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A Well-to-Wheel Comparison of Several Powertrain Technologies

Matthew J. Atkins, Charles Robert Koch
University of Alberta

ABSTRACT

In order to evaluate the potential of several powertrain configurations, a well-to-wheel analysis is performed. Specifically, downsizing / supercharging and variable valve timing is examined and compared against other alternative vehicle concepts. In order to have a fair comparison, each powertrain configuration was added to a base vehicle, such that each vehicle had the same range, the same physical characteristics and similar performance. Upstream energy use and greenhouse gases were calculated with GREET 1.5a and the downstream energy use and greenhouse gases with ADVISOR 3.2.

By downsizing / supercharging and adding variable valve timing, a spark ignition internal combustion engine can have comparable downstream overall efficiency, energy use, and greenhouse gas emissions, to a Diesel internal combustion engine. Analysis of the total energy use shows that efficiency improvements for an internal combustion engine should be made on the downstream stage (engine) while efficiency improvements for electric vehicle should be made on the upstream stage (electricity generation). Also, it was found that internal combustion engines are relatively insensitive to mass change compared to improvements in engine efficiency.

INTRODUCTION

Impending more stringent fuel consumption regulations and greenhouse gas requirements [1], [2] (LEV, Tier II [1]) are reasons why many automobile manufactures and researchers are looking at alternative vehicle powertrain configurations. Some of these alternative configurations are, fuel cell vehicles (FCV), electric vehicles (EV), or hybrid electric vehicles (HEV). In addition, several technologies that increase the efficiency of the spark ignition internal combustion engines (ICE) are being investigated by researchers, including downsizing / supercharging, variable valve timing, alternative fuels (Hydrogen, E85), and homogenous charged compression ignition (HCCI). To examine which of these alternative technologies has the most potential, it is important to examine the total fuel/propulsion system by doing a well-to-wheel analysis [2]. The upstream energy use and upstream greenhouse gases (GHG) are associated with the production, storage and distribution of the fuel. This upstream energy use and GHG emissions are important, because is some cases they can be much larger than the energy use and GHG emissions produced to propel the vehicle. The energy use and GHG emission associated with propelling the vehicle is referred to as the downstream energy use and GHG emissions. The combination of upstream and downstream energy use allows a well-to-wheel comparison.

An extensive study of 27 different fuel/vehicle pathways is performed in [3] which differs from this study in that here potential improvements to a conventional ICE are examined. In this paper, a well-to-wheel energy use and greenhouse gas analysis of various vehicle technologies is conducted in order to examine the potential of downsizing/supercharging and variable valve timing.

The upstream energy use and GHG emissions are calculated with GREET 1.5a – Transportation Fuel Cycle Model (Greenhouse gases Regulated Emissions and Energy use in Transportation) [4], [5]. GREET calculates the fuel-cycle GHG emissions and fuel-cycle total energy consumption, for specific fuel pathways.

The downstream energy use and GHG emissions are calculated with a computer simulation program called ADVISOR 3.2 (ADvanced VehIcle SimulatOR). Accurate analysis of the performance and fuel consumption of conventional, electric, fuel cell, and hybrid vehicle powertrains can be performed, [6] [7], [8] with the models being parameterized with experimental data. The lack of model parameterization data for new technologies is one of the difficulties in evaluating them with this method and access to data for new technologies [3] often remains proprietary.

Each vehicle configurations is designed such that it has the same range, physical characteristics and similar performance characteristics. This allows the energy consumption and GHG emissions of each vehicle configuration to be compared on a fair basis.

Eleven different powertrain configurations are chosen to get a wide range of different technologies which include downsized / supercharged ICE and variable valve timing. The following powertrain configurations are chosen:

1. Saturn 1.9L / Gasoline ICE - *Baseline*
2. Saturn 1.9L / E85 ICE
3. Mercedes 1.0L supercharged / Gasoline ICE
4. Saturn 1.9L with Variable Valve Timing / Gasoline ICE
5. Mercedes 1.0L supercharged with Variable Valve Timing / Gasoline ICE
6. Mercedes 1.7L / Diesel ICE
7. Electric vehicle / 50 Ah Lithium Batteries
8. Fuel cell vehicle / Gaseous (35 MPa) hydrogen
9. Fuel cell vehicle / Liquid hydrogen
10. Parallel hybrid electric vehicle with gasoline ICE
11. Hybrid electric vehicle based on the Toyota Prius

SIMULATION SETUP

In both the upstream and downstream analysis, carbon dioxide is considered as the only GHG. Nitrous oxides, carbon monoxide, and hydrocarbons, which are also greenhouse gases are omitted because of lack of data for some of the powertrain configurations. This is justified because these constituents makeup only a fraction (less than 10%) of the GHG when compared to the total carbon dioxide emitted [4]. The downstream carbon dioxide is calculated by balancing the stoichmetric combustion equation, as the CO_2 is related to the carbon content of the fuel.

UPSTREAM ENERGY AND GREENHOUSE GAS EMISSIONS

The GREET model is used to calculate the upstream energy and GHG emissions of the production, transportation, and storage of the primary energy (feedstock) and the production, transportation, storage, and distribution of the fuel itself. Since this is a well-to-wheel analysis, any energy or GHG emissions associated with the complete lifecycle such as manufacturing of the vehicles is neglected.

The fuel pathways used in the analysis are:

- Near-term technologies are used for all the fuels except for gaseous (GH_2) and liquid hydrogen (LH_2) which are considered to be long-term technologies

- Conventional gasoline, and conventional Diesel are produced from crude oil with a recovery efficiency of 98%.

- Ethanol is produced from 100% corn with 33% production from dry milling and 67% from wet milling. Although it is unlikely that enough corn could be produced in the US for ethanol to be universally used as a transportation fuel [3], it is possible that a plurality of regional solutions could evolve, each of which is suited for the particular region. For example in Brazil ethanol is used to reduce gasoline imports.

- Electricity generation is based upon the United States national average mix, with 1.0% generation from residual oil, 14.9% from natural gas, 53.8% from coal, 18.0% from nuclear power and 12.3% from other renewable sources.

- Hydrogen is centrally produced from steam methanol reforming (SMR) from North American produced natural gas (NG). Hydrogen is also produced with steam credits as this is currently the most efficient way to produce hydrogen [4], [9].

A summary of the upstream total energy use and CO_2 emissions for the various forms of energy used in this study are given in Table 1.

Table 1 - Upstream Total Energy Consumption, and Upstream CO_2 Emissions

Fuel	Upstream Total Energy (J/MJ)	Upstream CO_2 Emissions (g/MJ)
Gasoline	262,049	18.5
Diesel	197,564	14.1
E85	561,759	-12.2
Electricity	3,261,902	195.1
GH_2	634,356	92.0
LH_2	1,484,523	138.5

VEHICLE SIMULATION

The driving cycle simulation is performed using data from the literature and using NREL's ADvance VehIcle SimulatOR (Advisor 3.2) [10].

A standard rolling chassis is used for all the simulations. This gives all the vehicles the same physical size (e.g. frontal area, drag, rolling resistance). The rolling chassis is based on a 1994 Saturn SL1, with a glider mass of 592 kg, a drag coefficient of 0.335 and a frontal area of 2.0 m^2. Each vehicle also has the same wheel / axle assembly and has a constant accessory load of 700 W. A constant cargo mass of 136 kg was added to the base vehicle and the appropriate control strategy was used for each different vehicle.

The drivetrain components are added to the base chassis such that all the vehicles meet a minimum performance level and all have the same range. The performance level and range are chosen based on the Partnership for a New Generation of Vehicles (PNGV) [11]. The vehicle attributes were chosen based on consumer acceptability and are listed in Table 2.

Table 2 - PNGV Performance and Range Requirements

Vehicle Attributes	Parameters
Acceleration	0 to 60 mph (96 km/h) in less than 12 sec
Grade	6.5% at 55 mph (89 km/h) for 1200 sec
Range	380 miles (612 km) on Federal Combined Cycle

To obtain the range, an initial vehicle simulation is run and then fuel mass is iteratively adjusted until the vehicle is able to travel the 380 miles. The mass of the fuel tanks is also adjusted to the required fuel volume. For the liquid fuel vehicles, 25% of the mass of the fuel is added to account for the mass of the fuel tank. The gaseous and liquid hydrogen tanks are scaled from published data.

VEHICLE TECHNOLOGIES

Saturn 1.9L Gasoline (Baseline) and E85 ICE

Both the gasoline and E85 ICE use the same Saturn 1.9L engine with a five speed manual transmission and a standard catalyst for a stoichiometric engine and both engines have a peak power of 95 kW. The E85 ICE requires 14.4 kg more fuel (E85) than the conventional gasoline ICE to travel the 380 miles on the combined cycle due to the lower energy content of ethanol compared to gasoline.

Mercedes 1.0L Supercharged / Gasoline ICE

A 2.0L supercharged M111 E20 Mercedes engine is scaled down to 1.0L supercharged engine with a peak power output of 62 kW. This is the minimum power needed to meet the acceleration requirement. The 1.0L engine uses a five speed manual transmission and a standard catalyst for a stoichiometric engine.

Saturn 1.9L / Mercedes 1.0L with Variable Valve Timing / Gasoline ICE

Engine data for a fully variable valve engine was not currently available; therefore, it had to be simulated. Variable valve timing is most beneficial [12] in the low load and the low engine speed region, where it reduces throttling losses. Therefore, the engine efficiency of the Saturn 1.9L ICE and Mercedes 1.0L ICE is increased linearly from a maximum of 20% at the lowest load to 0% at mid load. This efficiency increase was also only applied from lowest engine speed to mid engine speed. This results in a 15% fuel consumption improvement for the 1.9L Saturn and an 11% fuel consumption improvement for the 1.0L Mercedes. The powertrain configuration uses the same transmission, and catalyst as the previous ICE configurations.

Mercedes 1.7L / Diesel ICE

The Diesel 1.7L ICE is a Mercedes 1.7L direct injection turbo Diesel (CI) with a peak power rating of 60 kW. A five speed manual transmission and standard catalyst designed for a CI engine is used.

Electric vehicle / 50 Ah Lithium Batteries

The electric vehicle (EV) uses 50 Ah Lithium ion cells made by Worley Energy Cells. Lithium ion cells are used because they currently have a high charge density of 140 Wh/kg compared to nickel metal-hydride batteries which have a specific energy of 73 Wh/kg [13]. Each Lithium cell has a nominal voltage of 3.7 Volts and a mass of 1.5 kg. The EV uses a total of 178 modules each module containing three cells, in order for the vehicle to travel 380 miles on the combined cycle. A 75 kW Westinghouse AC induction motor / inverter with a one-speed transmission is used.

Fuel Cell Vehicle / Liquid and Gaseous Hydrogen

The hydrogen fuel cell vehicle (FCV) uses an ANL Model – 50 kW (net) ambient pressure hydrogen fuel cell system [10]. As in the EV, a 75 kW Westinghouse AC induction motor / inverter with a one-speed transmission is used. The FCV uses 25 Hawker Genesis 12 Volt 26 Ah lead acid batteries, where each module has a mass of 11 kg.

The LH_2 FCV requires 5.55 kg or 78.4L of liquid hydrogen to travel the required range, while the GH_2 FCV requires 5.61 kg or 283.9L of hydrogen stored at a pressure of 34.5 MPa. The hydrogen fuel tanks are scaled from published data and the liquid tank weighs 29.9 kg, while the gaseous tank weighs 83.3 kg [14, 15].

Hybrid Electric Vehicles

A 1.0L Geo SI engine with a peak power of 41 kW, a 75 kW Westinghouse AC induction motor / inverter, a five-speed manual transmission and a standard catalyst for a SI engine is used as a base parallel hybrid electric (HEV) in ADVISOR. Energy is stored in 25 Hawker Genesis 12 Volt, 26 Ah lead acid batteries. A modified Toyota Prius was also included since it was found to have much better performance compared to the base hybrid and is thus perhaps more representative of a modern hybrid.

The Prius HEV uses all the drivetrain components from the Toyota Prius, but uses the standard glider chassis used in this study of 592 kg instead of 918 kg for a stock Prius. The Prius uses a 1.5L (43kW) SI engine, 40 spiral wound NiMH batteries, a 30 kW permanent magnet motor/controller, a 15-kW permanent magnet generator and Toyota's CVT gearbox.

VEHICLE MASS

Figure 1 shows the mass break down of each vehicle. All the vehicles had the same glider mass (592 kg) and cargo mass (136 kg). The Lithium EV has the largest mass (1670 kg) because of the large number of batteries needed to travel the required 380 mile range. The Prius HEV is the lightest vehicle at 1006 kg. Both FCV's are heavier than all the ICE vehicles due to the added weight of the hydrogen tanks.

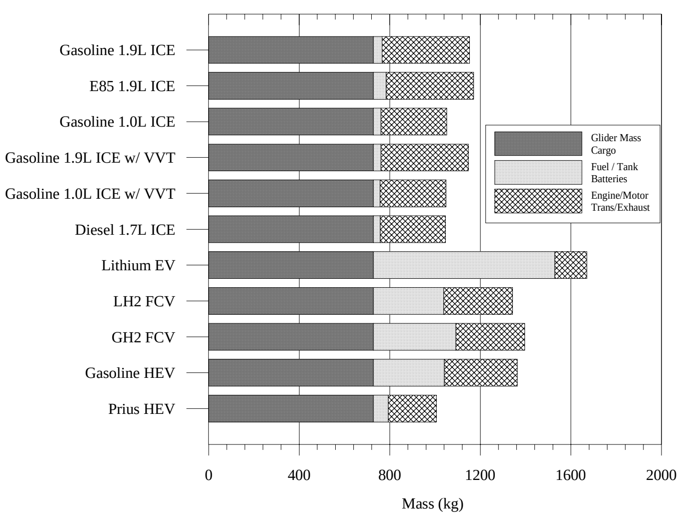

Figure 1 - Vehicle Mass Breakdown

SIMULATIONS RESULTS

VEHICLE PERFORMANCE

For consumer acceptability, certain minimum performance criteria must be met. Figures 2 and 3 show the vehicle acceleration and the grade performance characteristics for each vehicle configuration.

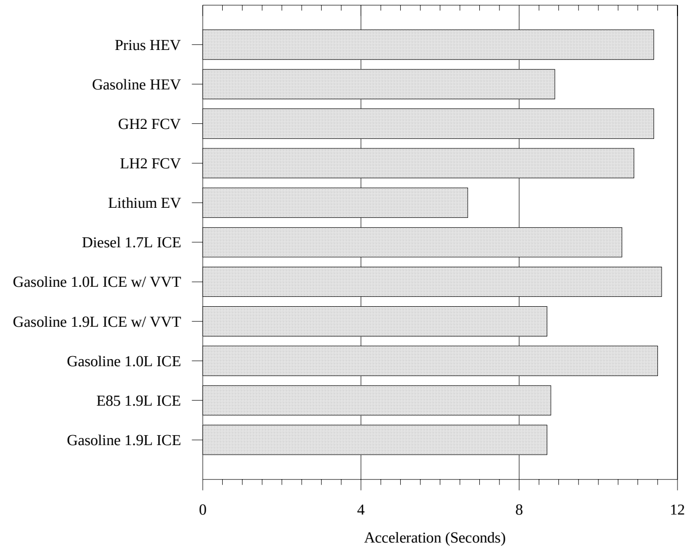

Figure 2 – Vehicle Acceleration (0-60mph)

The EV had the fastest 0 to 60 mph acceleration because of the electric motor high torque capabilities. The downsized/supercharged ICE and downsized/ supercharged VVT ICE had a slower acceleration than the base ICE, but they also had 35% less power. Both downsized ICE's had comparable acceleration to the Prius HEV and FCV's.

The grade requirement is not met by the gasoline HEV, although it had a relatively fast acceleration time. Again the downsized / supercharged ICE's had worse grade performance compared to the baseline ICE.

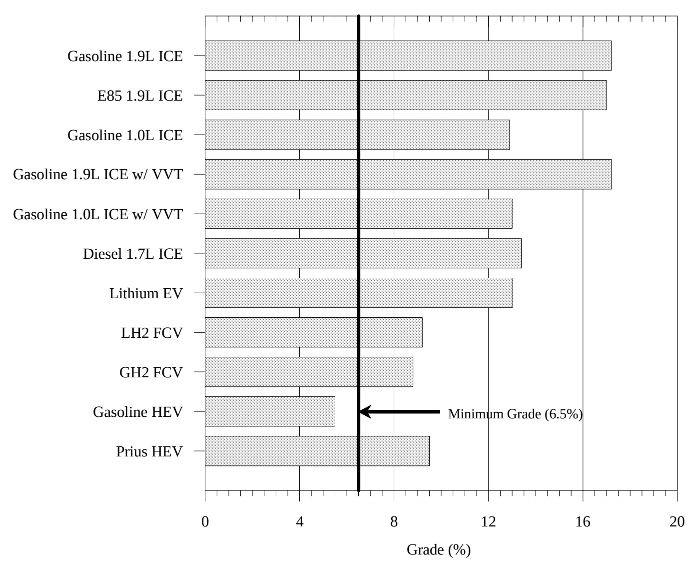

Figure 3 - Grade Requirement

DOWNSTREAM OVERALL EFFICIENCY

The downstream overall efficiency of the vehicle system is defined as the energy output of the drive system (at the wheels) over the energy input to the system. The energy input is the lower heating value (LHV) of the fuel multiplied by the volume of fuel used.

$$Overall\_Efficiency = \frac{Energy\_Output}{Energy\_Input} \quad (1)$$

Figure 4 shows the overall efficiency of the vehicle configurations over the urban, highway and combined cycles. The EV has the highest overall downstream efficiency because of the high efficiency of the electric motor. This high downstream efficiency of electric vehicles is partially offset by the large energy requirement to generate the electricity in the upstream stage as shown in Table 1.

The ratio of city to highway overall efficiency is 0.74 for the EV and 0.56 for both LH_2 and GH_2 FCV's which is larger than 0.50 (average) for the ICE's and HEV's. Thus, the EV, compared to the ICE vehicles studied here, would realize a proportionally larger improvement in fuel economy if the driving cycle was changed to emphasis more urban driving.

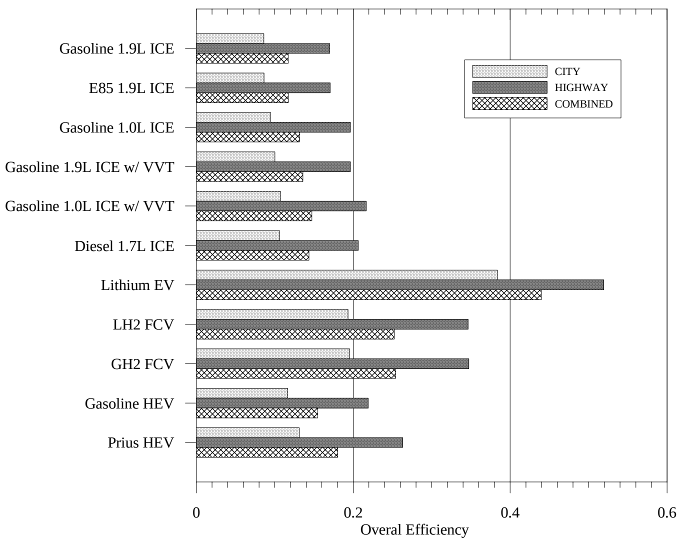

Figure 4- Overall Efficiency

The baseline ICE (gasoline 1.9L ICE) has a downstream efficiency on the combined cycle of 11.7%, which is significantly lower than the EV (44.0%) or FCV's (25.2%). Several ways are available to increase the downstream efficiency of the combustion engine. Reducing the displacement of the engine and then supercharging the engine results in a more efficient engine with a downstream efficiency of 13.2%. A variable valve timing (VVT) engine has reduced part load throttling losses compared to a conventional engine which result in an overall efficiency of 13.6%. By downsizing / supercharging and adding VVT the overall efficiency of the ICE is improved to 14.7% a 26% improvement over the base ICE engine, which is slightly better than the Diesel 1.7L ICE. Recent research into homogeneous charged compression ignition (HCCI) has the shown the potential to increase the efficiency of ICE's even further [16]. Figure 5 shows how the downstream overall efficiency of the ICE can be significantly improved by implementing available technologies. In addition, current research areas such as HCCI combustion have the potential to further improve the efficiency of the ICE engine.

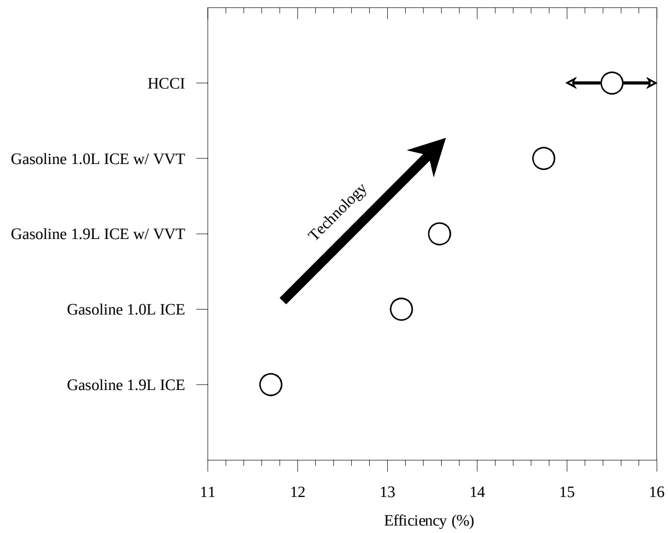

Figure 5 – ICE Efficiency vs. Technology

FUEL CONSUMPTION

Fuel consumption (FC) in liters per one hundred kilometers or fuel economy in miles per gallon is a widely used measure to compare the efficiency of vehicles. Since liquid fuel is sold by volume (liters or gallons) this is what the consumer needs to calculate costs. However, one complication with this measure of fuel consumption (FC) is that different fuels have different energy content per volume. For example, the baseline gasoline 1.9L ICE has a fuel consumption of 6.7 L/100km, while the GH_2 FCV has a fuel consumption of 46.4L/100km. But, the lower heating value of gasoline is 42.6 MJ/kg (with a density of 0.749 kg per liter) with the corresponding values for hydrogen being 120 MJ/kg with 0.020 kg per liter (at 34.5 MPa). Gasoline equivalent fuel consumption, which is the equivalent amount of gasoline needed to get the same energy requirement from another fuel, can be used to compare different vehicle fuel consumption on an equal energy basis. Gasoline equivalent fuel consumption is computed by multiplying the fuel consumption by the ratio of the fuel density to gasoline density, and the ratio of the fuel lower heating value to the gasoline lower heating value as given by.

$$FC\_ge = FC \times \frac{\rho(fuel)}{\rho(gasoline)} \times \frac{LHV(fuel)}{LHV(gasoline)} \quad (2)$$

Figure 6 shows the both the fuel consumption and the gasoline equivalent fuel consumption. It is important to note that despite equivalent fuel economy being an effective way to compare the downstream energy efficiency, the actual fuel economy must be used to calculate fuel tank size and to calculate costs if the fuels are sold by volume. The Lithium EV had the lowest gasoline equivalent fuel consumption of 2.1 L/100km, followed by the FCV's at 3.5 L/100km. The gasoline HEV had similar fuel consumption to the base ICE. Both the downsized / supercharged 1.0L ICE and 1.9L ICE with VVT fuel consumption improved 15%, and the 1.0L ICE with VVT improved 24% over the baseline ICE.

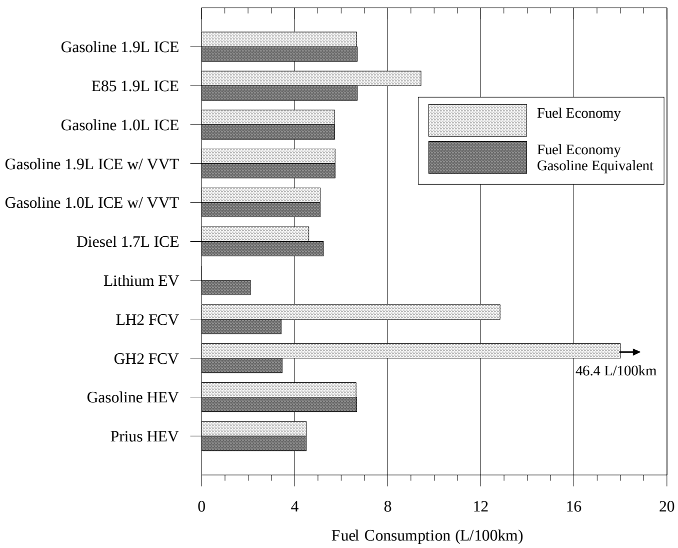

Figure 6 - Fuel consumption

VEHICLE SENSITIVITY

In order to understand the relative importance of changes to the vehicle and powertrain, a normalized equivalent fuel consumption function was defined as follows:

$$\frac{FC}{FC_{nom}} = S_1\overline{m} + S_2\eta_{FS} + S_3\eta_{Batt} + S_4\eta_{Engine} + const \qquad (3)$$

FC_{nom} is the nominal fuel consumption, which has already been calculated for each vehicle and is shown in Figure 6, while FC is the fuel consumption for a vehicle configuration that is perturbed from the nominal configuration. The terms $\overline{m} = m/m_{nom}, \eta_{FS}, \eta_{Batt}, \eta_{Engine}$ are the normalized vehicle mass, the fuel cell stack peak efficiency, the battery coulombic efficiency, and the engine efficiency, respectively. These are the independent variables in Equation 3. S_1 to S_4 are calculated by varying about the nominal configuration of each of the independent variables in the equation and then finding the fuel consumption using the simulation at 2 points above and below the nominal. These results are linearized and the slope is determined to calculate the sensitivity. In Equation 3 the fraction change in fuel consumption (FC/FC_{nom}) is equal to the normalized mass slope (S_1) times the change in mass fraction, plus normalized fuel stack efficiency slope (S_2) times the fuel stack efficiency, plus normalized battery efficiency slope (S_3) times the battery efficiency, plus normalized engine efficiency slope (S_4) times the engine efficiency, plus a constant. The normalized slopes for the FCV, EV and ICE are given in Table 3.

Table 3 - Normalized Slopes

Vehicle	Component	Normalized Slope
Gasoline 1.9L ICE (baseline)	Mass (S_1)	0.273
	Engine Efficiency (S_4)	-2.567
GH_2 FCV	Mass (S_1)	0.380
	Fuel Stack Efficiency (S_2)	-1.461
Lithium EV	Mass (S_1)	0.367
	Battery Efficiency (S_3)	-1.126
Prius HEV	Mass (S_1)	0.424
	Battery Efficiency (S_3)	-0.227
	Engine Efficiency (S_4)	-2.273
Gasoline 1.0L w/ VVT ICE	Mass (S_1)	0.414
	Engine Efficiency (S_4)	-2.888
	Engine Technology	-7.613

Here the normalized mass slope is a positive valve, indicating that an increase in mass will increase the normalized fuel consumption (FC/FC_{nom}). The normalized fuel stack efficiency, battery efficiency, and engine efficiency slopes are negative values indicating that an increase in these efficiencies will decrease the normalized fuel consumption (FC/FC_{nom}).

The sensitivities of the FCV and EV indicated that the vehicles are more sensitive to changes in fuel stack efficiency / battery efficiency than in changes in mass. The Prius HEV is the most sensitive to mass changes compared to the other vehicles configurations. The Prius HEV is also significantly more sensitive to changes in engine efficiency than the battery efficiency.

The normalized engine efficiency slopes of both the Gasoline 1.9L ICE and Gasoline 1.0L with VVT are larger than the normalized mass slopes. This indicates that ICE vehicles are more sensitive to improvements in engine efficiency compared to reductions in vehicle mass.

The affect of engine technology was also considered. The slope of the overall efficiency (combined cycle) of the Gasoline 1.9L, Gasoline 1.0L, Gasoline 1.9L with VVT, and Gasoline 1.0L with VVT was normalized with the base Gasoline 1.9L fuel consumption. The normalized engine technology slope is shown in the last row of Table 3. By changing engine technology from the baseline Gasoline 1.9L to the Gasoline 1.0L with VVT, the efficiency improvements occurs in the normal engine operation range (low load/speed) over the combined cycle. Therefore, this shows that greater benefit can be gained from focusing on improvements in the normal engine operation range than improvements to peak engine efficiency.

WELL-TO-WHEEL ENERGY USE AND GREENHOUSE GAS EMISSIONS

The upstream and downstream energy use and emissions data are combined to give the well-to-wheel energy use and GHG emissions.

Figure 7 shows that the E85 1.9L ICE had the highest energy use at 3.34 MJ/km. The E85 1.9L ICE has the same downstream energy use as the gasoline 1.9L ICE, but the E85 fuel requires more than twice the energy to produce. The benefit of E85 is not in the energy use but in the GHG emissions. In this study ethanol is produced from corn which uses CO_2 when it is produced. As a result the upstream GHG emission for E85 is negative (see Table 1).

The Lithium EV, LH_2 FCV and baseline 1.9L ICE have nearly the same total energy use, however, the energy makeup was quite different between the Lithium EV and baseline 1.9L ICE. The upstream energy use for the gasoline 1.9L ICE is about 21%, where as the upstream energy use for the Lithium EV is about 76%. Thus, to realize large improvements in an ICE the efficiency improvements should be made downstream on the engine while for an EV efficiency improvements should be made on the upstream stage (electricity generation).

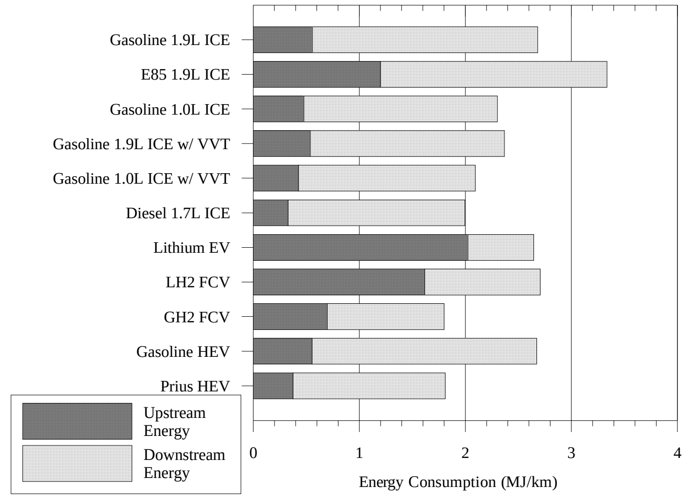

Figure 7 - Total Energy Consumption

The energy use for the GH_2 FCV was 34% lower than for the LH_2 FCV. This is caused by expending approximately 30% of hydrogen's energy content in order to liquefying the gas to 20K [17]. The GH_2 FCV energy use is only slightly lower than the Prius HEV. The gasoline HEV and the baseline gasoline 1.9L ICE have similar total energy consumptions, indicating that a HEV vehicle must be carefully design in order to realize reduced energy. The energy use of the GH_2 FCV is only 0.6% lower than the Prius HEV.

The 1.7L Diesel ICE had the lowest energy use (2.00 MJ/km) of all the ICE's. The addition of variable valve timing and downsizing / supercharging the gasoline 1.9L ICE decreased its energy use by 22% from the baseline to (2.09 MJ/km) which is only 4% higher than the 1.7L Diesel. The gasoline 1.0L ICE with VVT energy use is only 14% higher than the Prius HEV (1.81 MJ/km) indicating that this is also a viable alternative to HEV's or perhaps in combination.

The LH_2 FCV, GH_2 FCV and Lithium EV do not produce any downstream GHG emissions. All of the GHG emissions are produced in the upstream stage in the making of the fuel / electrical energy. The GH_2 FCV had the lowest GHG emissions at 101 g/km, with Lithium EV coming in second at 116 g/km. The LH_2 FCV GHG emissions are 151 g/km which is higher than both the Diesel 1.7L ICE (144 g/km) and the gasoline 1.0L ICE with VVT (148 g/km). Thus, for GHG emissions, it seems that liquid hydrogen is a poor fuel compared to either gasoline or Diesel. However, it should be noted that CO_2 is the only GHG emission consider in this analysis, methane (CH_4) and nitrogen oxide (N_2O) are not included.

The baseline gasoline 1.9L ICE vehicle produced the most GHG emissions (193 g/km), however, the gasoline 1.0L ICE with VVT was only 2.4% higher than the Diesel 1.7L ICE and 14% higher than the Prius HEV (130 g/km).

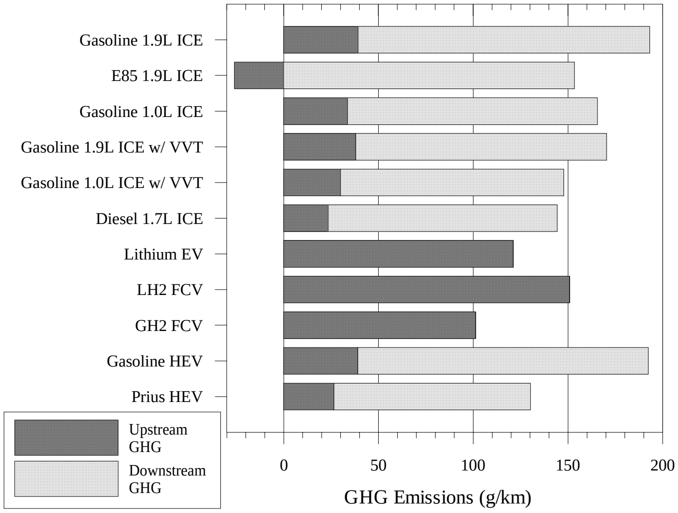

Figure 8 - Total GHG Emissions

The results from well-to-wheel energy use and GHG emissions indicate that ICE's, with the successful implementation of new engine concepts, can be competitive relative to FCV and HEV.

CONCLUSION

A well-to-wheel energy use and greenhouse gas emission analyses is conducted to determine the potential of variable valve timing and downsizing / supercharging. It was found that by downsizing / supercharging and adding variable valve timing, an ICE can have comparable downstream overall efficiency, energy use and GHG emissions to a Diesel ICE.

An analysis of the total energy use shows that for ICE's efficiency improvements should be made on the downstream stage (engine) and for EV's efficiency improvements should be made on the upstream stage (electricity generation).

Internal combustion engines are relatively insensitive to mass change, but very sensitive to improvements in engine efficiency. A larger fuel consumption improvement can be achieved from the same increase in engine efficiency than in other efficiencies or in vehicle mass. It was also found that greater benefits could be achieved by focusing on improvements in the normal engine operation range than improvements to peak engine efficiency.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ADVISOR - ADvance VehIcle SimulatOR (

E85 - Mixture of 85% ethanol and 15% gasoline

EV – Electric Vehicle

FCV – Fuel Cell Vehicle

FC – Fuel Consumption

FTP – Federal Test Procedure

GHG – Green house gases

GH_2 – Gaseous Hydrogen

GREET - Greenhouse gases Regulated Emissions and Energy use in Transportation

ICE – Internal Combustion Engine

HEV – Hybrid Electric Vehicle

LHV – Lower Heating Value

LH_2 – Liquid Hydrogen

M85 - Mixture of 85% Methanol and 15% gasoline

NREL – National Renewable Energy Laboratory

PM – Particulate Matter

PNGV - Partnership for a New Generation of Vehicle