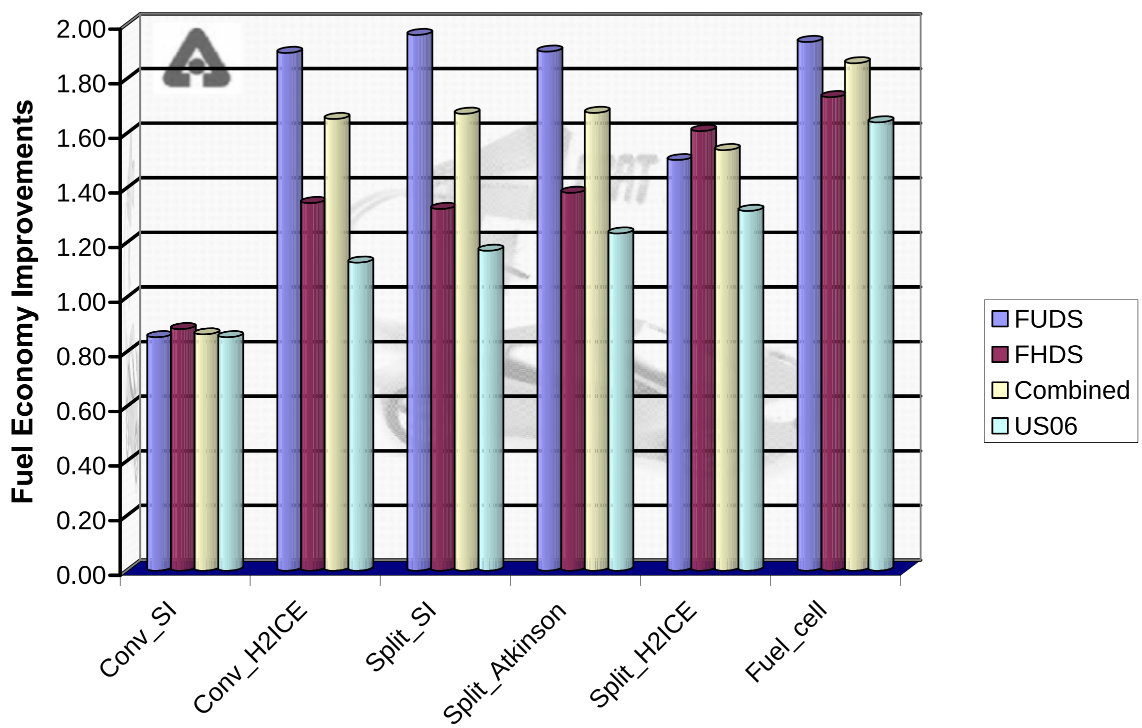
APPENDIX 3- OTHER STUDY RESULTS


Pump To Wheel Efficiency - Cycle Comparison
Pump To Wheel Efficiency (%)
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Conv_SI
Conv_H2ICE
Split_SI
Split_Atkinson
Split_H2ICE
Fuel_cell
FCHEV
FUDS
FHDS
Combined
US06

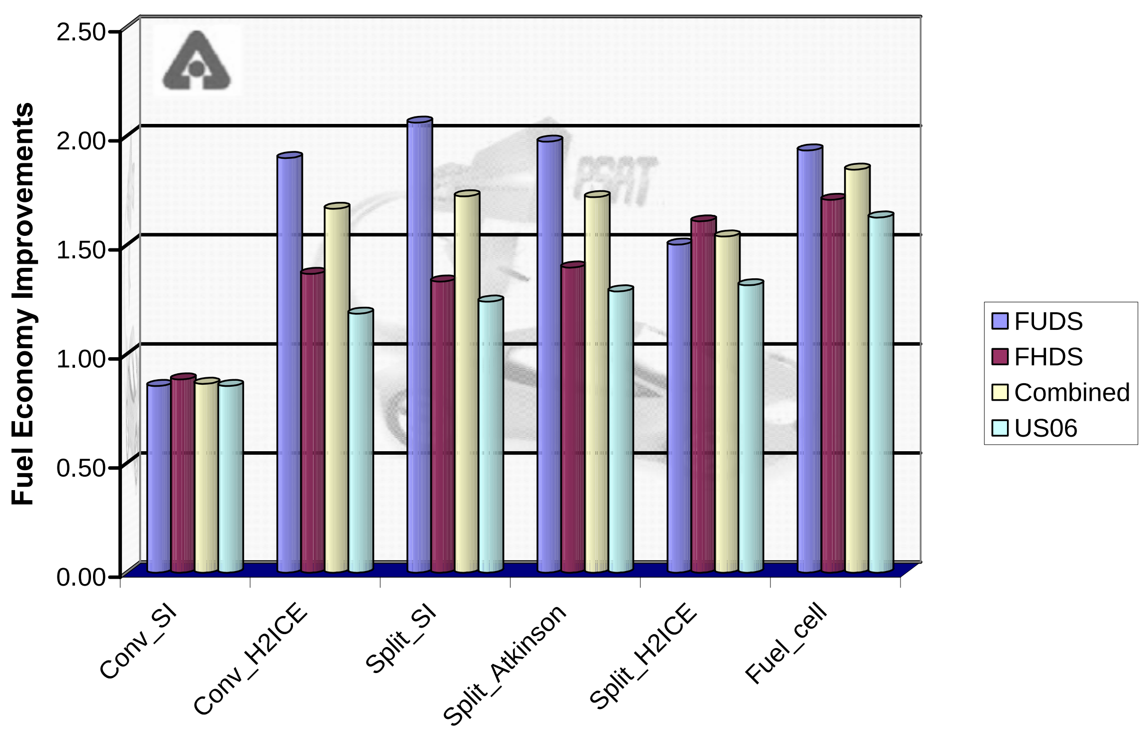

Well To Wheel Efficiency - Cycle Comparison
Well To Wheel Efficiency (%)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
Conv_SI
Conv_H2ICE
Split_SI
Split_Atkinson
Split_H2ICE
Fuel_cell
FCHEV
FUDS
FHDS
Combined
US06

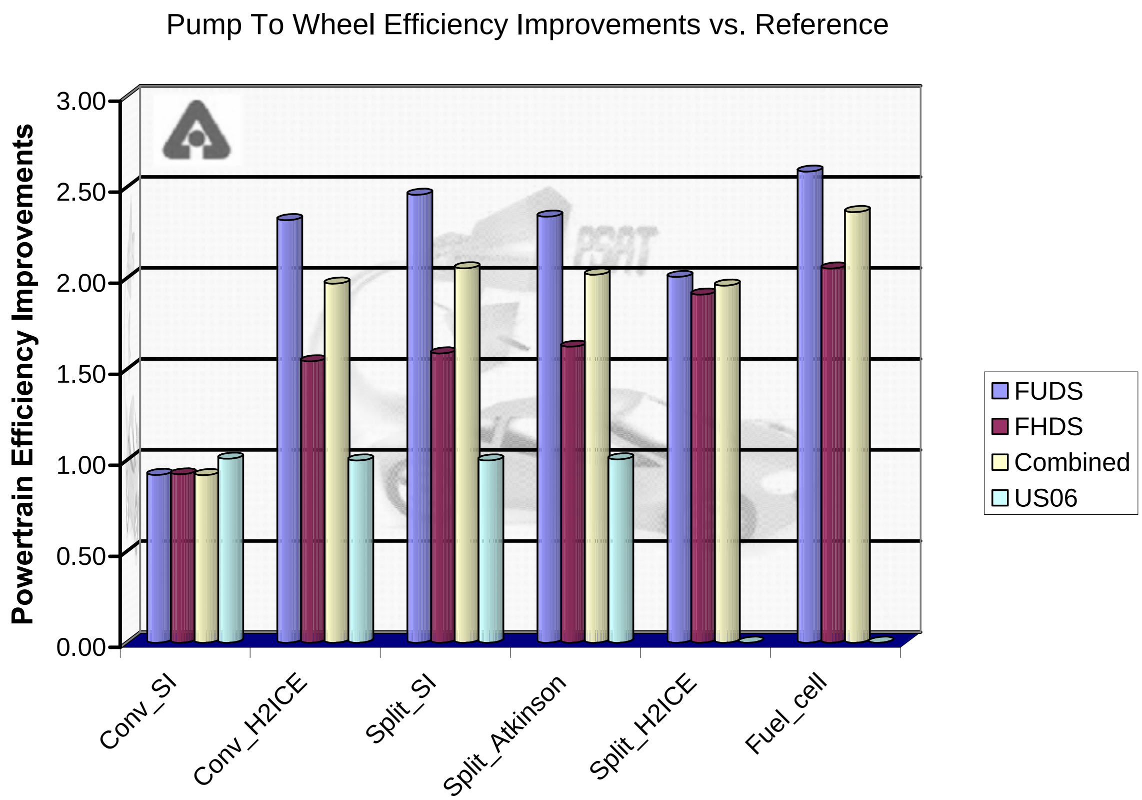

Pump To Wheel GHG - All Cycles
Green House Gases (g(GHG)/mile)
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Conv_SI
Conv_H2ICE
Split_SI
Split_Atkinson
Split_H2ICE
Fuel_cell
FCHEV
FUDS
FHDS
Combined
US06

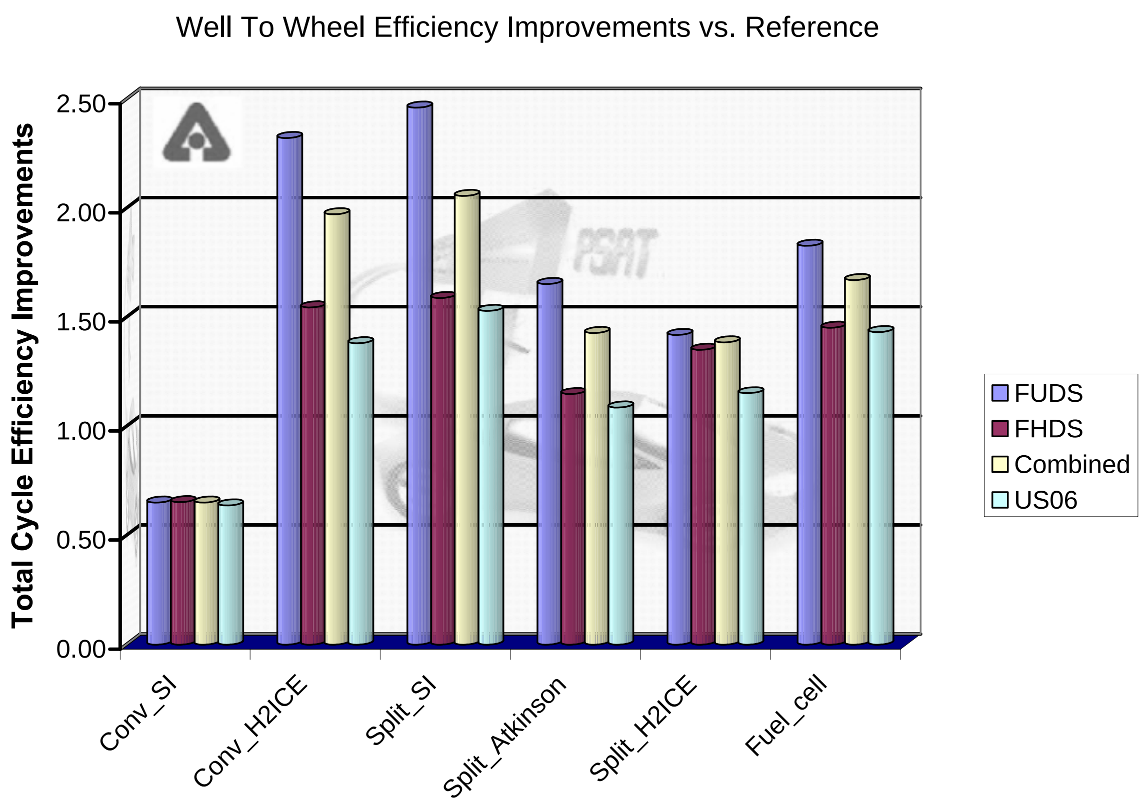
Fuel Economy Gasoline Equivalent - Improvements vs. Reference

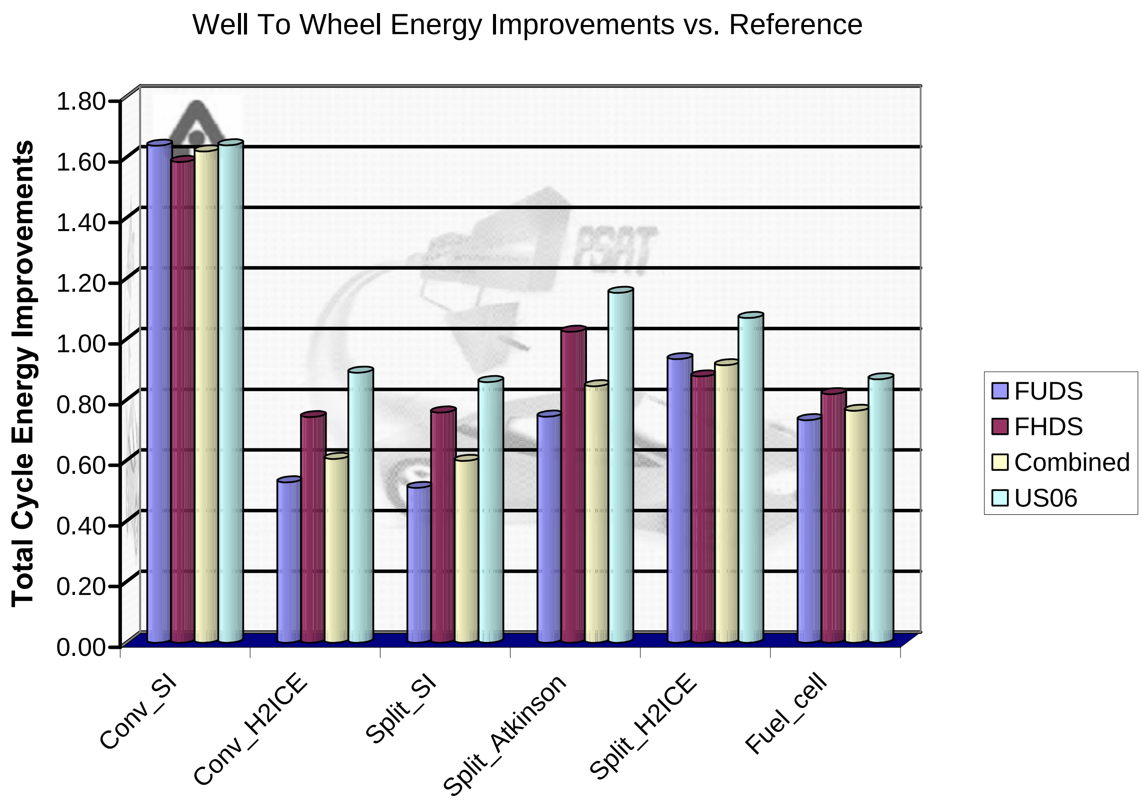


Fuel Economy Gasoline Equivalent - Improvements vs. Reference




Pump To Wheel Efficiency Improvements vs. Reference
Powertrain Efficiency Improvements
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Conv_SI
Conv_H2ICE
Split_SI
Split_Atkinson
Split_H2ICE
Fuel_cell
FUDS
FHDS
Combined
US06


Well To Wheel Efficiency Improvements vs. Reference
Total Cycle Efficiency Improvements
2.50
2.00
1.50
1.00
0.50
0.00
Conv_SI
Conv_H2ICE
Split_SI
Split_Atkinson
Split_H2ICE
Fuel_cell
FUDS
FHDS
Combined
US06


Well To Wheel Energy Improvements vs. Reference
Total Cycle Energy Improvements
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Conv_SI
Conv_H2ICE
Split_SI
Split_Atkinson
Split_H2ICE
Fuel_cell
FUDS
FHDS
Combined
US06