MODELING AND ANALYSIS OF A FUEL CELL VEHICLE

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Abstract: *This paper presents some fuel cell drive systems performances by simultion. The hydrogen consumption and the vehicle range are determined using simulation for a medium class passenger car with PEM (proton exchange membrane) fuel cell as the primary electric energy source. Regenerative braking and electrical energy management were implemented in the global model in order to have a correct determination of fuel consumption during a standard drive cycle. The closed loop control for PEM, which is necessary for maintaining a high efficiency level, is detailed as well.*
Matlab/Simulink programming environment and the power electronics library SimPowerSystems were used for modeling and simulation. While there are a number of simulation tools to choose from, each simulation model element has a suitable resolution to detailed model dynamics. The model was validated by comparison of the results with data given by manufacturer for the simulated passenger car.

Keywords: fuel cell, electric drive system, simulation, PEM, PMSM.

INTRODUCTION

In order to comply to more stringent emissions regulations for motor vehicles new solutions are implemented in the purpose of increasing the efficiency of well to wheel energy conversion, while maintaining or even increasing dynamic performance and passenger comfort. These requirements lead to reducing green house gas emissions quantified as CO_2 equivalent/100 km. A comparison between different propulsion systems based on present technology is presented in figure 1 (1).

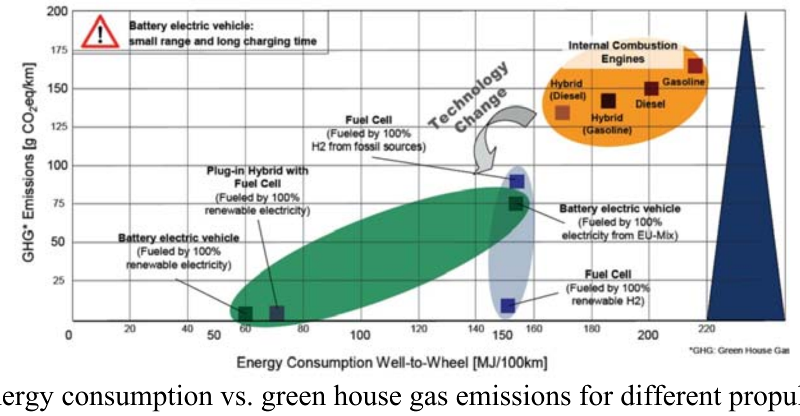

Figure 1. Energy consumption vs. green house gas emissions for different propulsion systems

Electric vehicles have a series of advantages that lead to lowered energy consumption and gas emissions (especially in urban environment). The main disadvantages concerning the use of electric energy as the main energy source are long recharging time and a lack of electric charging infrastructure, thus limiting mobility of the electric vehicle. The implementation of fuel cell represents an efficient solution for improving vehicle range and a reduced recharging time. Also, creation of a hydrogen charging infrastructure can be achieved much more easily due to fewer stations necessary.

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Honda is one of pioneers in applying fuel cell technology to automobiles, introducing the FCX model as early as 2002 in Japan and USA (2). In 2004 the Japanese company developed a new FCX version fitted with a fuel cell capable of cold start at -20^{0}C. Increasing of the dynamic performance and capacity to work in a wide range of climate conditions made the fuel cell power train, developed on FCX models, competitive with the internal combustion engine in terms of performance, drivability, reliability and economy.

Dynamic modeling with a high degree of accuracy of the integrated vehicle-powertrain system is required for fuel cell power train systems synthesis and fast optimization of the necessary control and command system. In addition, if it is desired to follow a drive cycle it is necessary to create a control loop with a driver model.

DRIVE SYSTEM MODELING

Considering the state of the art in fuel cell vehicle development, Honda FCX Clarity 2010 model, presented in figure 2 (3), was chosen as study case.

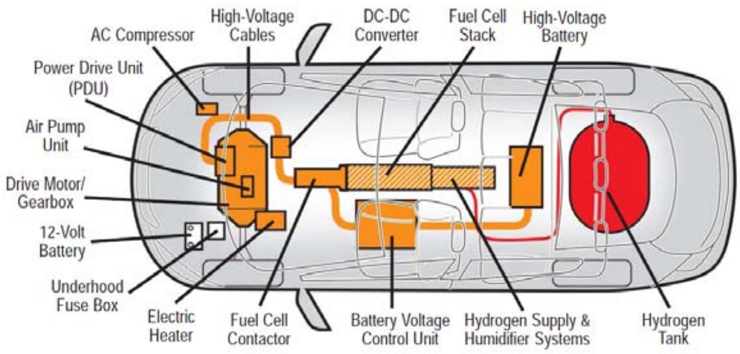

Figure 2. The main components of the powertrain of Honda FCX Clarity (2010 model)

The global model is presented in figure 3 and contains the following subsystems:
1. The Driver is based on a PID controller and has the role of maintaining a small difference between real and reference speed;
2. The Electric Drive System is made up of the fuel cell, the Li-ion battery, the DC/DC converter, the inverter and the PMSM (permanent magnet synchronous motor);
3. The Vehicle is based on a longitudinal dynamic model of the automobile;
4. The H2 Consumption and Range calculates the fuel consumption and range during a drive cycle.

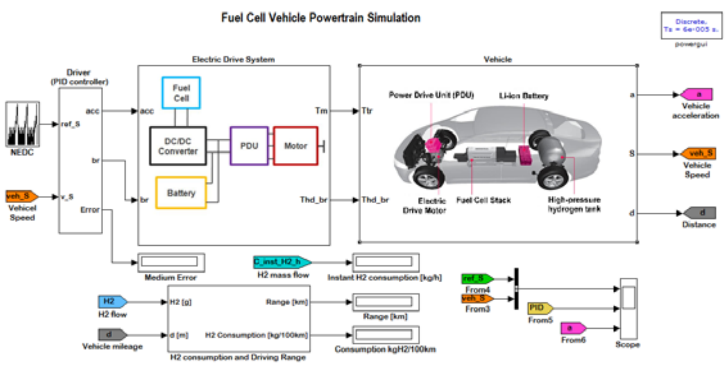

Figure 3. Global model in Simulink

The parameters needed for the vehicle longitudinal dynamics model were adopted or computed using the vehicle technical specifications presented in (4).
The electric drive system is detailed in figure 4.

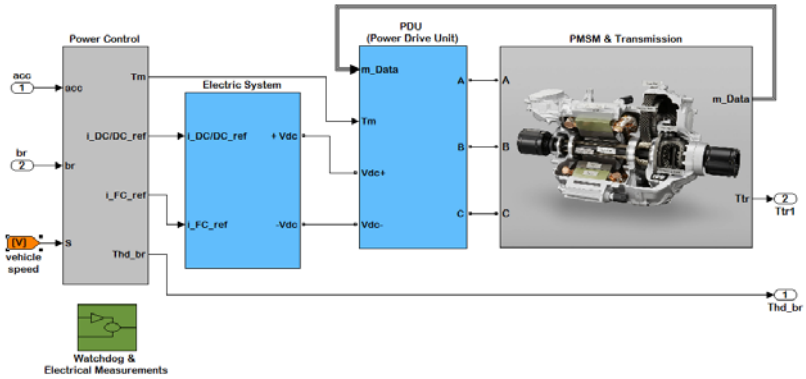

Figure 4. Electric Drive System

The Electric Drive System is made up of four main blocks and a safety module:
1. Electric power management block (Power Control);
2. Electric system block (Electric System);
3. Electric motor controller block (PDU - Power Drive Unit);
4. Permanent magnet synchronous motor and Transmission block (PMSM & Transmission);
5. Safety and electrical measurements module (Watchdog & Electrical Measurements).

Inside the Power Control block are three modules: battery recharge current estimation, drive power estimator and current estimator. The modules are presented in Figure 5.

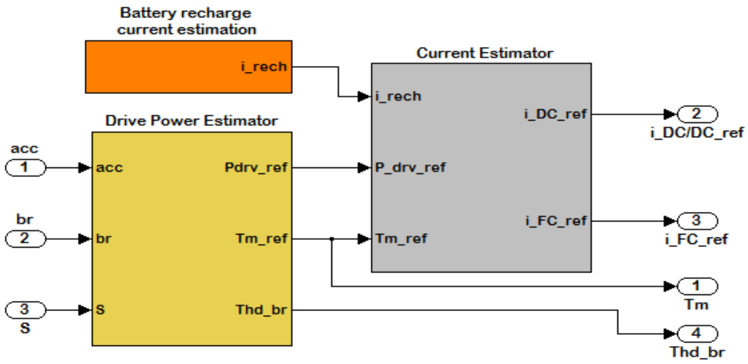

Figure 5. Power Control modules

The Battery recharge current estimation determines the recharge current (i_rech) according to SOC (battery state of charge). The battery is recharged at a constant current of 15 A when SOC is less than 80% while the vehicle is stationary or cruising. When regenerative braking is applied the current will be proportional to braking torque, but no higher than 60 A.

Based on signals from the accelerator pedal position (acc), brake pedal position (bra) and vehicle speed (S), the Drive Power Estimator module carries out the following functions:
- Estimates the reference power necessary for traction (Pdrv_ref);
- Estimates the reference motor torque (Tm);
- Calculates braking torque for the hydraulic braking system (Thd_br).

The estimated traction power is limited between -12.5kW and 100 kW, while the estimated motor torque has a lower limit of -256 Nm and an upper limit of 256 Nm.

The Electric Current Estimator calculates the reference values for the following:
- Fuel Cell current (i_FC_ref);
- DC/DC converter current (i_DC/DC_ref).

The reference Fuel Cell current estimated is limited between a minimum of 2.7 A and a maximum of 330 A while the DC/DC converter current is saturated between 2.8 A and 347 A.

The Electrical System comprises two modules and a block:
- Fuel Cell Stack;
- DC/DC converter;
- Generic Li-ion Battery block.

The detailed Electrical System is shown in figure 6.

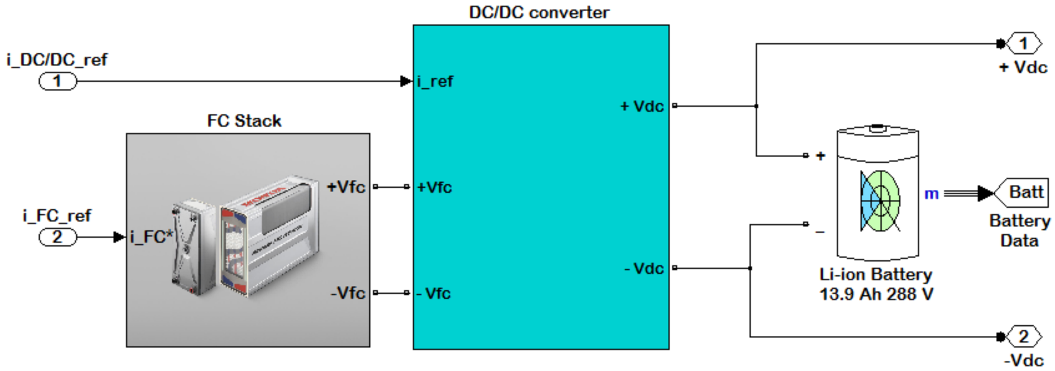

Figure 6. Electrical System

The DC/DC Converter (figure 7) contains a Bus Duty Cycle Controller block which controls the IGBT module in the Power Electronics block. The FC Stack and Li-ion Battery are connected to the Power Electronics block.

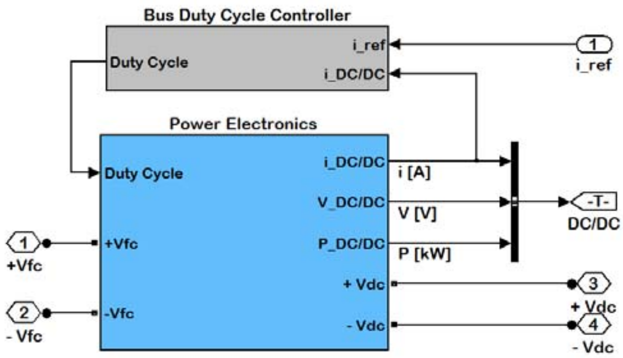

Figure 7. DC/DC converter

The electrical diagram for Power Electronics block is based on a Buck DC/DC converter (figure 8). In order to speed up the simulation process a mathematical average current model was used for the IGBT Module.

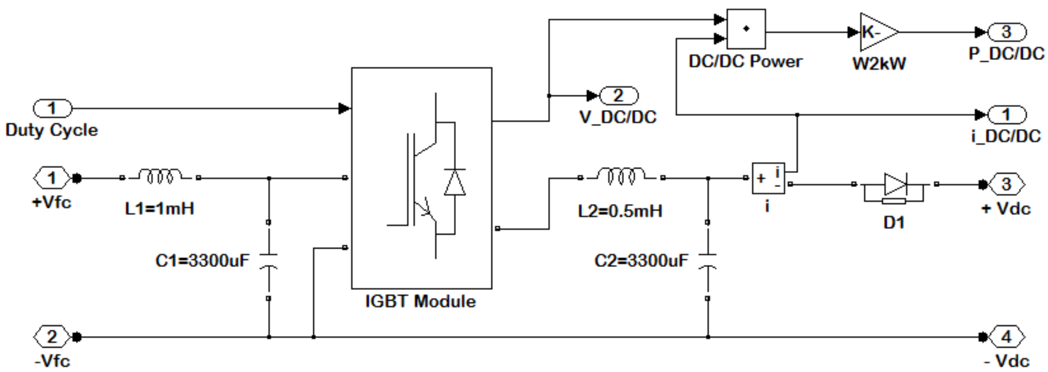

Figure 8. Power Electronics

Fuel Cell Stack command and control architecture is shown in figure 9.

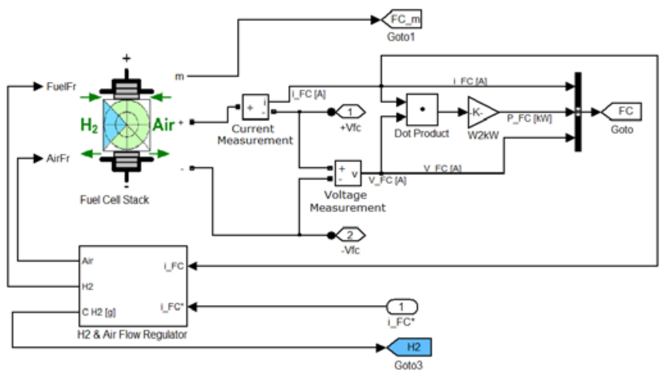

Figure 9.Fuel Cell Stack command and control

Fuel Cell Command and Control uses a mass flow regulator (H2 & Air Flow Regulator) in order to manage the consumption of hydrogen and air according to estimated electrical current consumption. The system involves two closed loop configurations. One use a direct measurement of the Fuel Cell electrical current (i_FC) and the other is based on the estimated current consumption which is calculated in the Power Estimator. The highest value from these two is always used to calculate the mass flow of the PEM Fuel Cell. Voltage (V_FC) is also measured in order to determine the Fuel Cell stack electrical power (P_FC). Information regarding electrical current, voltage, electrical power and Fuel Cell stack parameters (FC_m) are used in the Watchdog & Electrical measurements module. H_2 consumption is calculated from the fuel mass flow in order to estimate vehicle range.

The equivalent circuit of the PEM Fuel Cell is shown in figure 10, as shown in (5).

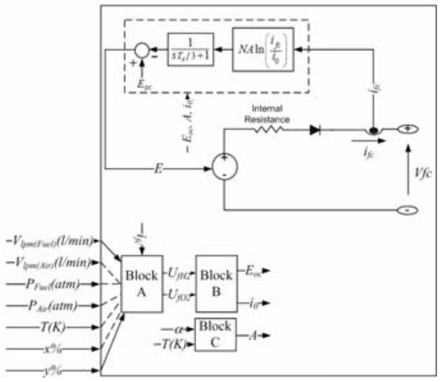

Figure 10. PEM Fuel Cell equivalent electrical circuit

This detailed model available in SymPowerSystems Library from Symulink represents a particular fuel cell stack when the parameters such as pressures, temperature, compositions and flow rates of fuel and air vary. The variations of these parameters affect the open circuit voltage (E_{oc}), the exchange current (i_0) and the Tafel slope (A) as follows:

$$E_{oc} = K_c E_n \tag{1}$$

$$i_0 = \frac{z \cdot F \cdot k \cdot (P_{H2} + P_{O2})}{R \cdot h} e^{-\frac{\Delta G}{RT}} \tag{2}$$

$$A = \frac{R \cdot T}{z \cdot \alpha \cdot F} \tag{3}$$

where:
R - universal gas constant;
F - Faraday constant;
z - number of moving electrons;

E_n - Nernst voltage, which is the thermodynamics voltage of the cells and depends on the temperatures and partial pressures of reactants and products inside the stack (V);
α - Charge transfer coefficient, which depends on the type of electrodes and catalysts used;
P_{H2} = Partial pressure of hydrogen inside the stack (atm);
P_{O2} = Partial pressure of oxygen inside the stack (atm);
k - Boltzmann's constant;
h - Planck's constant;
ΔG - Size of the activation barrier which depends on the type of electrode and catalyst used;
T - Temperature of operation (K);
K_c - Voltage constant at nominal condition of operation.

The rates of conversion (utilizations) of hydrogen (U_{fH2}) and oxygen (U_{fO2}) are determined in Block A as follows:

$$U_{fH_2} = \frac{60000 \cdot R \cdot T \cdot N \cdot i_{fc}}{z \cdot F \cdot P_{H_2} \cdot V_{lpm(H_2)} \cdot x\%} \tag{3}$$

$$U_{fO_2} = \frac{60000 \cdot R \cdot T \cdot N \cdot i_{fc}}{2z \cdot F \cdot P_{aer} \cdot V_{lpm(aer)} \cdot y\%} \tag{5}$$

where:
N - number of cells;
i_{fc} - generated electric current;
P_{H2} - absolute supply pressure of hydrogen;
$V_{lpm(H2)}$ - hydrogen flow rate;
P_{air} - absolute supply pressure of air;
$V_{lpm(air)}$ - air flow rate;
$x\%$ - percentage of hydrogen in the fuel;
$y\%$- percentage of oxygen in the air.

Based on relations (4) and (5) it can be concluded that for the fuel cell stack to work at an optimum efficiency, close to nominal conversion values, a flow control system is necessary. For the purpose of solving this problem a control block was realized. It regulates the mass flow of hydrogen and air in function of the estimated electric current consumption of the drive system. Hydrogen mass flow is determined with the formula:

$$\dot{m} = \frac{p \cdot M}{R \cdot T} \cdot V_{lpm(H_2)} \cdot \frac{1}{60000} \left[\frac{g}{s} \right] \tag{6}$$

where:
p - hydrogen pressure;
M - hydrogen molar mass.

For the electric motor and controller a dynamic model was used. It is based on AC6 block from SymPowerSystems Lybrary. The speed controller is based on a PI regulator. The output of this regulator is a torque set point applied to the vector controller block. These values are used in the vector controller to generate the reference sinusoidal current waves needed to command a three phase IGBT inverter.
The Battery block from SymPowerSystems Lybrary was implemented for the Li-ion polymer battery. The battery model is a generic dynamic model parameterized to represent most popular types of rechargeable batteries.
The transmission subsystem contains a gear ratio of 9.44:1 and a constant efficiency of 96%.

RESULTS

The instantaneous hydrogen consumption, as it can be observed in figure 11, rises to a maximum of 0.8 kg/h when accelerating and it drops to a minimum value of 0.05 kg/h while regenerative braking is in use.
The high fuel cell response time is caused by the "charge double layer" phenomenon due to the buildup of charges at electrode/electrolyte interface and the dynamics of external equipments, like regulators, compressor and loads (6).

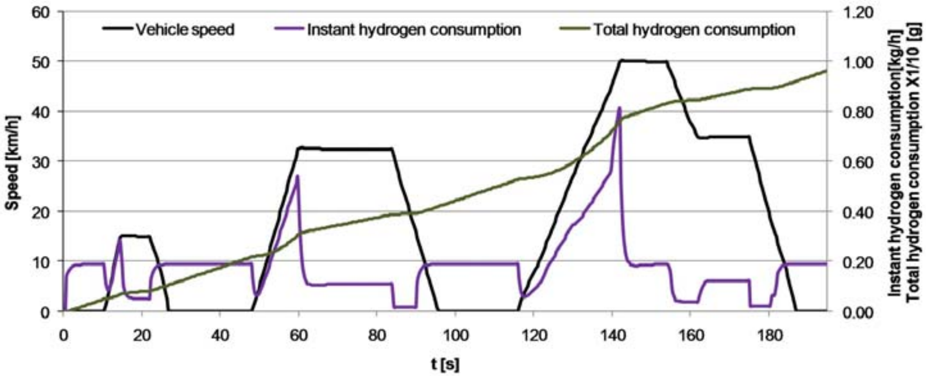

Figure 11. Hydrogen consumption and vehicle speed during ECE15 cycle

The surplus of electrical energy goes into the battery, thus maintaining the system in balance. This phenomenon can be observed in figure 12, as a high negative current at the battery terminals, while going from positive acceleration to steady speed.

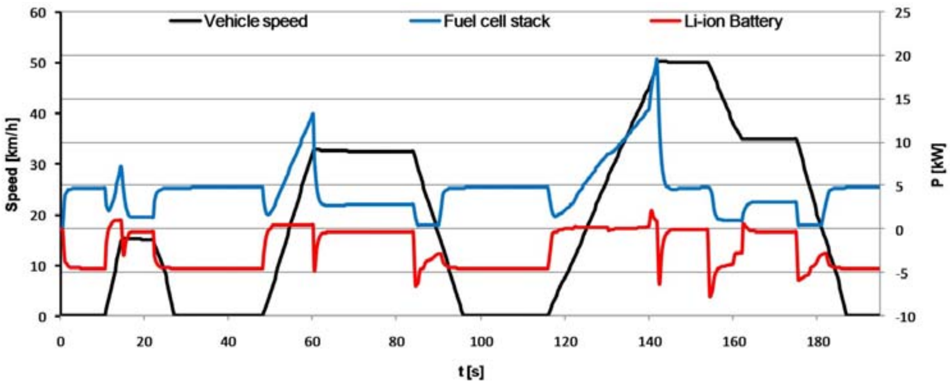

Figure 12. Vehicle speed and electrical power for fuel cell stack and battery during ECE15 cycle

The fluctuation for effective and maximum theoretical efficiency of the fuel cell, in ECE15 cycle, can be observed in figure 13.

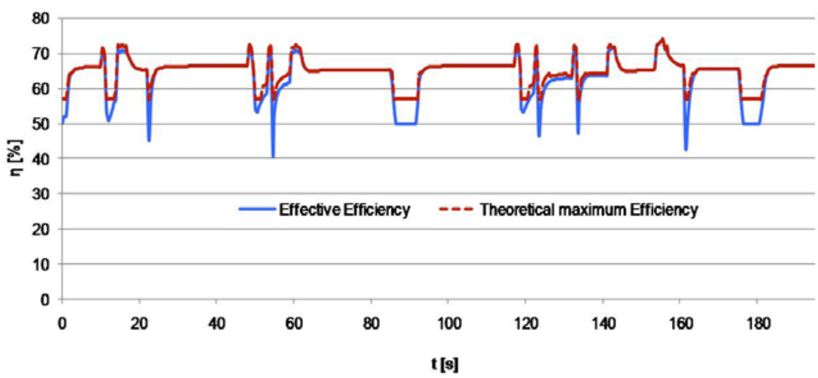

Figure 13. Fuel cell stack efficiency during ECE15 simulation

CONCLUSIONS

The mean value obtained for effective efficiency of the fuel cell stack was 63.88%. This result is very close to the mean maximum theoretical value which could be obtained in case of an ideal control (64.95%). Therefore, the efficiency of the algorithm implemented for the control of hydrogen and air mass flow was demonstrated. The error concerning the vehicle speed compared with NEDC reference speed, by using the block for acceleration and braking command (Driver- PID Controller), is very small (0.67 %).
An estimated hydrogen consumption of 0.832 kg/100 km and a range of 441 km are obtained for NDEC cycle if 93% of fuel tank is used. However, according to (7), there is a limit for the allowable energy change in the rechargeable energy storage. Because this limit was exceeded a hydrogen consumption correction coefficient was calculated and applied. After this correction the fuel consumption is 0.823 g/100km (equivalent with a gasoline consumption of 2.905 l/100 km) and the range is 446 km. An error of 3.04% has resulted when compared to the range stated by Honda for NEDC (460 km) (2).
The calculated tank to wheel efficiency, during the NEDC test procedure, was 57.92 %, which is a reasonable high value for a modern vehicle, compared to ICE powered vehicles with a tank to wheel efficiency of 20.6% for a DI gasoline engine and 21.1% for DI Diesel, as specified in reference (8).

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