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Research Article

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Enhancing the fuel economy of a plug-in series hybrid vehicle system

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Abstract: In this paper, the design and simulation of a hybrid vehicle with a fully functional driving model is presented. Actual velocities and desired velocities are compared and matched to get the optimum values of a vehicle. Fuel economy is calculated to get miles per gallon gasoline equivalent (MPGe). The MPGe for a hybrid vehicle is compared with the MPGe for a conventional vehicle to get the best MPGe in a hybrid car. A higher performance of output power of a vehicle is obtained.

Keywords: Hybrid electric vehicle, plug-in series, fuel economy, lithium-ion battery

1 Introduction

Plug-in hybrid electric vehicles contain both internal combustion engine (ICE) and electric motor. An alternative or traditional fuel drives these types of automobiles [1]. Hybrid-electric vehicles are used as plug-in series powertrain and have emerged as alternative vehicles to decrease fuel consumption. A hybrid vehicle model could be built with a fully functional driving model, mobility model and power system model with driving the Environmental Protection Agency (EPA) drive cycles. Also, the energy required to drive the vehicle design can be determined by the EPA's Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Driving Schedule (HWFET) [2], and US06 driving schedules. Chevrolet Cruze is an automobile produced by the American manufacturer General Motors (GM), spanning two unrelated models. Under a joint venture with GM, Suzuki in Japan manufactured the original iteration – a subcompact hatchback – between 2001 and 2008 [3, 4].

Since 2008, the "Cruze" nameplate has referred to a globally developed, designed, and manufactured four-door compact sedan, complemented by a five-door hatchback body variant from 2011. Badge Holden Cruze in Australasia and Daewoo Lacetti Premiere (from 2008 to 2011) in South Korea, the new generation models do not serve as replacements for their Suzuki-derived predecessor. Instead, they replace two other compact models: the Daewoo Lacetti sold internationally under various titles and the North American-specific Chevrolet Cobalt. GM phased out the production of Cobalt and its badge-engineered counterpart, Pontiac G5 in 2010, as the manufacturing of Chevrolet Cruze in the United States commenced. Table 1 shows the specifications of Chevrolet Cruze.

Table 1: J300 Specifications

J300/Chevrolet Cruze	
Production	2008-Present
Platform	GM Delta II
Body style	4-door sedan
Engine	1.8L Ecotec I4
Wheelbase (in)	106.6
Length (in)	181
Width (in)	70.4
Height (in)	58.1
Suspension (front)	MacPherson Strusts
(rear)	Torsion Beam Axle
Weight	1.5 tonne
Wheel radius, r	0.330 m
Gear ratio	1
Engine power	100 kWh
Engine torque	160 Nm

2 Selected Model

This hybrid vehicle has a plug-in series hybrid drive, which operates on both gasoline fuel engine and an electric motor. The fuel tank capacity is 15.6 gallon. It has a total weight of 1500 kg. It features a 1.8L VCDi I4 (gasoline) with

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four cylinders. Also, it gives 134.1 horsepower at 6000 rpm and 118 lb-ft of torque [160 Nm] at 3800 rpm.

This hybrid car has an all-electric mode and a series drive mode. The series hybrid drive is a drive train in which two electrical power sources feed a single electric motor that drives the vehicle. The unidirectional energy source is a gasoline fuel tank and the unidirectional energy converter is an IC engine coupled to an electric generator. The output of the electric generator is linked to a power DC bus through a controllable electronic convertor (rectifier). The bidirectional energy source is a battery pack, which is used in the lithium-ion battery connected to the power DC bus by means of a controllable, bidirectional power electronic converter (DC/DC converter). The power bus is also connected to the controller of the electric motor. The traction motor can be controlled as either a motor or a generator, and in forward or reverse motion. This drive train may need a battery charger to charge the lithium-ion batteries by wall plug-in from a power grid [5, 6].

The drive train needs a vehicle controller to control the operation power flows based on the driver's operating command through accelerator and brake pedals and other feedback information from the components. The vehicle controller will control the IC engine through its throttle, electric coupler, and traction motor to create the demanded propelling torque or regenerative braking torque. Figure 1 shows a plug-in series powertrain.

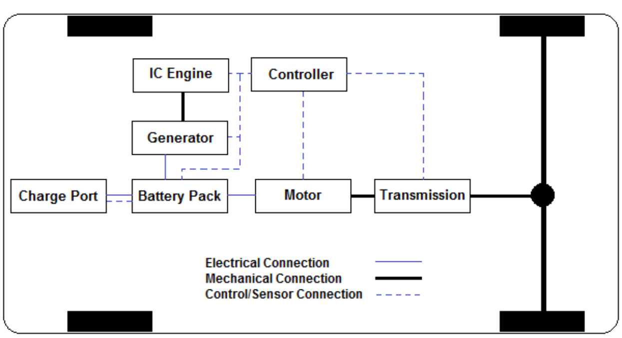

Figure 1: Plug-in series powertrain

The throttle is obtained from the tractive force generated by the inverse dynamics and fed to the engine. The engine outputs its angular velocity, which is fed to the torque converter. The latter outputs the turbine torque and the impeller torque. Using gear selection system, the force is adjusted based on the velocity.

3 Subsystem Modeling

Inverse dynamics is used to calculate the resulting forces from a desired behavior of a given system. The motion is prescribed and the inverse model is used to determine the required effort variables such as forces, torques, and pressures. The purpose of using the inverse model is to look at how much the desired parameters differ from the simulated parameters.

Two drive cycles are used—Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Driving Schedule (HWFET)—to get the actual velocity from each cycle [7].

In this vehicle model, the desired velocities taken from the UDDS data represent the input, and the tractive force F_X using Eq. (1) represents the output [8]:

$$F_X = (m + m_r)\,a_x + F_{rr} + F_{aero} + F_{grade} \tag{1}$$

where m is the vehicle mass, m_r is the rotational inertia mass, $a_x$is the acceleration, F_{rr} is the rolling resistance (Eq. (2)), F_{aero} is the aerodynamic force (Eq. (3)) and F_{grade} is the force from inclination (Eq. (4)).

$$F_{rr} = \mu_{rr} W \tag{2}$$

$$F_{aero} = \frac{1}{2}\rho C_d A V^2 \tag{3}$$

$$F_{grade} = W \sin\theta \tag{4}$$

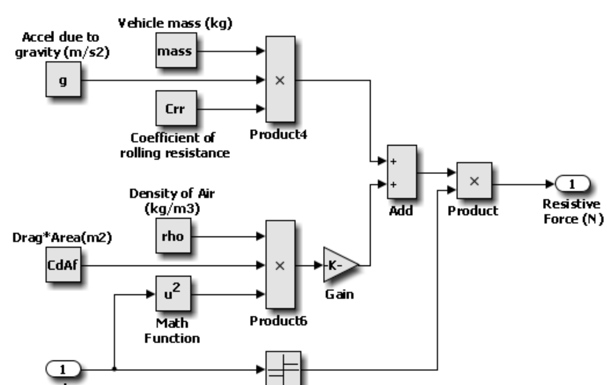

Figure 2: Resistant forces (N)

The difference between desired velocity and actual velocity divided by time in second and multiplying by the total mass of vehicle is calculated to get inertial force (N). Figure 3 shows inertia force (N).

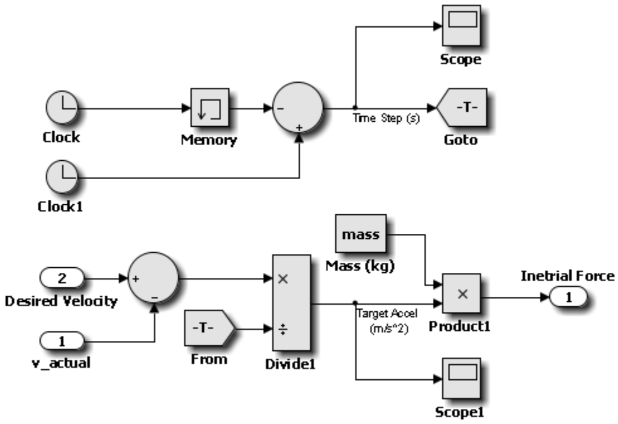

Figure 3: Inertia force (N)

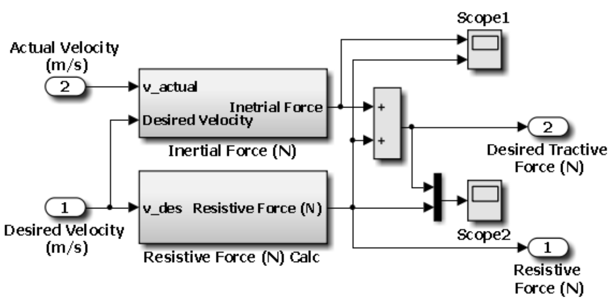

Figure 4: Inverse dynamic model

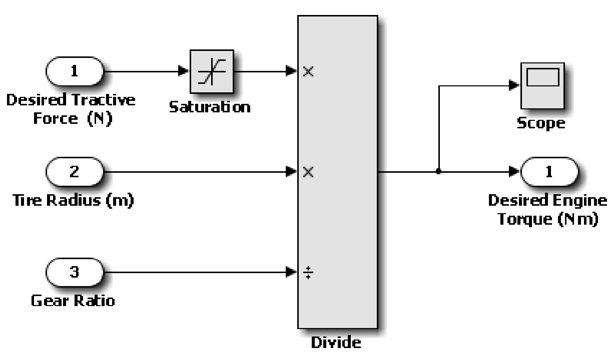

Figure 5: Engine torque model

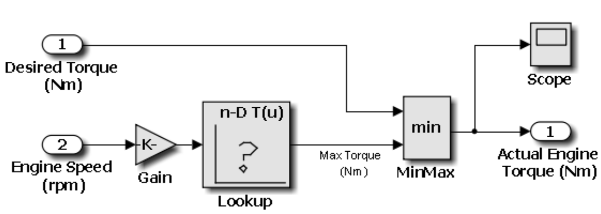

Figure 6: Engine torque control

The two previous figures are the subsystems of the model, which are represented in Figure 4. The actual velocity in the figure, which is shown in Figure 4, comes from forward dynamic. Then, by combining these two forces (inertia force and resistant forces), the desired tractive force is achieved. Figure 4 indicates the inverse dynamic model.

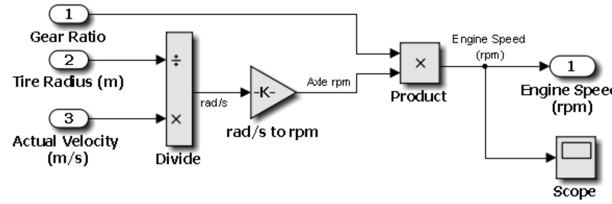

Figure 7: Engine speed calculation

4 Electric Motor Models

Electric motor models can be classified into three parts: engine torque, engine torque control, and engine speed calculation. The desired engine torque in the first model is calculated by using Eq. (5),

$$Te = \frac{r_{tire}}{GR_t GR_f n_t n_f} F_X \tag{5}$$

where GR_t is the gear ratio, GR_f is the final drive ratio and r_{tire} is the radius of the wheel. Their values are shown in Table 1. n_t and n_f are the efficiencies for transmission and final drive, respectively, assumed to be 1. Figure 5 shows the engine torque model.

Another part of this model is engine torque control. Actual engine torque is calculated by using the desired torque from engine torque model and engine speed from engine speed calculation. Figure 6 shows the engine torque control.

The other part of the model is engine speed calculation. The engine speed is calculated by applying Eq. (6),

$$\omega = \frac{GR_t GR_f n_t n_f}{r_{tire}} V \tag{6}$$

where ω is the engine speed (in rpm) and V is the actual velocity in meters per second. Figure 7 indicates the engine speed calculation.

All these three models of electric motor can be put in one subsystem. Figure 8 shows the subsystem of an electric motor [8].

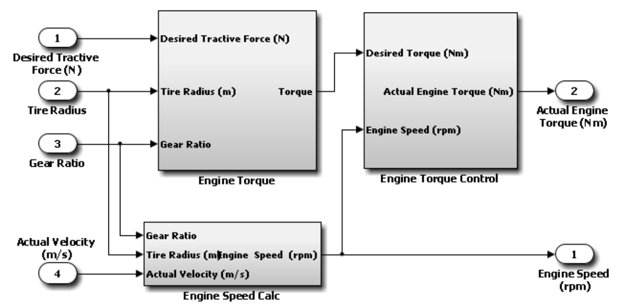

Figure 8: Electric motor subsystem

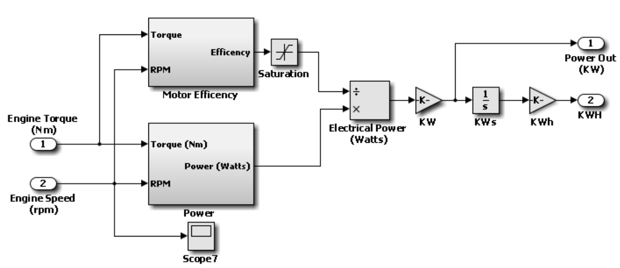

Figure 9: Power model

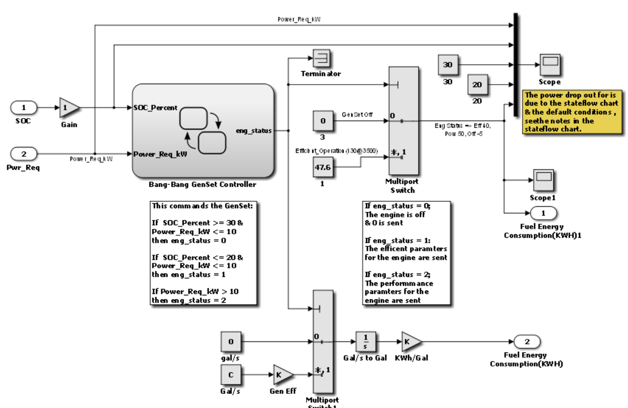

Figure 10: Genset

5 Power Calculation Model

Power in (kWh) is calculated by applying engine torque and engine speed from electric motor subsystem. Figure 9 indicates the power calculation.

6 Genset

The inputs of a genset are state of charge and power required from motor, as shown in Figure 10. These two inputs will go into a state flow (Figure 11) to decide engine status.

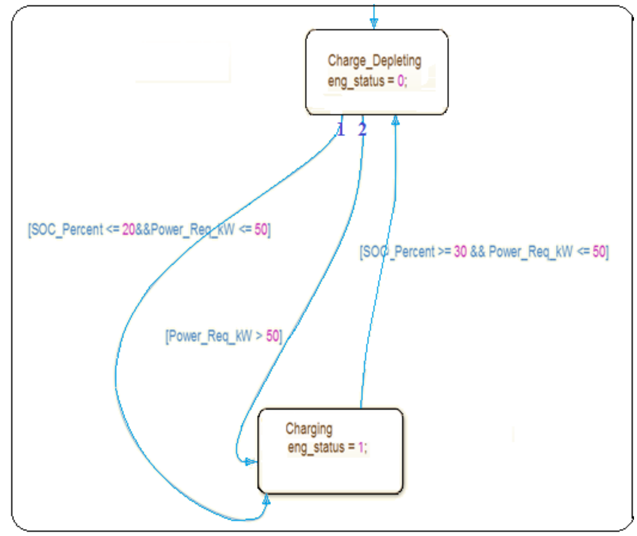

Figure 11: Genset state flow

The engine will be turned on when the state of charge is below 30% or the power required is greater than 50 kWh, which is the maximum that a battery can provide. The output of state flow will go into a switch: if the genset is on, the battery is charged with 47.6 kWh power; if genset is off, no power comes from the genset and the battery is not charged.

7 Internal Combustion Engine (ICE)

In order to maximize the efficiency, the engine will be running at a relatively efficient point. This point is determined by the combination BSFC curve, as shown in Figure 12. The rpm of this best efficient point is 3500 rpm with a 130 Nm torque. Additionally, each time the engine turns on, it should be kept running for at least 10 seconds.

8 Regeneration

The capability for recovering important amounts of braking energy is considered as one of the most significant features of a hybrid vehicle. The electric motor in Chevrolet Cruze can be controlled to run as a generator to convert the kinetic or potential energy of vehicle mass into electric energy, which can be stored in the energy storage and then reused. Generally, the braking torque required is much larger than the torque that an electric motor can generate, especially in heavy braking. In Chevrolet Cruze Hybrid, the mechanical friction braking systems have to link

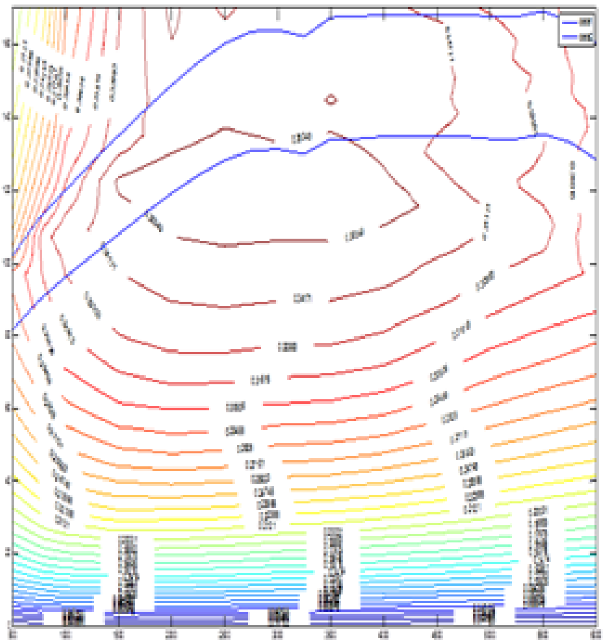

Figure 12: BSFC curve

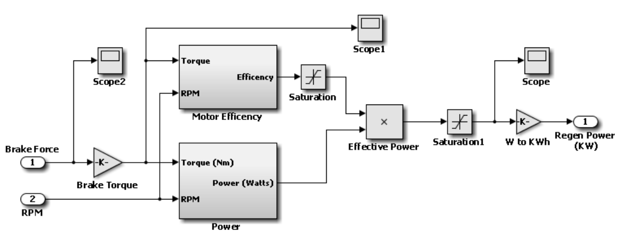

Figure 13: Braking or deceleration model

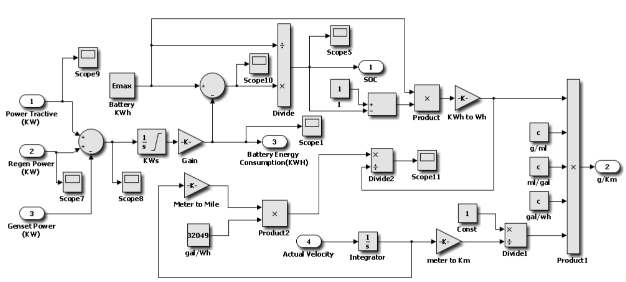

Figure 14: Battery model

with the electrical regenerative braking. Eq. (5) is utilized to get engine torque (in Nm). Then, Eq. (7) is applied to calculate the regeneration power (in kWh) from engine speed (in rpm) and engine torque:

$$P = T.\omega \tag{7}$$

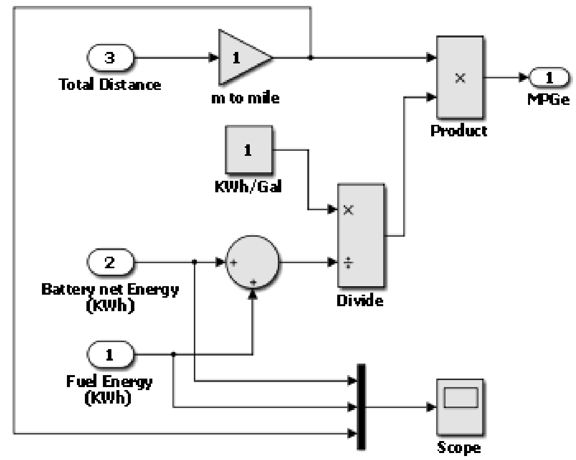

Figure 15: MPGe

where P is regeneration power (in kWh), T is engine torque (in Nm), and $\omega$is engine speed (in rpm). Figure 13 shows the deceleration or braking model.

9 Battery Modeling Simulation

Lithium-ion batteries can be considered as rechargeable batteries. Also, these batteries could give twice the amount of energy capacity than that of Nickel-Cadmium batteries and are more safe and stable [9]. They supply one of the best technology rates, such as energy-to-weight, more storage for energy, and also provide reduced self-discharge when they are not utilized [10]. Lithium-ion battery is utilized in this model. Also, the maximum voltage is 402 volts, maximum energy (Emax) is 3 kWh (16.6 kWh for ECOCAR 3), and the internal resistance of the battery circuit is 2.24 ohms. As shown in Figure 14, there are three inputs of the battery energy cost: the power from genset, the power from regeneration (negative value) and the power cost at the tractive force. When this energy cost value is positive, the battery is at depleting mode; when this value is negative, the battery is at charging mode. Also, the emission of the model can be calculated [8].

10 MPGe Calculations

The total energy (battery energy and fuel energy) cost into gallons of fuel (E10) that provides this power. When the total distance travelled is divided by this fuel volume, we get MPGe, as shown in Figure 15.

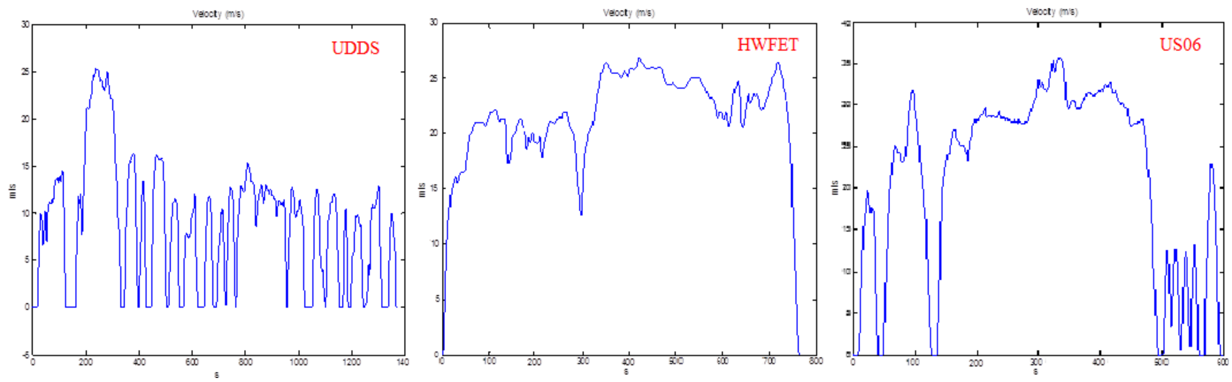

Figure 16: Actual velocities and desired velocity versus time for UDDS, HWFET, and US06

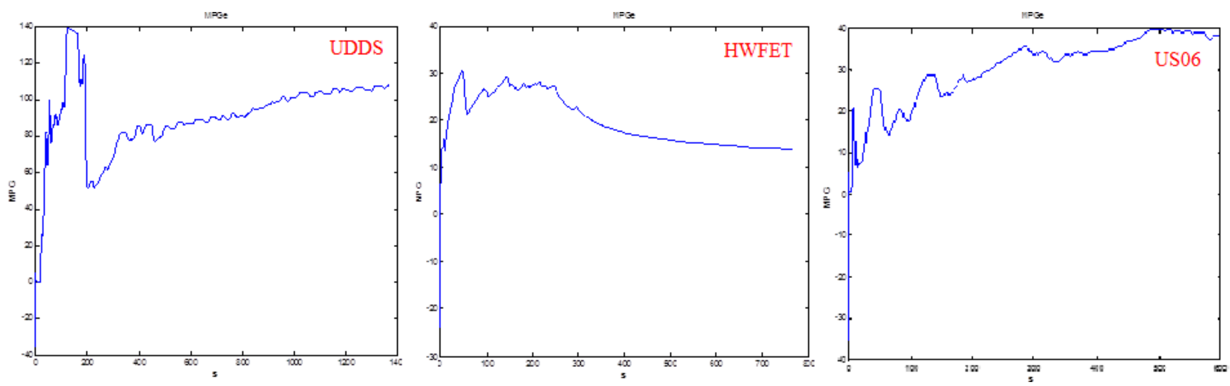

Figure 17: MPGe versus time UDDS, HWFET, and US06

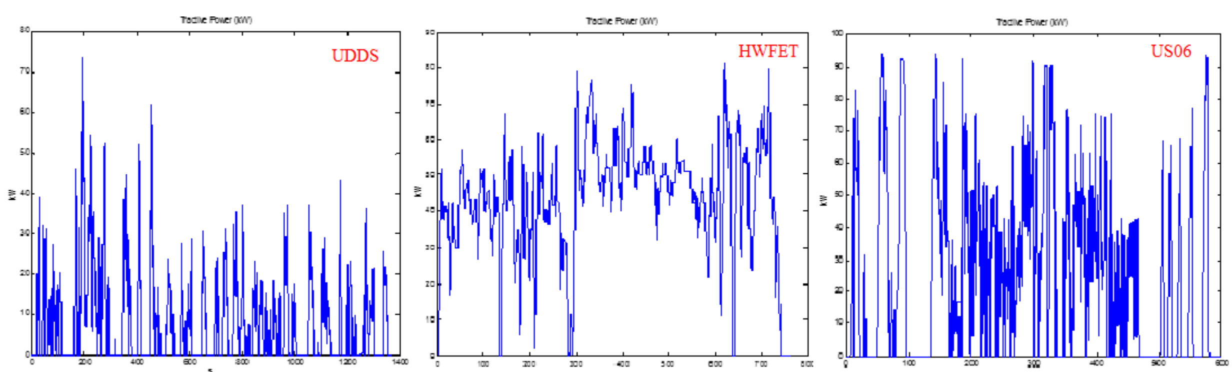

Figure 18: Tractive power (in kWh) versus time for UDDS, HWFET, and US06

11 Simulation Results

The model shows the charge of sustaining (CS) and charge of depleting (CD) and the MPGe for UDDS, HWFET, and US06 by using the utility factor that is equal to 0.2486.

To begin with, the increase in the UDDS data is demonstrated in the figures below. For example, the range of UDDS rose to 20.2 Km. In addition, charge of sustaining (CS) increased exactly 30% more than HWFET, which is equal to 41 MPGe. Moreover, charge of depleting (CD) grew 108 MPGe. In contrast, a decline of HWFET can be certainly observed in the figures below. For instance, a 29.54% reduction in the range, which is equal to 15.0 Km, appeared. Moreover, charge of sustaining (CS) reduced to 31.27 MPGe. Furthermore, charge of depleting (CD) decreased to 94.26 MPGe.

As a result, the data clearly represent the combined values between UDDS and HWFET. To illustrate, the range was 17.86 Km. Furthermore, charge of sustaining (CS) and charge of depleting (CD) were 36.638 MPGe and 101.817

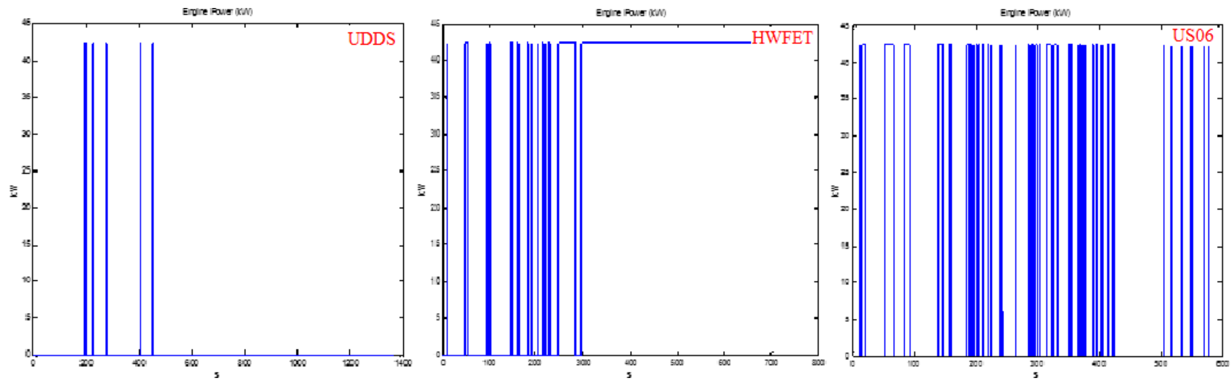

Figure 19: Engine power (in kWh) versus time for UDDS, HWFET, and US06

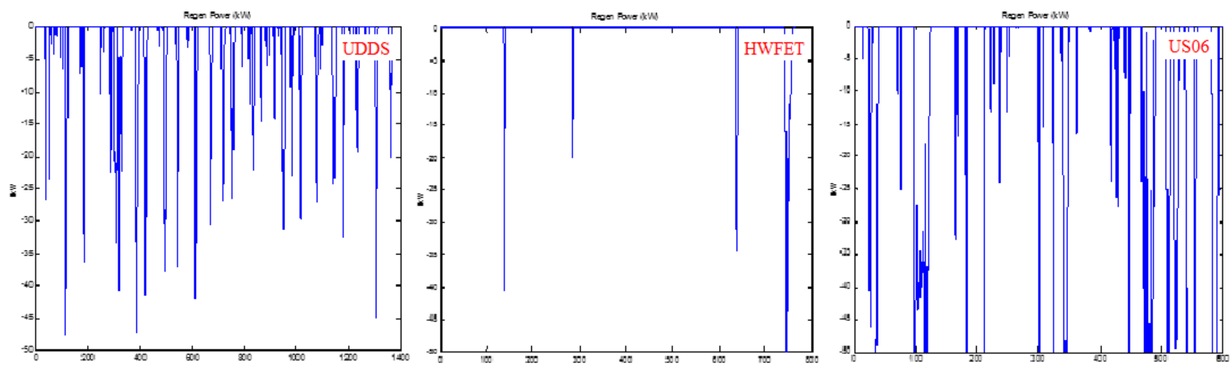

Figure 20: Regenerative braking power in (kWh) versus time for UDDS, HWFET, and US06

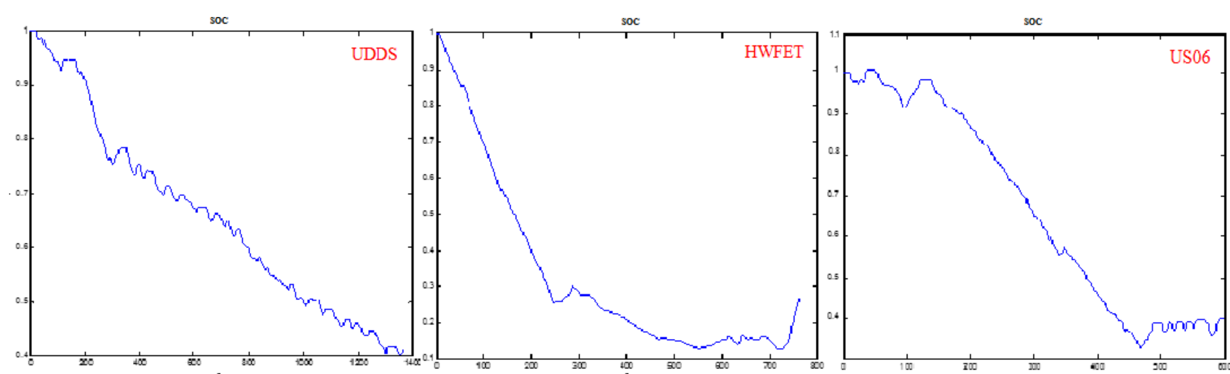

Figure 21: State of charge (SOC) for UDDS, HWFET, and US06

MPGe, respectively. So, the miles per gallon equivalent sticker with UF = 0.2486 was 43.57.

The engine will be operating at a relatively efficient point. This point is determined by the combination BSFC curve, as indicated in Figure 22. The speed of engine (in rpm) of this efficient point is 3500 rpm with a 130 Nm torque. Moreover, every time the engine operates, it is advisable to keep it operating for at least 10 seconds. This process is to get maximum efficiency.

12 Conclusion

Showing a design and simulation of a hybrid electric vehicle with a fully functional driving model is so significant. For instance, the comparison between actual velocities and desired velocities in Urban Dynamometer Driving Schedule and Highway Fuel Economy Driving Schedule is important to acquire optimum values of a vehicle. Furthermore, calculating MPGe to obtain less fuel consumption is done by this implementation. So, the higher performance

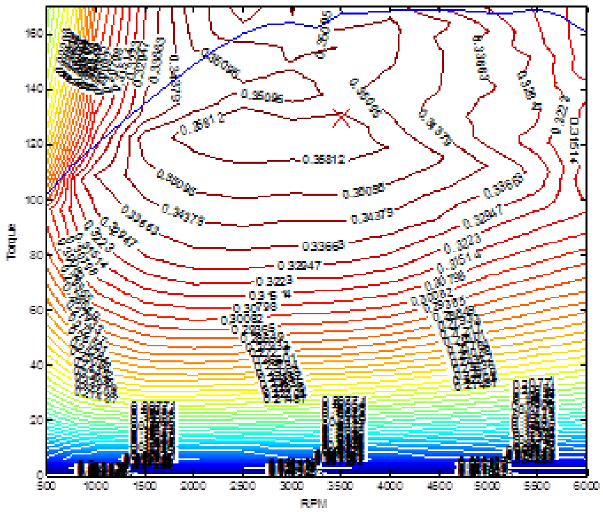

Figure 22: Torque (Nm)—speed (rpm) curve of ICE

of output power for a hybrid vehicle is gained because it consists of two power modes. One of them is gasoline engine energy, and the other is electric energy. The electrical energy that is represented by battery can support gasoline engine to drive the car, and the engine will charge the battery to prevent the depleting state. Therefore, the hybrid vehicle is better than conventional vehicle for the reasons given above in terms of performance, less emissions, and fuel economy.

Developing or debugging this model is done by using some parameters like density of air, gear ratio, coefficient of friction between the wheel tire and road surface, and coefficient of drag. Also, to get an optimum solution, scope and display for the correction of values are used.

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