

**THE PERFORMANCE OF IC ENGINE AND FUEL CELL HYBRID
PROPULSION SYSTEMS IN LIGHT DUTY VEHICLES**

by

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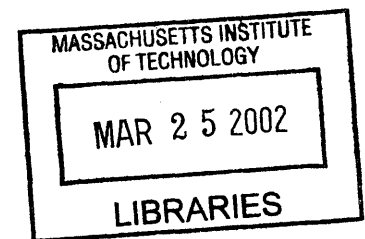
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ABSTRACT

The report *On the Road in 2020* provided a methodology for analyzing the performance of future light-duty vehicles and offered a broad comparison among these vehicles. This study furthers *On the Road in 2020* by investigating two issues: the impact of driving schedule on the performance of these vehicles and the performance of fuel cell vehicles based on more optimistic assumptions than those used in the original study. It focuses on three propulsion systems: internal combustion engines operating on gasoline, fuel cells operating on hydrogen created from steam reforming gasoline, and fuel cells operating on a direct hydrogen feed. In addition, it investigated hybrid forms of these three systems.

Using a simulation package used in its parent report based on the more optimistic assumptions concerning fuel cells, this study found that vehicles with fuel cells consumed less fuel and energy than those with gasoline engines. Fuel cells operating on direct hydrogen feed exhibited lower fuel and energy consumption than those operating on gasoline-reformate. The choice in driving schedule affected the actual fuel consumption for a specific vehicle configuration. Comparing against the IC engine non-hybrid vehicle, the gasoline-reformate fuel cell vehicle reduced fuel consumption by typically 30-40% for most driving schedules, though the US06 schedule only improved the consumption by about 15%. Hydrogen fuel cell vehicles reduced fuel consumption by typically 50-60%, though the US06 schedule did so by only 35%. Comparing against the IC engine hybrid vehicle, reduction in fuel consumption was more consistent for fuel cell hybrid vehicles over all driving schedules tested (typically 20% for gasoline-reformate and 40% for hydrogen). Hybridization of all propulsion system types resulted in large reduction in fuel consumption (typically 35-50%) for European and Japanese schedules, but only about 5-15% for US06 schedules.

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CHAPTER 1: INTRODUCTION

1.1 Background

The last century has witnessed dramatic changes in transportation technology. At the turn of the twentieth century, Americans traveled around cities in horse-drawn carriages and around the country on train. The development of road and air transportation has made traveling quicker and more flexible. The introduction of the automobile has not only allowed individuals the means for personal mobility, it has influenced society by infusing itself in its culture. Cars made urban distances small, creating the possibility of residential areas in suburbs. Air transportation has made transatlantic travel shorten from a matter of weeks to a matter of hours. The last hundred years has seen the world become a smaller one.

There is no reason to believe that the next hundred years won't bring similar changes to the field of transportation. In fact, the transition to the 21st century has brought along great optimism for technology of the future. However, we face problems that weren't faced in 1900. Supplies of fuels currently used are depleting the cheapest sources quickly due to enormous consumption. Pollution has become a serious problem, especially in large urban areas around the world. Greenhouse gas (GHG) emissions are believed to contribute to the growing problem of global warming. Transportation applications account for a large share of fuel consumption and emissions in the United States and the world. With the risk of oil crises and government regulations, solutions in transportation technologies must deal with the problems in fuel consumption and emissions¹.

1.2 “On the Road in 2020” Report

The Massachusetts Institute of Technology Energy Laboratory released a study in October 2000 entitled *On the Road in 2020* (OTR 2020). The study provided an assessment of future vehicle technologies in light of the issues raised above. Realizing that the analysis is not limited to vehicle propulsion system performance alone, the report provides a “life cycle” analysis of potential future vehicle technologies. The life cycle includes all stages involved in bringing the fuel and vehicles together for use on the road. This brings to light the fact that fuels and vehicles which have low GHG emissions on the road but high GHG emissions in their manufacture provide no advantages over current technologies. The characteristics of each

fuel/vehicle combination were analyzed and led into the studying the impacts on the stakeholder groups involved in bringing fuels and vehicles to the road:

- Fuel manufacturers and distributors
- Providers of raw materials
- Vehicle manufacturers and distributors
- Consumers (end users) of the fuel and vehicle technologies
- Governments on all levels

A wide variety of fuels and vehicles were analyzed. Fuels included gasoline, diesel, compressed natural gas, methanol, hydrogen, and electric power. Vehicle propulsion systems included internal combustion engines (ICE), electric motors, and fuel cell systems. Included in the vehicle systems were various transmissions and body designs.

The report had no intent of predicting the future; it simply made some broad comparisons of potential vehicle technologies based on reasonable assumptions. In addition, this report has limitations as does any report of its nature – making projections of future trends. It did not consider the effects of transitioning from current to new technologies. Also, only light-duty vehicles were analyzed using the standard United States driving schedules. Clearly results could differ for heavy-duty vehicles and other driving behaviors. Lastly, the report considered only technologies believed significant for transportation purposes in 2020.

In its conclusions, the study emphasized that in a life-cycle analysis, all stakeholder groups must see benefits. Continually evolving traditional gasoline engine cars offer some advantages over current vehicles, but advances in propulsion and other vehicle technologies provide significant improvement over the evolved vehicle. More specific findings are listed as follows:

- ICE hybrids consumed 30% less fuel than their non-hybrid versions.
- Results for the fuel cell hybrid depended on the fuel:
 - Pure hydrogen gave much lower fuel consumption results.

- However, when employing a fuel processor to convert gasoline or methanol to usable hydrogen, the fuel cell system offered no fuel consumption advantages over evolved conventional ICE vehicle propulsion systems.
- Though the electric vehicle performed the best, creating the infrastructure to supply the electrical power and the limitations of battery technology negate the advantages provided by low energy consumption and emissions.

1.3 Motivation behind Study

OTR 2020 provided insight into the potential of future vehicle technologies by analyzing their life cycles from the sources of energy and raw materials to the integration of vehicle and fuel for use by the consumer market. It established a methodology that made possible further analysis of these vehicles.

However, the paper did not proceed without constructive criticism. Some parties believed that assumptions for fuel cell vehicles were too conservative and that they could out-perform future ICE vehicle technology. In addition, only two driving schedules were used to test their performance. With this in perspective, the purpose of this paper is to evaluate the performance of various potential future light-duty vehicles by exploring their propulsion systems. It aims to do so by doing with the following goals:

- Establish same or new assumptions for vehicle configurations
- Observe the effect of using more optimistic assumptions for fuel cell vehicles
- Determine the impact of driving behavior on future vehicles
- Draw broad comparisons among the various vehicles

For simplicity, not all propulsion systems evaluated in OTR 2020 were re-evaluated in this study. This paper discusses vehicles with the following propulsion systems:

- Gasoline ICE
- Gasoline ICE/electric motor hybrids
- Fuel cell vehicles using direct hydrogen

- Fuel cell vehicles using gasoline reformat
- Fuel cell hybrids using direct hydrogen (have a battery to supplement fuel cell)
- Fuel cell hybrids using gasoline reformat (have a battery to supplement fuel cell)

Methanol-powered fuel cells are not analyzed in this report. OTR 2020 provided an analysis of methanol-powered fuel cells and determined that their performance lies between fuel cells running on direct hydrogen and gasoline reformat. The same can be assumed for this study.

Just as with the OTR 2020 report, this paper does not intend to look into a crystal ball and make predictions of what the future will bring. It provides an analysis of possible technologies and intends to draw conclusions as to how they could perform in about twenty years, hopefully offering insight as to what level of vehicle technology can be expected at that time. As this paper only discusses vehicle performance, this is not a well-to-wheels study like OTR 2020. It is confined to tank-to-wheels performance.

CHAPTER 2: VEHICLE SIMULATION MODEL

2.1 Basic Description

The simulation model provides the means of providing results for the vehicle system analysis. Created at Eidgenössische Technische Hochschule (ETH) in Zurich by Guzzella and Amstutz, this model used a Matlab/Simulink interface to calculate fuel consumption for a variety of vehicle system configurations². Specifically, Matlab is used to establish the parameters describing the vehicle system and Simulink models the physics involved in the vehicle's performance. Modifications of the model were made for OTR 2020, with further changes employed for this report. This model accounts for the basic physics involved in vehicle performance, but does not account for specific details that would difficult to estimate accurately for 20 years in the future.

2.2 Simulation Overview

The structure of each vehicle system is broken down to a set of modules that model the physics of its different components. Instead of following the path of energy from the fuel through the propulsion system and transmission to the wheels, this model follows the reverse path. It back-calculates the fuel and energy consumptions by demanding the vehicle to execute a specified driving schedule. The driving schedule is one method of representing a specific driving behavior. It relates velocity against time and describes a speed profile the vehicle must execute. Chapter 3 describes the driving schedules used in this study.

For each time step (typically every second), the velocity is fed to the wheels, since the vehicle's speed is seen at the wheels. To get to the demanded speed, the vehicle must fight resistances due to friction, aerodynamic drag, and inertial requirements (force required to accelerate). Once the total resistance is calculated, it is translated into a torque required from the transmission or control logic, depending on the system configuration. The nature of the transmission and/or control logic dictates the power requirement from the power train, from which the energy requirement is calculated. In addition to details characterizing these system components (i.e. transmission, control logic, and powertrain), the vehicle configurations analyzed in this study are documented in Chapters 4 and 5.

CHAPTER 3: DRIVING SCHEDULES

3.1 Application

A driving schedule represents a driving behavior by relating a vehicle's velocity against time. Though it is impossible to identify all driving behaviors that exist, several representative driving schedules have been established. The United States Environmental Protection Agency (EPA) has created various driving schedules to test vehicles for emissions and fuel economy. Its testing involves running a vehicle on a chassis dynamometer, a mechanism that simulates driving speed. The different driving schedules are run on the dynamometer, and the propulsion system operates to match the speed. Emissions and fuel economy data are gathered and compared against the government regulations. All these schedules and test procedures for the EPA are documented in the Code of Federal Regulations³.

In addition to US driving schedules, Europe and Japan each have their own standard driving schedules based on its respective typical driving patterns to test vehicles for emissions and fuel economy. To perform vehicle analyses that account for driving patterns from around the world, this study uses driving schedules from the US, Europe, and Japan. These schedules provide the performance input to the simulation model.

3.2 Description of Driving Schedules

OTR 2020 used two driving schedules in its analysis: the Federal Test Procedure 75 (FTP 75) and the Highway Fuel Economy Test (HWFET). The former is hereafter referred to as the Urban schedule and the latter is the Highway schedule. Vehicles that enter the market in the United States have rated fuel economies based on its performance of these schedules.

The Urban schedule was created from the Urban Dynamometer Driving Schedule (UDDS). The UDDS is based on typical driving in city areas, with prescribed sequences of parking and fueling. It consists of two bags: "505" and "866." Emissions data is collected for each bag and sampled. The values "505" and "866" signify the first 505 and the last 866 seconds of the cycle, respectively. The Urban schedule takes the UDDS and adds the 505 portion on the tail end of the driving schedule. The velocity profile is shown in Figure 3.1.

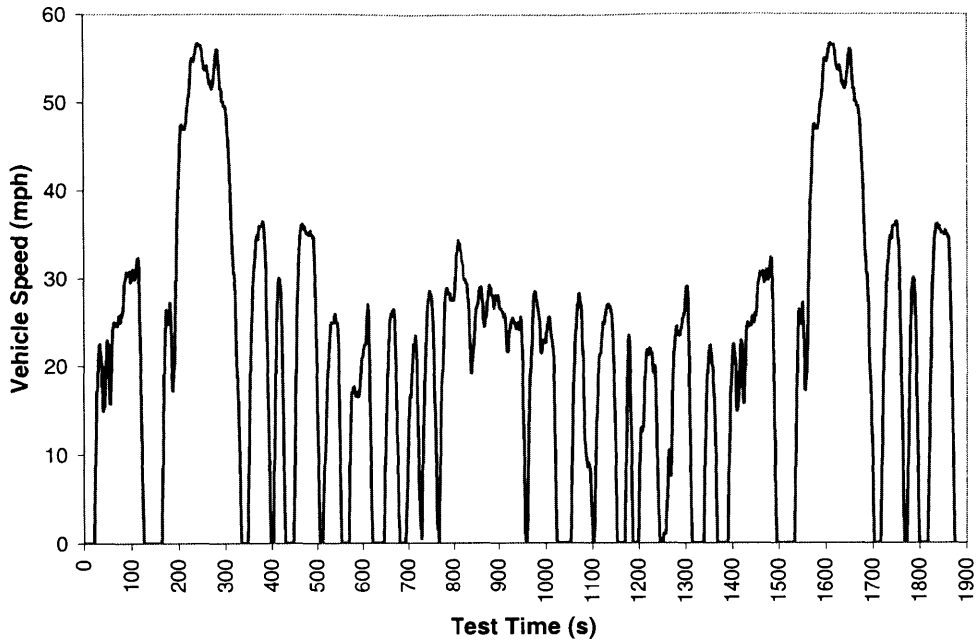


Figure 1. The Federal Test Procedure 75 (FTP 75) driving schedule

The Highway schedule represents driving on freeways. Tests using this schedule examine fuel economy performance more so than emissions. Figure 2 shows the highway schedule.



Figure 2. The Highway Fuel Economy Test (HWFET) driving schedule

The EPA determined that the Urban and Highway schedules did not adequately represent common driving behaviors. The Urban schedule did not prescribe quick accelerations and decelerations, and the Highway did not prescribe sufficiently high speeds to be representative of common driving habits. In 1996, the EPA started to employ a new driving schedule that accounts for these more aggressive demands. Named the US06, this schedule constitutes what the EPA refers to as the Supplemental Federal Test Procedure (SFTP). Seen in Figure 3, this more demanding schedule further validates a vehicle's compliance of emissions standards.

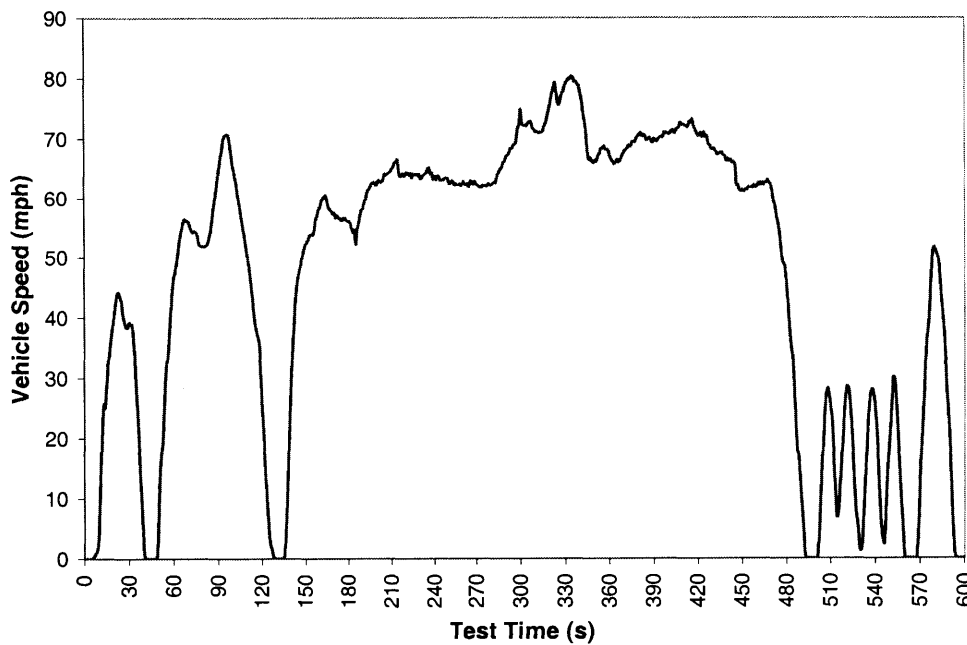


Figure 3. The Aggressive US06 driving schedule

For its emissions testing, Europe used a low-speed driving profile representing city driving (as seen in Paris or Rome) until it introduced the Extra Urban Driving Cycle (EUDC), a high-speed profile resembling the US Highway schedule. The combination of the low-speed urban cycle and the EUDC resulted in the creation of the New European Driving Cycle (NEDC)⁴. Figure 4 shows how the schedule exhibits steady speeds and accelerations as opposed to the US driving schedules.

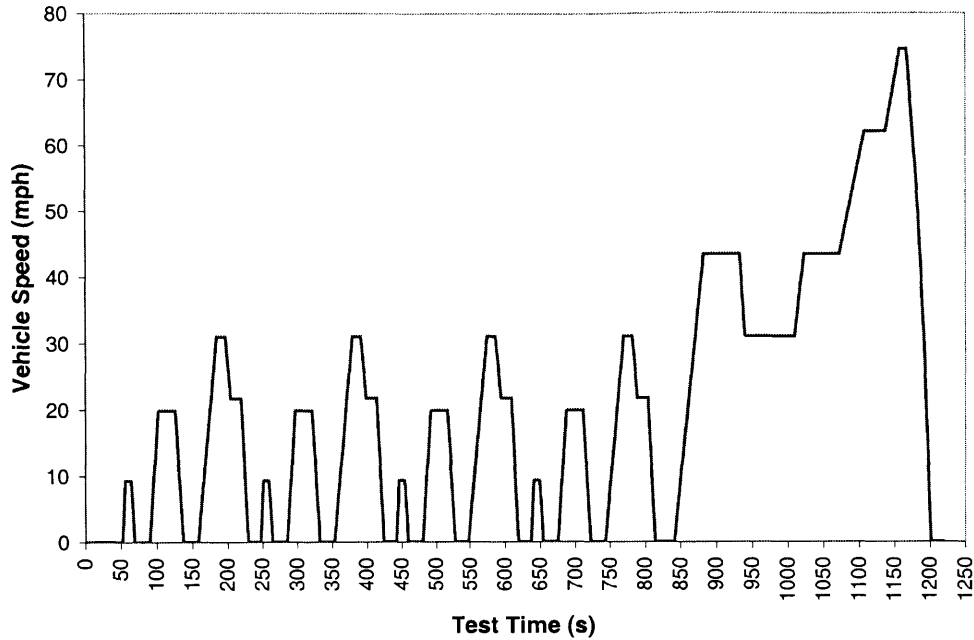


Figure 4. The New European Driving Cycle (NEDC)

Similarly, Japan added a higher-speed profile (referred to as the 15 mode) to a very low-speed, low-acceleration driving schedule (referred to as the 10 mode)⁴. The 10-15 mode resembles the shape of the NEDC, but with lower speeds, as shown in Figure 5. The cycle's significance lies in the fact that Japanese driving patterns are dominated by lower-speed, urban driving.

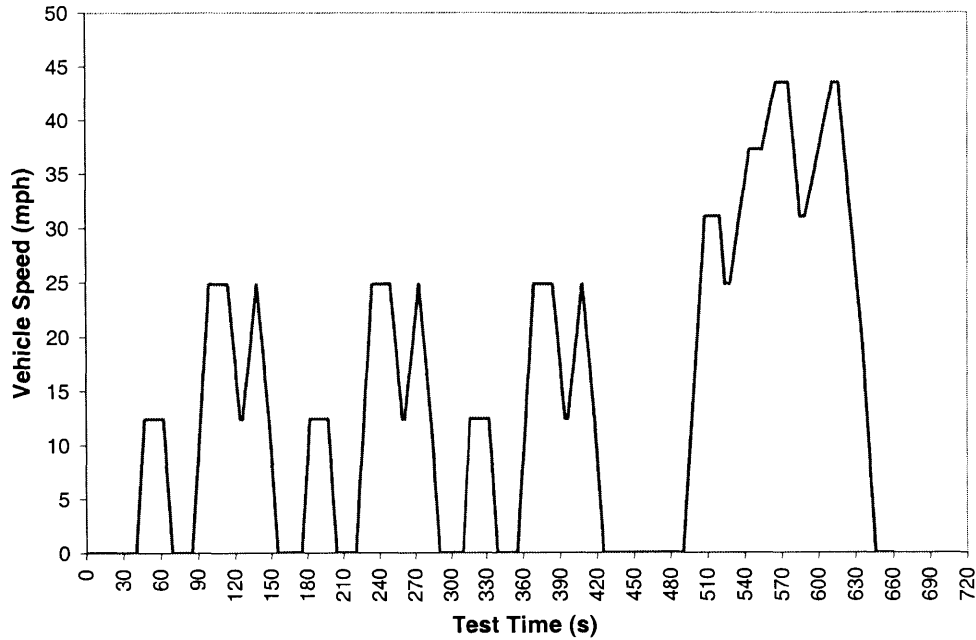


Figure 5. Japan's 10-15 mode driving schedule

3.3 Comparison of Schedules

The driving schedules described thus far demonstrate different characteristics. To compare them, the following characteristics are analyzed:

- Time duration
- Portion of time when idle
- Average speed
- Maximum speed
- Maximum acceleration

Table 1 shows the length of each cycle and the percentage of the cycle where the vehicle stands at idle.

Table 1. Time characteristics of driving schedules

Driving Schedule	Duration (s)	% of Time at Idle
Urban	1877	19.2
Highway	765	0.7
US06	601	7.5
Europe	1220	27.3
Japan	660	32.4

The Urban schedule is the longest cycle, with a substantial portion at idle. The European and Japanese schedules feature a large amount of time spent at idle. The Highway and US06 schedules have shorter durations but exhibit speeds that keep the vehicle in motion.

Figure 6 describes the speed characteristics of the driving schedules. In particular, it features the mean (average) speed and the maximum speed of each schedule.

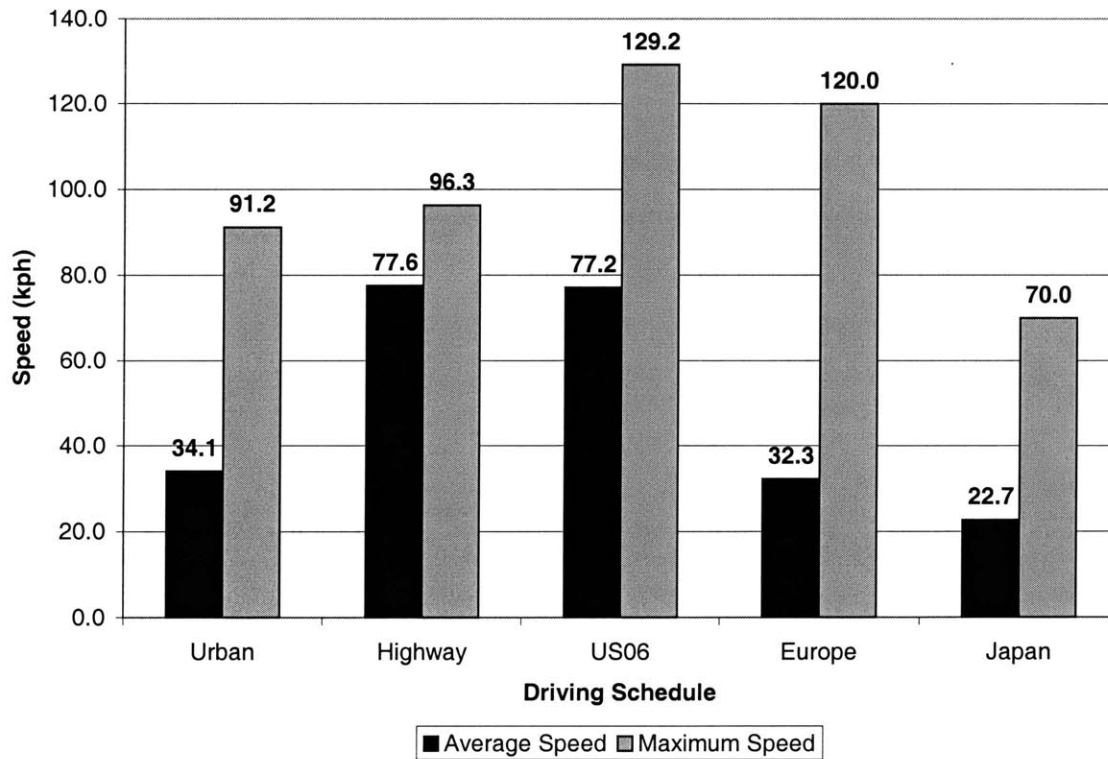


Figure 6. Average and maximum speeds for the driving schedules (kilometers per hour)

Both the European and Japanese schedules exhibit low average speeds, resulting from the substantial idling. This occurs despite the European cycle's high maximum speed from the

EUDC. The Urban and Highway schedules have similar maximum speeds, but the Highway cycle's average speed nearly matches its maximum. This demonstrates that this schedule maintains speeds near its maximum for a longer period of time, also proven by its infrequency at the idle state. The chart reveals that the US06 exhibits both a high average speed and high maximum speed. The disparity between the two indicates a large variance in its speed range.

Showing the maximum acceleration is an indication of the demands of the driving schedule. This is demonstrated in Figure 7.

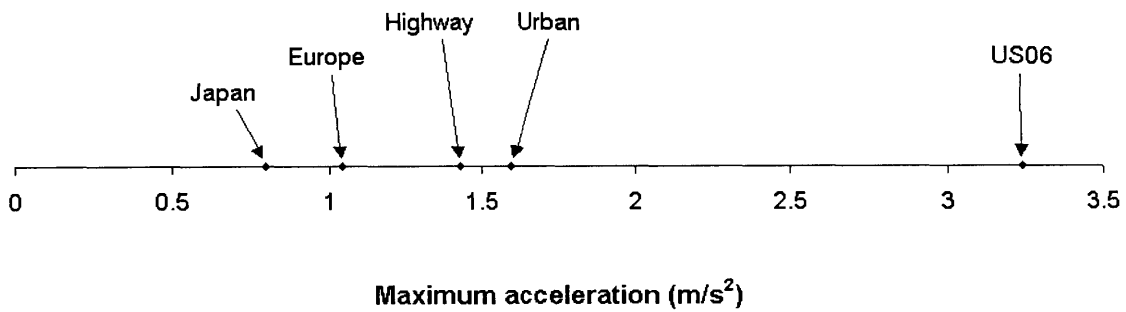


Figure 7. Maximum accelerations displayed for each driving cycle

In summary, the Japanese cycle represents the least demanding schedule in terms of speed and acceleration, while the US06 exhibits the most demanding performance from a vehicle. The Urban and the European cycles provide a diverse range of driving behaviors based on the disparity between average and maximum speeds that they demonstrate.

CHAPTER 4: ICE VEHICLES

4.1 IC Engines in Vehicle Transportation

From its inception, the internal combustion engine has developed into one of the world's most prevalent propulsion devices. The main reason behind using IC engines in vehicle transportation is their high power density or usable power per unit weight. As a heavy engine would hinder a vehicle's ability to accelerate, a light power plant that provides the necessary power for the vehicle is a necessity.

Though heat engines had existed beforehand, the ICE originated in the 19th century due to significant advances by several individuals. Two categories of IC engines have a large presence in today's world: the spark-ignition (SI) and compression-ignition (CI). The SI ICE developed from an idea of Nicolaus Otto in the mid-19th century and involves the ignition of a fuel and air mixture in a closed cylinder to produce mechanical work. The primary fuel used today in this engine is gasoline for its high energy content and volatility when ignited. This engine dominates the passenger vehicles, which comprise much of the light-duty vehicle market⁵.

The CI ICE evolved from work done initially by Rudolf Diesel, who found that injecting fuel into air heated and pressurized by compression in a cylinder did significant work with higher efficiencies than SI IC engines. The CI ICE in most cases runs on diesel fuel, as it releases its energy in conditions seen in the engine cylinder. Though they have higher efficiencies, diesel engines have high particulate and NO_x emissions, which are strictly regulated for passenger vehicles in the US. However, they meet high torque requirements as needed for towing. Thus diesels dominate the heavy-duty truck market. In Europe, diesels are prevalent in the passenger vehicles because their higher efficiencies offset the high price of fuel there.

Throughout the 20th century, an enormous amount of resources have gone into further research and development of the ICE, resulting a highly refined power plant used extensively around the world to provide the means of vehicle transportation. Entering the new millennium, more advances in ICE technology are underway in an effort to improve efficiency and lower emissions. Research in this field is in fact far from stagnant.

4.2 System Description

Vehicle comparisons in OTR 2020 included two types of ICE fuel types: gasoline and diesel. The diesel ICE showed the better efficiencies (lowest energy consumption) than the gasoline ICE. This study focuses on gasoline ICE propulsion systems rather than diesel for several reasons despite having lower efficiency. First, emissions standards for diesel engines are becoming more restricting, thus more emphasis will be placed on gasoline engines pending improvements in diesel engine emissions. Second, IC engines running on gasoline provided a more direct comparison with fuel cells running on gasoline-reformed hydrogen (discussed in Chapter 5), eliminating any differences caused by choice of fuel. Third, since few modifications were made to the model used in OTR 2020, the results for the diesel engine should consistently show improved efficiency than gasoline engines, as proven in OTR 2020.

The vehicle models used in this study are built from those used in OTR 2020, which are described in detail in AuYeung, 2000⁶. Any modifications made to the models for this report are documented henceforth. Unchanged portions are simply summarized for the sake of cohesion.

The conventional ICE vehicle model takes the driving schedule as its input and back-calculates fuel and energy consumption data in the following steps:

1. Every second, the torque and speed required at the wheels to achieve the demands of the driving schedule.
2. Torque and speed requirements at the wheels is input to the transmission model and results in the torque/speed needed from the ICE.
3. Fuel needed to provide the torque/speed is calculated with the engine model.
4. Fuel requirements are translated into fuel consumption (L/100 km) and energy consumption (MJ/km) data.

The torque and speed required at the wheels is determined by calculating the resistances needed to be overcome by the vehicle to achieve the speed prescribed by the driving schedule. Three resistances exist for a flat grade:

1. Rolling friction:

$$F_{friction} = \mu_{roll} mg \quad [1]$$

2. Aerodynamic drag:

$$F_{drag} = \frac{1}{2} c_d \rho_{air} A_f v^2 \quad [2]$$

3. Force needed to accelerate:

$$F_{accel} = ma \quad [3]$$

Converting force to torque by multiplying by wheel radius and translational speed to angular speed by dividing by wheel radius, these values are what is required by the transmission. The transmission model consists of two main parameters: efficiency and gear ratio. The efficiency for transmissions is estimated to be 88% in 2020, up from today's typical 75-80%. For simplicity, this efficiency applies at all power levels. The gear ratios are based on values for a 5-speed transmission. The gear ratio is preset based on the vehicle's velocity at each second. The simulation is run twice for these vehicles in case the driving schedule is not met due to inadequate power. The first time the simulation is run, a script determines if the engine and transmission met the power requirements. If not, the gear number is decreased by one (downshifted), and the gear ratio changes accordingly to allow the engine to provide the appropriate power to the wheels.

All ICE efficiencies are based on values of mean effective pressure (mep), which is the work done per cylinder volume in an engine. In forward logic, fuel energy is converted to indicated engine work through an indicated engine efficiency as seen in equation 4. Indicated mep is calculated from indicated work through equation 5.

$$W_i = m_f Q_{LHV} \quad [4]$$

$$imep = \frac{W_i}{V_d} \quad [5]$$

This efficiency value is projected to be 0.41, compared to typical current values of 0.38. The usable work from the engine is less than the indicated work, since the engine has to fight frictional effects. The relation is as follows:

$$bmep = imep - fmep \quad [6]$$

where bmep stands for brake mep and fmep is frictional mep.

The simulation follows the reverse order of this logic scheme, determining the fuel energy requirement from the brake power requirement.

Using the lower heating value of gasoline (43.7 MJ/kg), the fuel energy is converted to total fuel consumption. This total consumption is divided by distance to get fuel consumption in L/100 km, the standard unit in Europe. To represent fuel economy in mpg:

$$\text{mpg} = \frac{235.21}{L / 100 \text{ km}} \quad [7]$$

4.3 ICE Hybrid Technology

Recent concern about emissions and fuel economy has sparked much interest in looking at alternative methods of vehicle transportation. Research and development has investigated battery-driven electric vehicles, which employ the electric motor as the powerplant. These offer high efficiency and no-emission functionality. However, batteries don't offer the energy capacity to drive distances capable of ICE vehicles. They must be charged from an external grid frequently to operate. This makes these electric vehicles difficult to make feasible in today's automotive market.

Nevertheless, not all is lost with electric powerplants. In fact, instead of replacing IC engines with electric motors, work was done to bring them together to incorporate the advantages of both. This has led to the rise of hybrid powertrain vehicles. Hybrid ICE vehicles use both an IC engine and an electric motor to supply substantial power and operate over a long distance without refueling while simultaneously reducing fuel consumption and emissions.

Two fundamental hybrid configurations are defined as series and parallel⁷. In the series arrangement, the gasoline engine generates electricity to power the battery, which in turn powers

the motor. The motor is the only device that powers the wheels directly. The parallel arrangement features both the gasoline engine and electric motor attached to the wheels.

Thus far, two hybrid vehicles have entered the US automotive market: the Honda Insight and the Toyota Prius. The Insight features a simplified parallel setup. The gasoline engine, made smaller to improve efficiency, runs at all times. The vehicle then employs the Integrated Motor Assist (IMA) module which supplements the gasoline engine with power from the electric motor in cases of extra acceleration and uphill climbing. The batteries are recharged primarily from regenerative braking, thus eliminating the need to supply charge to the battery from an external grid⁸.

The Toyota Prius incorporates elements of both parallel and series configurations in its hybrid methodology. The electric motor works as both a power source for the wheels and as a generator for the batteries. In low speeds, the electric motor provides all the power to the wheels while the engine either idles disengaged or is turned off. In normal city driving, the gasoline engine starts to power the wheels while the electric motor supplements it in high acceleration or uphill climbing conditions. In coasting or decelerating modes, the batteries recover energy through the motor-turned-generator. All these modes are accomplished using a planetary gear system developed for the Prius which allows for the gasoline engine to run at its most efficient levels at all times⁹.

Both vehicles incorporate the use of a continuously variable transmission. Instead of having discrete ratios the transmission can operate at, the CVT features a pulley system that adjusts to the loads of the vehicle to find the optimal ratio. In other words, the CVT has an infinite amount of gear ratios within a set range. This allows for smooth, seamless driving along with more efficient vehicle operation⁸.

4.4 Model Structure for ICE Hybrids

In addition to the system components used in the conventional ICE vehicle, the model for the ICE hybrid incorporates models for the electric motor, battery, and logic. OTR 2020 adopted a parallel hybrid setup featuring the motor bypassing the ICE and connecting to the wheels with a single gear ratio⁶. This was done to provide a closer comparison to pure electric vehicles and to improve efficiency of the vehicle. This study uses this system model.

Once the resistances at the wheels are calculated, the model determines the contributions required from the ICE and the electric motor. The possible scenarios are possible in the power logic control:

- At low loads and decelerations, only the electric motor runs. Low loads are defined by a hybrid threshold value preset for the model. For decelerations, the motor runs as a generator and provides power to recharge the batteries. Engine on/off technology allows the ICE to consume zero power in this state. Without it, the ICE would idle.
- At loads above the hybrid threshold, only the ICE runs. If the batteries are low on charge, the engine supplies additional power to recharge them. The battery state of charge (SOC) determines whether the engine recharges it. SOC is the ratio of the total amount of charge in the battery to its charge capacity. The initial SOC is 0.5, and under this value the engine operates in its recharging role in addition to any power required to drive the vehicle.
- For loads above the IC engine's capability, the electric motor assists the ICE to supplement its power input. This occurs in situations of heavy acceleration.

The efficiency of the electric motor is defined by a torque-speed efficiency map. In addition, the power inverter operates at an efficiency of 94%. For the battery, a 5% loss occurs during discharge with an additional 15% loss occurs in the charging state.

The data resulting from running the hybrid ICE simulation is fuel consumed by the ICE and final battery SOC. In addition, the model calculates the energy consumption from the fuel and battery use. However, adding the two does not accurately reflect the total energy consumption in the vehicle. Indeed, if the battery is depleted from its initial state, a certain amount of fuel is necessary to recharge the battery. Running the fuel from the tank through the engine and charging the battery, the typical efficiency is 22.5%. Thus, fuel energy equivalent to 4.4 times the energy consumed by the battery is required to accurately represent the total energy used in the battery. As a note, in most cases, the battery energy depleted is so small compared to that used by the ICE the factor is negligible.

CHAPTER 5: FUEL CELL VEHICLES

5.1 Motivation to Research Fuel Cells

Pollution and depleting sources of fuels are pressuring automotive manufacturers and energy companies to consider investigating alternative propulsion systems powered by new fuels. The goals are to use systems that run with higher efficiency to reduce fuel consumption, alternative fuels to decrease dependence on gasoline, and lower emissions of greenhouse gases and local pollutants to a level that significantly lessens its harmful impact on the environment.

This motivation has caused stakeholders to revisit an idea older than the Otto cycle: fuel cells. Sir William Grove established an experiment in 1839 that reversing the electrolysis process of water creates a voltaic potential¹⁰. While sending a current through water breaks it up into its hydrogen and oxygen parts, combining hydrogen gas and oxygen gas with the assistance of a chemical catalyst created electric current. While batteries use stored chemicals to provide electricity through electrochemical processes, fuel cells use the flow of fuel to do so.

Fuel cells provide several advantages over typical power sources in use. They

- produce no harmful emissions, unlike IC engines
- exhibit higher power densities (power per unit weight) than batteries, although lower than IC engines
- work at high efficiencies
- require few moving parts, improving their robustness

Interest in fuel cells was rekindled in the 1950's due to these attributes. Specifically, they fit the needs of the space program. Batteries needed for missions were too heavy, fuel for gas turbines and IC engines was too heavy due to low efficiencies, and nuclear power wasn't practical for short time frames. Like many other technologies concerned with the space program, fuel cells were considered for land and sea. Namely stationary power generation, auxiliary power applications, and vehicle technology presented the main arenas of fuel cell development¹¹.

A couple examples of fuel cell applications in development and use today are the breathalyzer and cellular telephone power supply. The breathalyzer detects the blood-alcohol

level of an individual and is commonly used by law enforcement to prevent drunken driving. When one breathes into the device, the ethanol in the stream is chemically broken down to create a voltaic potential. A certain potential indicates the alcohol amount in the bloodstream¹⁰.

Recent developments in cellular phone technology have introduced fuel cells as a potential means of power supply to substitute for the battery in the far future, though not available as of yet in the worldwide market. The performance of batteries in cellular phones is limited by its low storage capacity. When in use, the batteries drain from full charge too quickly. Fuel cells offer longer duration limited by the amount of fuel (methanol) that can be stored¹². When the fuel runs out, the cartridge containing the methanol is simply replaced. This also has potential use in other handheld devices, such as palm pilots and laptop computers. In this manner, fuel cell technology is taking steps to becoming more significant in today's world.

5.2 The Proton Exchange Membrane

Typically a fuel cell consists of a catalytic anode, a catalytic cathode, and an electrolyte. In general terms, fuel flows to the anode. At the anode, the catalyst takes electrons from the fuel and sends them through the external circuit to the cathode. The positively charged remainder of the fuel passes through the electrolyte to the cathode, where it reacts with the electrons returned from the circuit. The premise behind the operation of the fuel cell is that the electrons are separated and sent through the circuit to create an electric potential. If this does not occur, then the system serves no purpose but transport. The catalyst serves the purpose of allowing the fuel cell to function more efficiently.

Several types of fuel cells exist, categorized primarily by the electrolyte material. Each type offers unique advantages and disadvantages since they operate using different materials at different temperatures. For vehicle applications, the appropriate choice allows for quick startup and simplest design, which requires low operation temperature and simple chemical reactions. This is satisfied with the Proton Exchange Membrane (PEM).

The PEM features a solid, immobile electrolyte. Figure 8 shows the schematic depicting the basic operation of the PEM. Hydrogen gas comes in contact with the anode, which splits it into protons and electrons. The proton-rich electrolyte allows the passage of protons, while a catalyst draws the electrons into a circuit around the cell. At the cathode, the protons combine

with the electrons that traveled through the circuit and oxygen gas from the air to produce the fuel cell's major byproduct, liquid water.

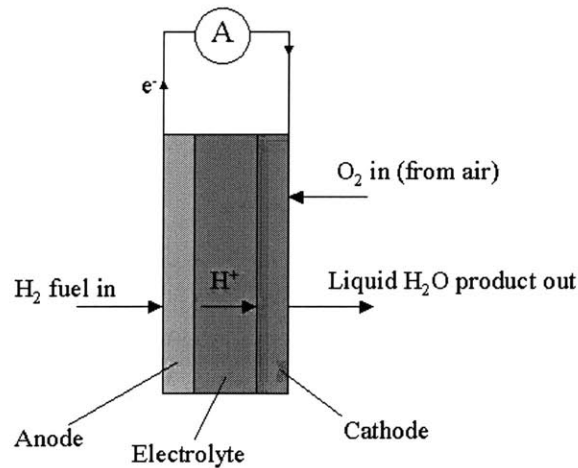


Figure 8. Basic schematic of PEM fuel cell

Equations 7 and 8 outline the chemical reactions at the anode and cathode, respectively. Equation 9 represents the net chemical reaction¹⁰.



The low operating temperature (for this study, 80°C) allows the PEM to start-up relatively quickly from ambient conditions relative to other fuel cell types. However, this also hinders the chemical processes involved in the reactions. A major disadvantage with PEM fuel cells is its need for platinum catalysts to allow them to serve their function. Platinum is, of course, very expensive, though improvements in the technology have reduced its cost impact on entire fuel cell systems¹¹. Fuel cell options that use catalysts made of cheap materials must run at higher temperatures, which does not allow the fuel cell to startup quickly enough to satisfy vehicle transportation demands.

5.3 Fuel Cell Voltage Output

Henceforth, this chapter aims to describe the new assumptions for fuel cell vehicles by investigating each part of the system individually and comparing their assumptions to those used in OTR 2020. These parts include the following:

- Individual fuel cells, which comprise the stack
- Fuel processor assemblies
- Auxiliary systems that assist the operation of the stack
- Fuel processor assemblies that provide on-board hydrogen generation

The voltage output from an individual fuel cell is limited by the electrochemical reaction taking place. Accordingly, for a reaction involving hydrogen gas and oxygen gas to make liquid water, the ideal voltage for a cell is about 1.22 V at 80°C and atmospheric pressure of reactants. Since PEM fuel cells operate below water's boiling point, the actual voltage divided by this ideal voltage corresponds with the higher heating value (HHV) efficiency. In contrast, combustion that takes place in a gasoline ICE produces gaseous water (among other products); thus all efficiencies are reported as lower heating value (LHV) figures.

Figure 9 plots the cell potential of an individual cell against current density when operating on a direct hydrogen feed. This data is based on figures from a current fuel cell developed at Ballard¹³. An additional 0.05 V is added to Ballard's data representing feasible improvement by 2020 in fuel cell technology.

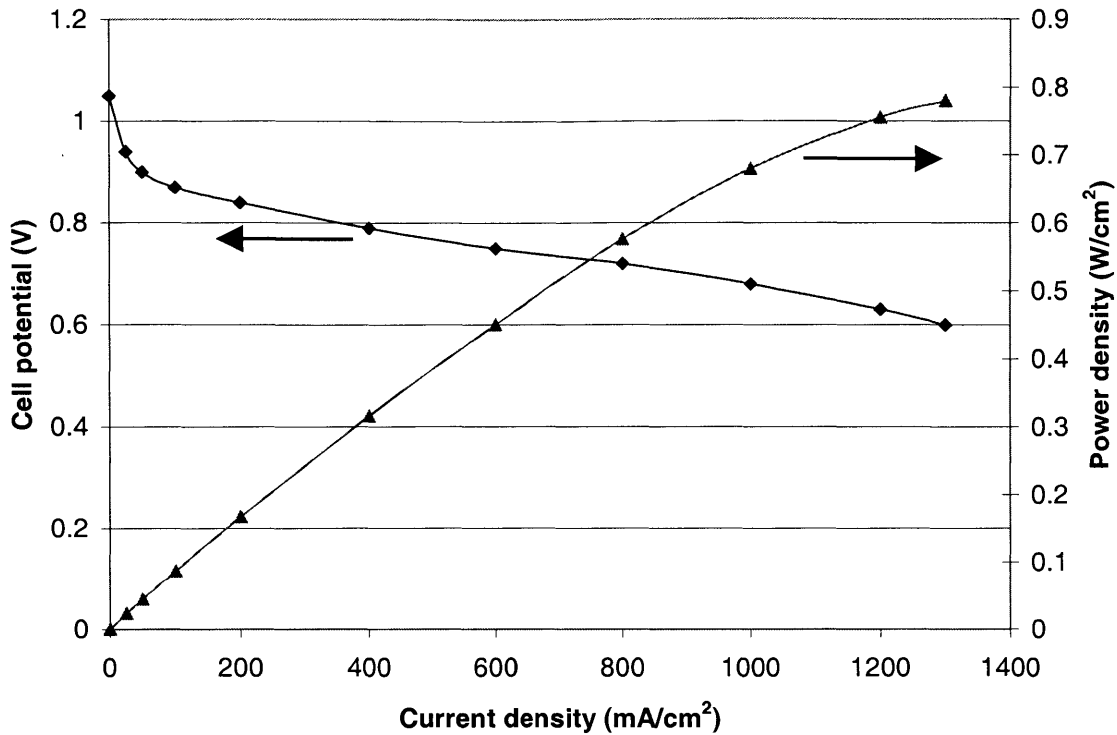


Figure 9. Cell polarization curve for PEM fuel cell

The power density is calculated simply by multiplying the cell potential by the current density. Here density refers to a quantity per unit area (in this case, square cm). This area indicates the amount of active area of the fuel cell, given by the size of the electrode. More electrode area allows more chemical reactions to occur, increasing the total power capability of the fuel cell.

The cell potential never reaches the ideal 1.22 V. Three kinds of losses affect the shape of the curve¹⁰:

- **Activation losses:** Occurring at low current densities, these losses are caused by the chemical reactions happening slowly. Some potential is lost trying to facilitate the reaction.
- **Ohmic losses:** The mid-range of current densities shows a linear drop in voltage. This is caused by resistances in the fuel cell, as voltage is linear with current when a constant resistance is applied.

- Concentration losses: The power density graph levels out at 1300 mA/cm². At higher current densities, it will drop off, caused by dramatically decreasing cell potential. This is caused by the inability of the fuel cell to adequately transport the reactants and products in and out of the fuel cell.

Because of these losses, the fuel cell is not a 100% efficient device. However, it runs at least 50% efficient in the range of current densities displayed in Figure 9.

5.4 The Fuel Cell Stack

Practical fuel cells are typically designed to run at an average of around 0.7 V. Clearly, an electric motor powering an automobile required much more than 0.7 V. Since PEM fuel cells have a sandwich structure, connecting many a PEM in series dramatically increases the operating voltage of the fuel cell. Stacking PEM fuel cells supplies an appropriate amount of power to supply to a vehicle's electric motor. The resulting configuration is referred to as the fuel cell stack. In addition to increasing the voltage, stacking fuel cells increases the active electrode area and therefore the power of the fuel cell system.

Designing a fuel cell stack requires knowledge of the trade-offs involved. Running at current densities higher than that which exhibits maximum power density is unwanted: a lower power density is achieved operating at excessive currents. Operating at a lower current density clearly increases efficiency. However, the active area must be increased to achieve the same power output. This has a direct effect on the cost and weight of the stack. This study sets the standard design operating point of stacks to the current density at which maximum power density is exhibited.

The efficiency used in this report for the fuel cell stack are based on the data in Figure 9. OTR 2020 uses a different relationship to describe fuel cell efficiency. The curve, taken from Thomas et al.¹⁴, relates efficiency to gross power. To compare the new and old assumptions, a stack was "created" from the values in Figure 9. The results of this comparison are documented in Figure 10.

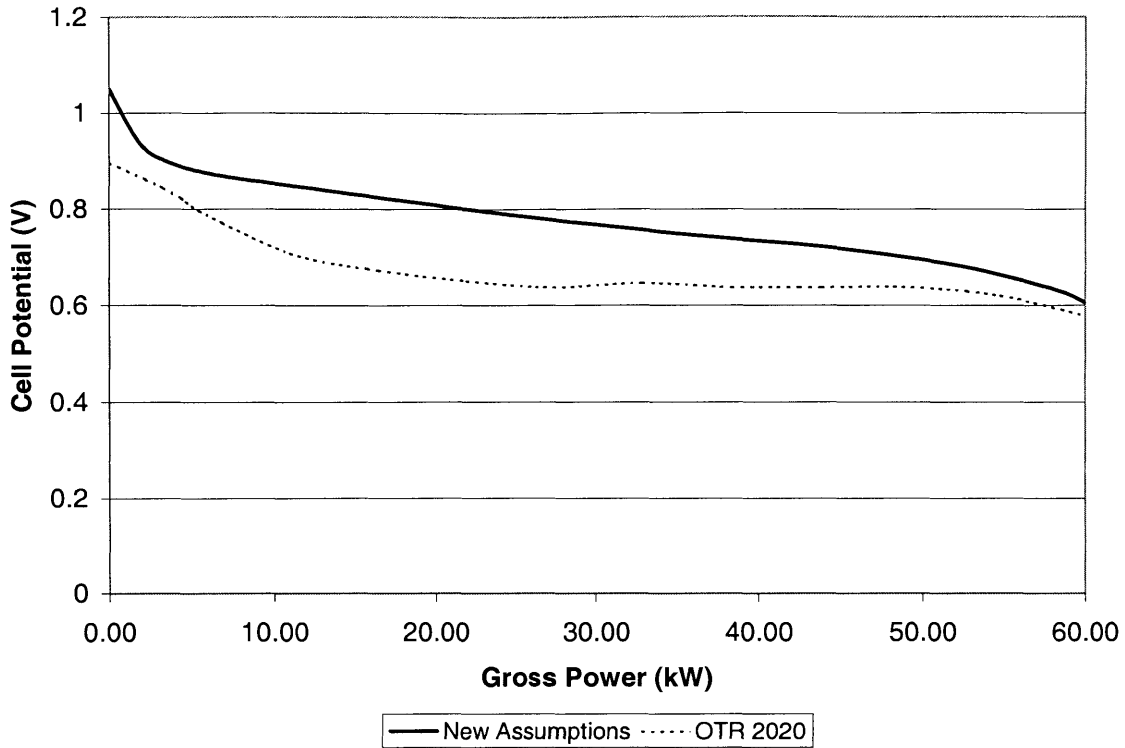


Figure 10. Equally-sized fuel cell stacks using data from OTR 2020 and this study

The stack can't run standalone; it requires compressors, pumps, blowers, and other auxiliaries to supply the fuel and air to the fuel cells and to manage the water and heat generated¹⁰. As with all devices, these operate at a less than perfect 100% efficiency. OTR 2020 assumed a constant percentage of power required for auxiliary systems: 15%. In reality, these auxiliary systems operate at lower efficiencies at low loads due to thermodynamic constraints. Table 2 shows the auxiliary power losses compared with the stack gross power level, defined as the power before auxiliary losses are included. These values are based on Figure 1 of Thomas et al¹⁴.

Table 2. Power required for fuel cell stack auxiliaries

% of Design Peak Gross Stack Power	Power for Auxiliaries as % of Stack Power	OTR 2020 Assumed Auxiliary Power
5	15	15
10	12	15
20	10	15
30	10	15
100	10	15

5.5 Fuel Processor Assemblies

A major obstacle for fuel cells to succeed as a means of vehicle propulsion lies in the lack of fuel infrastructure to supply direct hydrogen. The means for off-board generation of hydrogen and storing it in the vehicle presents a considerable challenge to fuel cell developers. An alternative strategy that has strong presence in the fuel cell world is the use of fuel processors in the vehicle.

Fuel processors take liquid fuels and through a series of chemical processes creates a stream of hydrogen gas that is subsequently fed to the fuel cell. Having such devices in the vehicle allows for the on-board generation of hydrogen for the fuel cell system. The advantage with this concept lies in the fact an infrastructure already exists for reformers: gasoline supply stations. The development and enhancement of reformer technology allows individuals to fill up the tanks of their fuel cell vehicles with gasoline – perhaps with composition and specifications somewhat different from current ICE fuel – rather than having to install brand new hydrogen infrastructure.

One disadvantage with fuel cell vehicles running on reformat (hydrogen reformed from a HC like gasoline) is that the vehicle takes an additional loss on overall system efficiency, explicitly laid out in Section 5.7. Figure 11 demonstrates the flow of energy from the fuel intake from the fuel tank to DC power output from the fuel cell stack.

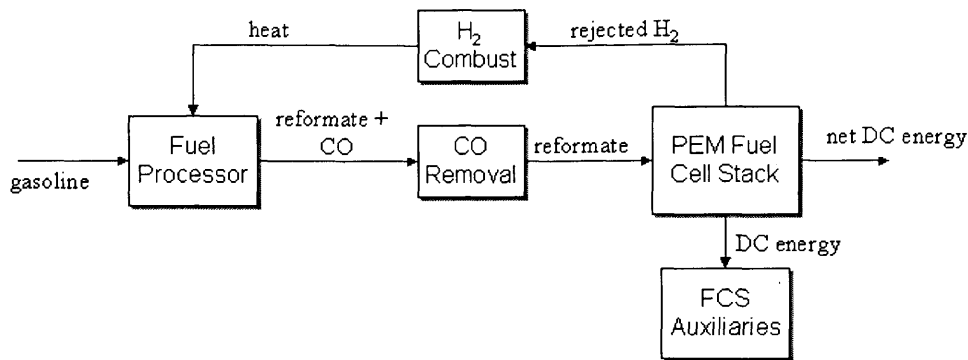


Figure 11. Schematic of fuel cell system including the fuel processor assembly¹⁵

The fuel reformer typically uses two types of chemical processes to convert HC to hydrogen gas. The first is steam reforming, which reacts HC with water vapor to create H₂ and CO, and then further reacts the CO with water to output more H₂ and CO₂. The second is partial oxidation, which similarly takes the HC but reacts it with oxygen from air to eventually produce H₂ and CO₂. The latest technology combines the two processes, since partial oxidation creates and supplies heat to the steam reforming process¹⁵.

Other than the CO in the reforming process, some residual amount exists in the reformate stream emanating from the fuel processor. The adsorption of CO onto PEM fuel cell anodes poisons the anode and causes severe degradation to the fuel cell stack¹⁰. Therefore, chemical processes are implemented to remove CO from the reformate stream.

Another disadvantage of reformate is that the hydrogen produced is dilute, typically about 40% of the total gas stream if the fuel processor is fed gasoline. Consequently, not all the hydrogen gas in the reformate is consumed by the fuel cell anode, and some unreacted hydrogen has to be vented from the stack. The percentage of hydrogen fed to the fuel cell stack that is actually consumed by the anode is referred to as the hydrogen utilization. Current fuel cells operate with 80-85% hydrogen utilization¹⁶. Though the H₂ not used is vented, it is not lost to the fuel cell system. It is combusted to produce heat for the steam reforming process. This improves the fuel processor efficiency because less partial oxidation must be enacted to provide that heat. Table 3 indicates the reformer efficiencies used for this study, assuming the 85% hydrogen utilization. Note that in OTR 2020, the gasoline reformer efficiency (LHV) was set to a constant

72.5% (79% HHV) with an addition 85% for hydrogen utilization. Issues pertaining to choice in heating value are addressed in Section 6.2.

Table 3. Efficiency of reformer operating on gasoline.

% of Design Peak Gross Stack Power	Efficiency (HHV_{H2,out}/HHV_{gasoline,in})	OTR 2020 Assumed Efficiency
5	80	79
10	86	79
20	89	79
30	89	79
100	89	79

Finally, fuel cells operating on reformat exhibit lower maximum power capabilities for a given stack size than those fueled by direct hydrogen. Figure 12 shows the cell potential and power density of a fuel cell operating on reformat. Figure 13 compares equally sized fuel cell stacks running on direct hydrogen and gasoline reformat. OTR 2020 included an additional 21.5% loss to account for this. However, this is a misinterpretation of the fact that there is a loss in maximum power in stacks operating on reformat. In reality, this lower stack capability only affects stack size and cost, not efficiency. This is a major difference that has been rectified in this study.

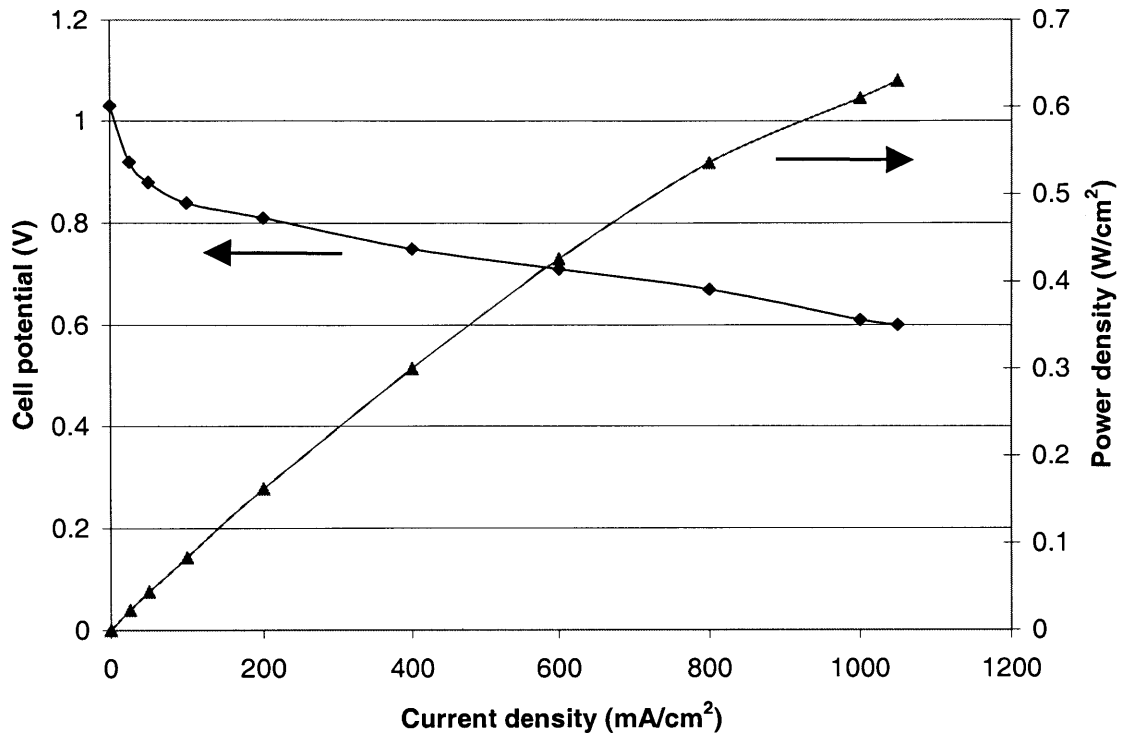


Figure 12. The power output characteristics for fuel cell fueled by reformat

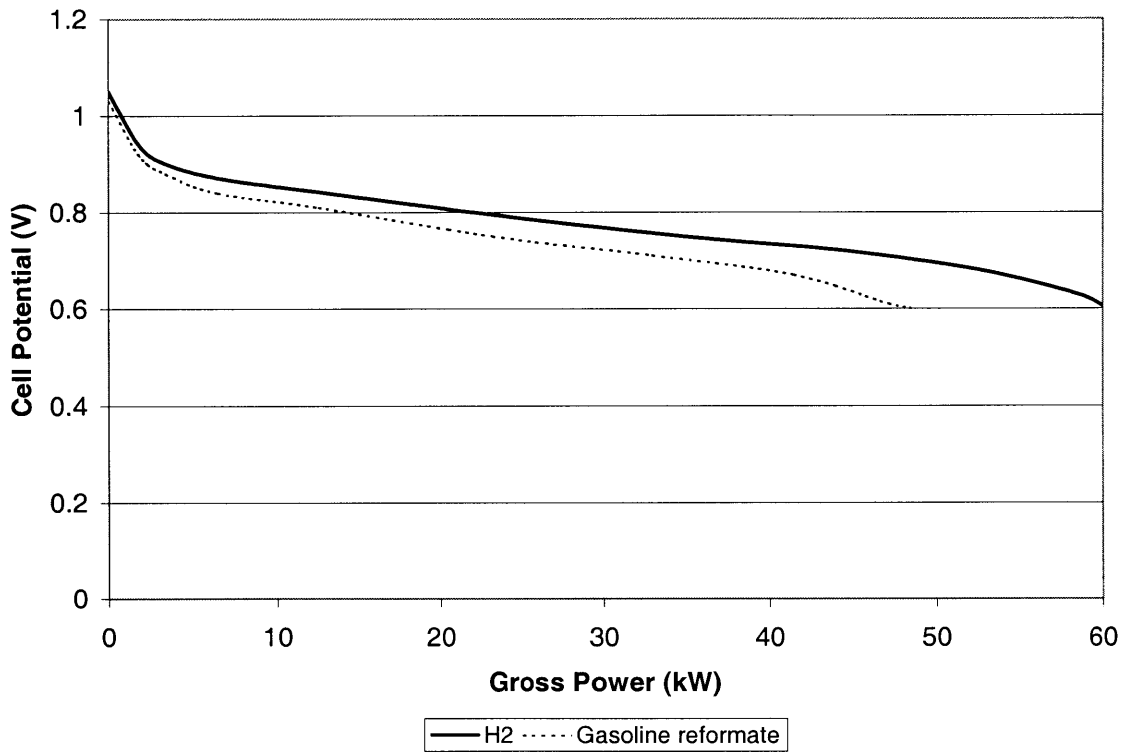


Figure 13. Equally sized stacks operating on direct hydrogen and gasoline reformat

5.6 Fuel Cell Hybrids

Just as batteries offer advantages in ICE propulsion system vehicles, they similarly do so for fuel cell vehicles. They provide opportunities to capture energy from regenerative braking, save fuel, and reduce fuel cell size. Unlike ICE hybrids, only one motor is necessary since both fuel cells and batteries supply electrical energy. Though it is not a hybrid of power trains, it is a hybrid of power sources. This paper will refer to vehicles running on fuel cells with the presence of batteries as *fuel cell hybrids*.

In addition to the fuel cell non-hybrids, a logic system determines the power split between the fuel cell and battery sources. Like ICE hybrids, batteries run the car at low powers and assists the fuel cell system at high loads. Regenerative braking is captured when the motor runs in reverse, limited by the specific power capability of the battery system.

Energy consumed in the battery must be incorporated into the total energy consumption within the vehicle. As with ICE hybrids, it is not a significant amount but should still be considered. Direct-hydrogen vehicles require a factor of 1.67 to translate energy consumed in the battery to equivalent energy from hydrogen fuel. Gasoline reformat vehicles require a factor of 2.3.

5.7 Model Structure for Fuel Cell Vehicles

The major change in structuring the fuel cell vehicle model lies in the fuel cell system. In a simulation that back-calculates, the power necessary to drive the electric motor is sent through the auxiliaries, then the stack, then the reformer where one exists to compute the fuel energy required from the tank. The efficiency of the auxiliaries is listed in Table 2 and that of the reformer system is listed in Table 3. Since these values depend on the maximum power of the fuel cell stack, this is the first parameter to be established.

The maximum power is determined by setting the maximum power per vehicle weight (OTR 2020 used 75 W/kg). Once this is set, the relationship between auxiliary system efficiency and power level is established from Table 2, as is the reformer efficiency from Table 3. For reformer systems, an additional 85% efficiency resulting from hydrogen utilization is incorporated.

The stack presents more involved computation. At higher current densities, the cells run less efficiently. At a set power level, increasing the active area decreases the current density, allowing the system to run more efficiently. However, tradeoffs arise because the system becomes larger, adding to vehicle load and total cost. Table 4 describes the weight and cost characteristics of fuel cell systems as predicted for 2020 along with DOE targets. The figures used in this study are based on current fuel cell systems available from Ballard. Cost figures were established to match DOE targets. This simply provides an optimistic outlook for the pricing of these systems, and represent about half of the cost established in OTR 2020.

Table 4. Optimistic cost and weight projections for fuel cell systems in vehicles.

Per Net kW at Design Peak Power	100% Hydrogen (Compressed gas)		40% Hydrogen (Gasoline reformat)	
	\$	kg	\$	kg
Stack and Auxiliaries*	28	1.8	35	1.8
Processor**	--	--	10	1.2
Total system***	28	1.8	45	3
US DOE long-term (~2008) targets for total system	28	1.8	45	3
US DOE current (2001) status	--	2.3	300	7
Assumptions in MIT report <i>OTR 2020</i> for total system	60	2.9	80	4.8

The choice in the design point (maximum current density allowed) affects these attributes. As stated earlier, this study chooses the design point at maximum possible power density. From this point, increasing the current density reduces both power density and efficiency, a useless endeavor. Lowering the current density allows one to determine a system more efficient but more costly and heavy. The maximum power density is about 20% less for gasoline reformat fuel cell systems. The values in Table 4 represent weight and cost at the maximum power density of the fuel cell stack.

From the design point, the active area is determined and used to calculate the stack efficiency curve: efficiency versus power level. Added to the auxiliary system and reformer

efficiencies, the fuel cell system is established. In addition, this establishes the system weight and cost. When the weight is calculated, this affects the total vehicle weight and the maximum power. This causes a need to recalculate the propulsion system weight. A modest iteration in Excel is employed to perform this computation.

Once the system is established, fuel and energy consumptions are calculated. For fuel cell hybrids, logic control after the electric motor and a battery parallel to the fuel cell are added. Energy calculations are calculated for both fuel cell and battery power sources.

CHAPTER 6: RESULTS AND DISCUSSION

6.1 Review of simulation parameters

Table 5 lists and describes those propulsion systems deemed feasible to operate light-duty vehicles in 2020:

Table 5. Propulsion systems analyzed in study.

Propulsion System	Description
Gasoline ICE	Conventional vehicle powertrain.
Gasoline ICE hybrid	Powertrain consisting of ICE and electric motor running in parallel.
Hydrogen FC	System consisting only of a fuel cell operating directly from hydrogen.
Gasoline FC	Like the Hydrogen FC, but operating on gasoline reformat instead.
Hydrogen FC hybrid	Hydrogen FC with addition of a battery.
Gasoline FC hybrid	Gasoline FC with addition of a battery.

All systems have advanced body designs with parameters documented in OTR 2020. The benefits of one propulsion over another may depend on the driving behavior. To determine whether such advantages are consistent over different driving styles, the driving schedules listed in Table 6 are used in this report.

Table 6. Driving schedules used in study.

Driving Schedule	Description
Urban	The US FTP 75 schedule, which describes typical city driving.
Highway	The US HWFET schedule, which describes highway driving.
US 06	The US06 schedule, which exhibits aggressive speed and acceleration.
Europe	The NEDC schedule, used in Europe for emissions and fuel economy tests.
Japan	The 10-15 mode, which Japan uses for its driving standard.

6.2 Heating Value

For ICE powertrains, the choice for the fuel's energy content has defaulted to its lower heating value (LHV). This has practically suited because of the nature of the combustion within

the engine: the fuel is reacted to produce gaseous water. Thus far, the LHV has been the appropriate measure.

However, with the introduction of PEM fuel cells, the temperature at which the reaction between hydrogen and oxygen takes place is below the boiling point of water. With liquid water as the product of said reaction, the higher heating value (HHV) is the applicable measure.

In keeping consistent with OTR 2020, the LHV is used. It should be noted that the appropriate measure for PEM fuel cell vehicles is HHV, but adjustments are made to keep consistent the energy consumption values reported. Additionally, any fuel consumption figures for vehicles operating on direct hydrogen fuel feed are given in gasoline-equivalent liters per 100 kilometers. This is computed using the LHV of gasoline.

6.3 Table of Results

Table 7 contains the following information:

- Energy consumption values based on the lower heating value of the fuel
- Gasoline-equivalent fuel consumption values
- Cost figures based on both optimistic DOE targets and more conservative OTR 2020 assumptions
- Vehicle configuration parameters that are most significant to given results

The parameters for the conventional gasoline ICE and the ICE hybrid are similar to those used in OTR 2020, while the methodology and system setup for the fuel cells are changed to account for the new assumptions in modeling. The Appendix breaks down each vehicle configuration into more detailed parameters.

Table 7. Fuel and energy consumption results for different vehicle configurations

Propulsion System		SI ICE	SI ICE	FC	FC	FC	FC
Fuel		gasoline	gasoline	gasoline	hydrogen	gasoline	hydrogen
Hybrid		non	hybrid	non	non	hybrid	hybrid
Total Mass	kg	1136	1155	1444	1229	1362	1209
Maximum Power	kW	85.2	86.5	108.3	92.2	102.1	90.6
Max. Battery Power	kW	0	28.8	0	0	34	30.2
Fuel Consumption	L/100 km						
Urban		5.545	4.003	3.783	2.563	2.974	2.125
Highway		3.874	3.035	2.534	1.820	2.268	1.674
US06		5.187	4.916	4.490	3.223	4.106	2.968
Europe		6.357	3.245	3.747	2.513	2.671	1.926
Japan		7.526	3.719	4.263	2.802	2.786	1.972
LHV Energy Use	MJ/km						
Urban		1.786	1.289	1.219	0.698	0.972	0.589
Highway		1.247	0.953	0.816	0.495	0.737	0.463
US06		1.671	1.462	1.447	0.877	1.176	0.730
Europe		2.047	1.320	1.207	0.684	1.011	0.613
Japan		2.424	1.419	1.373	0.763	1.117	0.669
Cost	\$						
DOE targets		19400	21100	21100	19300	20600	19900
OTR 2020 targets		19400	21100	24900	22200	23000	21800

6.4 Comparison of Non-hybrid Vehicles

The three non-hybrid vehicles are the conventional gasoline ICE, the fuel cell operating on gasoline reformat, and the fuel cell running on direct hydrogen feed. As no battery enters the picture, this comparison indicates differences in performance among the various propulsion systems. Figure 14 shows the fuel consumption results for these vehicles organized by driving schedules.

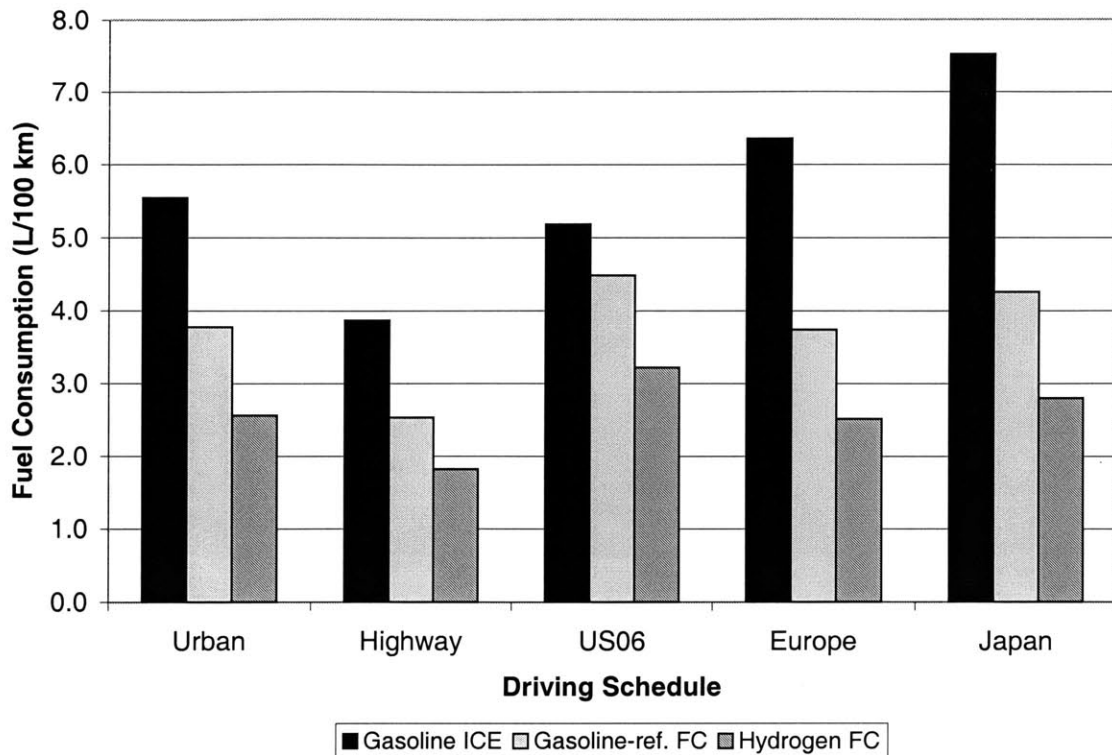


Figure 14. Comparison of non-hybrid vehicles

Clearly the fuel cell vehicles consume less fuel than the conventional gasoline ICE vehicle. Table 8 lists the fuel consumption reductions for these along with cost estimates. It can be observed that for both fuel cell vehicles the US06 cycle presents less fuel consumption reduction than the other cycles. It still provides lower consumption, but the fact that the powertrain runs at higher loads – thus giving lower efficiency – reduces the fuel consumption advantage provided with the other cycles. The Japan and Europe schedules provide more reduction in fuel consumption because these schedules operate the fuel cell system at lower loads and thus higher efficiencies.

Table 8. Fuel consumption reduction in fuel cell vehicles

	Gasoline ICE	Gasoline-ref. FC		Hydrogen FC	
	L/100 km	L/100 km	% reduction	L/100 km	% reduction
Urban	5.545	3.783	31.8	2.563	53.8
Highway	3.874	2.534	34.6	1.820	53.0
US06	5.187	4.49	13.4	3.223	37.9
Europe	6.357	3.747	41.1	2.513	60.5
Japan	7.526	4.263	43.4	2.802	62.8

6.5 Comparison of Hybrid Vehicles

To take advantage of regenerative braking and power assist capabilities, batteries are introduced to create hybrid vehicles. The comparison among the hybrid vehicles is similar in nature to that of the non-hybrid vehicles. However, this includes a battery in the vehicle configuration.

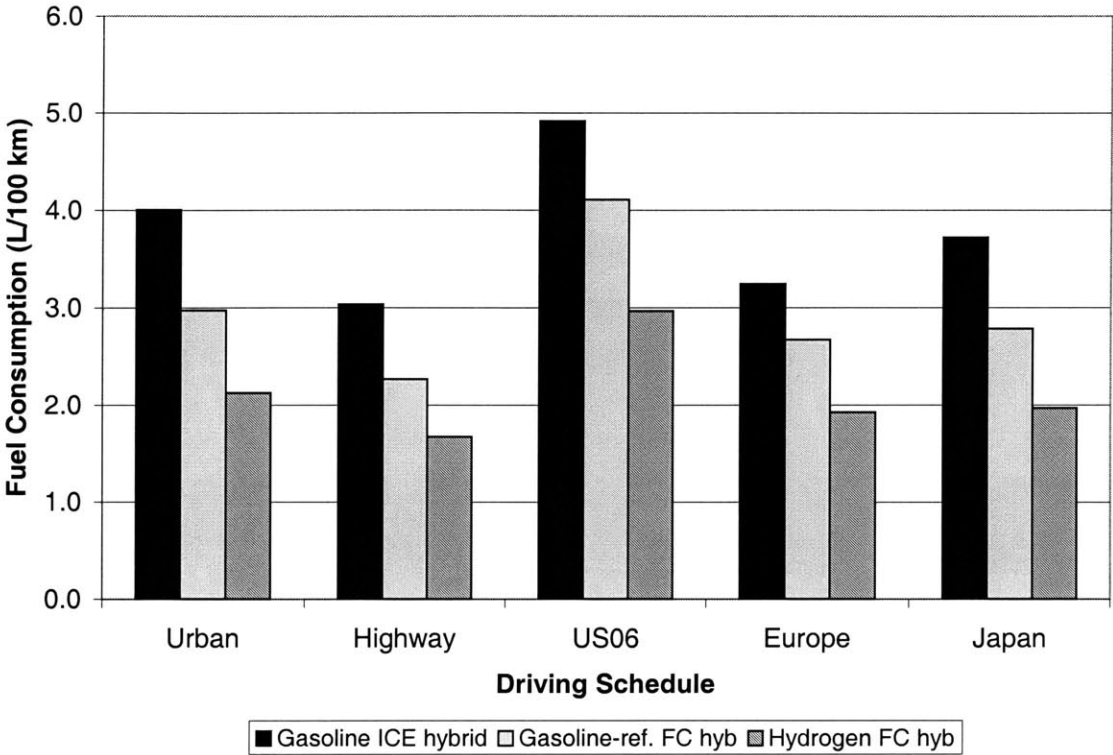


Figure 15. Comparison of hybrid vehicles

Again the fuel cell vehicles provide lower fuel consumption than the gasoline-electric ICE hybrid vehicle. Table 9 lists the percentage reduction in fuel consumption for each vehicle organized by driving cycle along with the vehicle’s estimated cost. Here the advantages are more consistent throughout the driving schedules. It seems as though the driving schedule does not impact the benefits of using a fuel cell rather than gasoline ICE, though the reduction in fuel consumption is considerable. Again, the US06 presents slightly less reduction as the other schedules, due to the fact that the fuel cell operates at lower efficiencies when observing higher loads.

Table 9. The fuel consumption reduction present in fuel cell hybrid vehicles

	Gas. ICE hyb.	Gasoline-ref. FC hybrid		Hydrogen FC hybrid	
	L/100 km	L/100 km	% reduction	L/100 km	% reduction
Urban	4.003	2.974	25.7	2.125	46.9
Highway	3.035	2.268	25.3	1.674	44.8
US06	4.916	4.106	16.5	2.968	39.6
Europe	3.245	2.671	17.7	1.926	40.6
Japan	3.719	2.786	25.1	1.972	47.0

6.6 Impact of Battery in Hybridization of Vehicles

In comparing the hybrid vehicles, the issue of hybridization arose as a major factor in determining the impact of the propulsion systems on fuel consumption. Figure 16 represents the impact of hybridization on gasoline ICE vehicles by comparing the conventional gasoline ICE with the gasoline ICE hybrid.

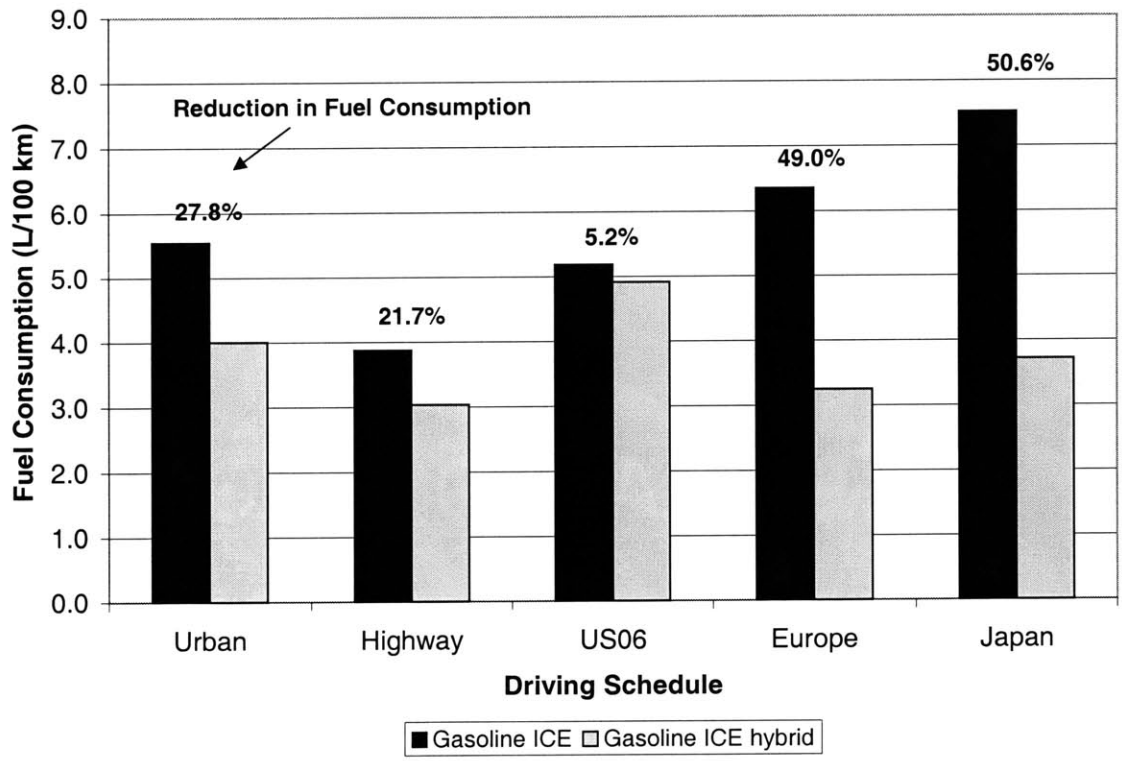


Figure 16. Effects of hybridization on gasoline SI ICE vehicles

It shows that driving the Europe and Japan schedules cuts fuel consumption in half, while only barely reducing the fuel consumption for the US06 schedule. Since the Europe and Japan schedules operate the vehicle at low loads, batteries power the car for a significant amount of time. This allows the engine to remain off. The gasoline ICE consumes a lot of fuel because the vehicle operates on lower gears, getting less distance for more fuel. On the other hand, the US schedules – particularly the US06 – require more engine power and thus more fuel.

Figure 17 shows the impact of hybridization on fuel cell vehicles running on gasoline reformat. A disparity similar to that observed in Figure 16 exists with the hybridization of gasoline reformat fuel cells. Again, the Europe and Japan schedules offer much more of a benefit when hybridization is introduced. However, hybridizing the fuel cells appears to provide less benefit than it does for gasoline IC engines. The higher efficiencies exhibited by fuel cells than for IC engines accounts for this difference.

When operating the fuel cell at low loads, the battery takes on a more significant portion of the power demand, saving fuel during the execution of these driving schedules. The US06 still demands more power from the primary propulsion system, in this case the fuel cell system.

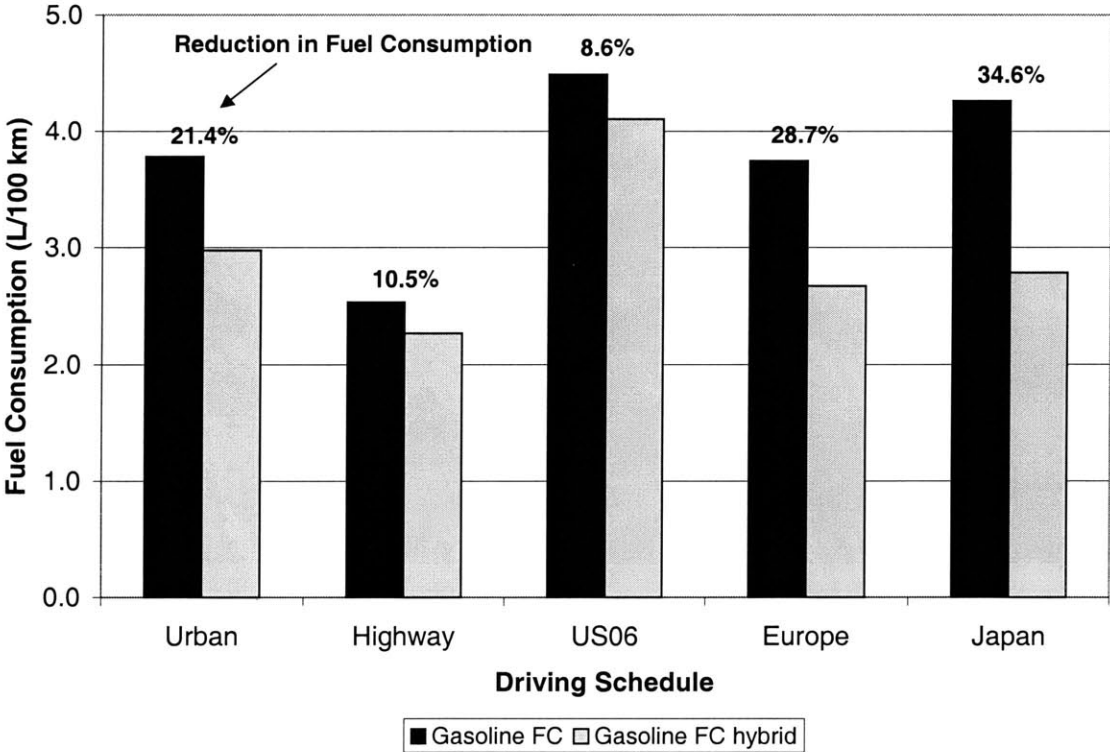


Figure 17. Effects of hybridization on fuel cell vehicles operating on gasoline reformat

Similarly, the hybridization of hydrogen fuel cells exhibits the same sort of advantages as that of the other propulsion systems, as shown in Figure 18. Again, the large improvement in the Europe and Japan driving schedules and the small improvement in the US06 schedule are due to the power demands of the propulsion system operating from the primary fuel (hydrogen). In addition, regenerative braking allows for more fuel reduction in the Europe and Japan schedules since the considerable amount of coasting and braking charges the battery, thereby allowing more power to be extracted from it rather than the primary fuel. From Figures 14 to 18, fuel consumptions vary depending on the driving schedule performed. In addition, the reduction in fuel consumption varies for each vehicle propulsion system depending on the driving schedule. However, the benefits of hybridization are consistent throughout all vehicle propulsion types: gasoline SI ICE, fuel cell operating on gasoline reformat, and fuel cell running on direct hydrogen feed.

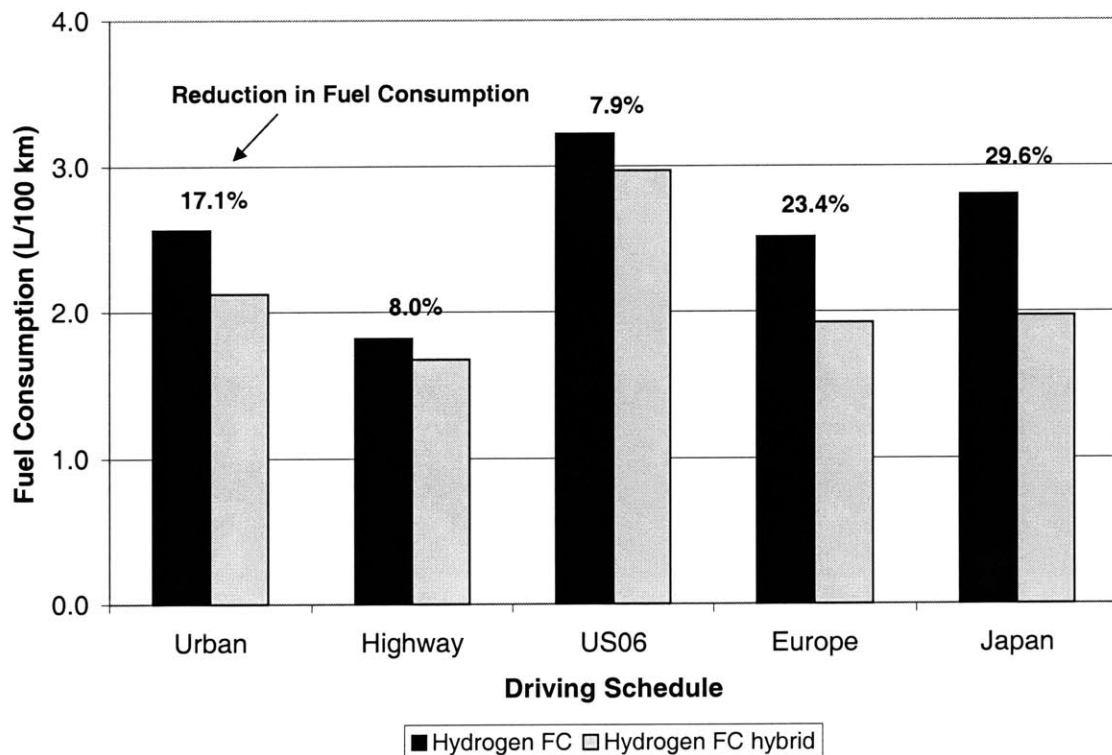


Figure 18. Effects of hybridization on fuel cell vehicles operating on direct hydrogen feed

6.7 Limitations

By no means do the results documented fully explain the performance of future vehicles. They simply provide some indication of the performance of these vehicles based on assumptions and parameters set in this study. Many factors must be addressed when implementing these technologies into vehicles viable and practical for personal transportation needs. Such factors include hybridization variables (size of battery and hybrid power threshold); the introduction of towing and grade into vehicle performance; optimizing fuel cell stacks for cost, weight, and efficiency; and designs of chassis and body. However, this study takes from OTR 2020 a well-defined methodology to understand and analyze potential vehicle technologies.

CHAPTER 7: CONCLUSIONS

On the Road in 2020 concluded that gasoline-reformate fuel cell vehicles did not consume less fuel and energy than conventional ICE vehicles. To determine whether more optimistic assumptions would allow this vehicle to compete with other potential vehicles, this study made more aggressive assumptions regarding fuel cell vehicles. In addition, it investigates the effects of driving schedule on the performance and benefits seen in potential future vehicle technologies. The results gotten from the vehicle simulation tests do depend heavily on these assumptions and led to the following conclusions:

- The choice in driving schedule has a strong impact on the fuel consumption figures for any vehicle configuration.
- Comparing against the IC engine non-hybrid vehicle, the gasoline-reformate fuel cell vehicle reduced fuel consumption by typically 30-40% for most driving schedules, though the US06 schedule only improved the consumption by about 15%.
- Hydrogen fuel cell vehicles reduced fuel consumption by typically 50-60%, though the US06 schedule did so by only 35%.
- Comparing against the IC engine hybrid vehicle, reduction in fuel consumption was more consistent for fuel cell hybrid vehicles over all driving schedules tested (typically 20% for gasoline-reformate and 40% for hydrogen).
- Hybridization of all propulsion system types resulted in large reduction in fuel consumption (typically 35-50%) for European and Japanese schedules, but only about 5-15% for US06 schedules. This occurred due to differences in power demands and the presence of regenerative braking.
- Though the cost assumptions based on DOE targets are extremely optimistic, it indicates the goals needed to achieve similar costs among all vehicles. With these targets, all vehicles lie within 5% of the mean vehicle price. Using OTR 2020 assumptions, the price values vary more, with fuel processor technology contributing to a cost increase.

The results laid out in this report by no means intend to offer the answers to what personal transportation must become in the next 20 years. It only provides some insight into the potential performance of different vehicles believed feasible in 20 years based on a set modeling and analysis methodology. Issues with developing the technology to make these vehicles possible only scratch the surface concerning making them a reality in the global market. Political, economic, and social pressures will be extremely relevant in determining what vehicles will arise in the future. Governments can actively promote a vehicle with promised funding and interest. A vehicle that is technologically “perfect” may not even enter the market if consumers don’t find it a good value financially.

However, these issues shouldn’t hinder those interested to perform research and studies to learn about and develop future vehicle technologies. This report aims to give people something to consider when thinking about what the future will bring us in terms of personal transportation.

APPENDIX: ADDITIONAL PARAMETERS

Table 10. Additional parameters supplementing results given in Table 7

Propulsion System		SI ICE	SI ICE	FC	FC	FC	FC
Fuel		gasoline	gasoline	gasoline	hydrogen	gasoline	hydrogen
Hybrid		non	hybrid	non	non	hybrid	hybrid
Total Mass	kg	1136	1155	1444	1229	1362	1209
Body & Chassis		756	756	794	763	794	763
Propulsion System		217	216	497	327	372	269
Battery		12	36	0	0	43	38
Fuel		22	16	25	4	25	4
Cargo		136	136	136	136	136	136
Vehicle Parameters							
Rolling Friction Coeff.	-	0.006	0.006	0.006	0.006	0.006	0.006
Drag Coeff.	-	0.22	0.22	0.22	0.22	0.22	0.22
Frontal Area	m ²	1.8	1.8	1.8	1.8	1.8	1.8
Auxiliary Power	W	1000	1000	1000	1000	1000	1000
Engine							
Maximum Power	kW	85.2	57.7				
Engine Size	cc	1645	1306				
Transmission Eff.	-	0.88	0.88				
Indicated Eff.	-	0.41	0.41				
Frictional MEP	kPa	124	124				
Fuel Cell							
Maximum Power	kW			108.3	92.2	68.1	60.4
Design Point	mA/cm ²			630	780	630	780
Battery							
Maximum Power	kW	0	28.8	0	0	34	30.2
Specific Energy	Wh/kg	-	50	-	-	50	50
Specific Power	W/kg	-	800	-	-	800	800
Hybrid Threshold	W	-	2000	-	-	2400	2100
Fuel Consumption L/100 km							
Urban		5.545	4.003	3.783	2.563	2.974	2.125
Highway		3.874	3.035	2.534	1.820	2.268	1.674
US06		5.187	4.916	4.490	3.223	4.106	2.968
Europe		6.357	3.245	3.747	2.513	2.671	1.926
Japan		7.526	3.719	4.263	2.802	2.786	1.972
Energy Consumption MJ/km							
Urban		1.786 1.920	1.287 1.384	1.219 1.310	0.698 0.826	0.972 1.045	0.589 0.696
Highway		1.247 1.341	0.953 1.024	0.816 0.877	0.495 0.586	0.737 0.792	0.463 0.548
US06		1.671 1.796	1.462 1.572	1.447 1.555	0.877 1.038	1.176 1.265	0.730 0.863
Europe		2.047 2.201	1.320 1.419	1.207 1.297	0.684 0.809	1.011 1.086	0.613 0.726
Japan		2.424 2.606	1.419 1.525	1.373 1.476	0.763 0.903	1.117 1.200	0.669 0.791
Cost \$							
DOE targets		19400	21100	21100	19300	20600	19900
OTR 2020 targets		19400	21100	24900	22200	23000	21800

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