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Parallel HEV Hybrid Controller Modeling for Power Management

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Abstract

In this paper, a parallel HEV hybrid controller is developed in the MATLAB/Simulink environment. Using the driver commands, the battery state of charge and the engine map, a set of efficient rules has been developed to efficiently split the power between the engine and the motor. The steps are: 1) Estimate the instantaneous torque demand. 2) Using the estimated torque, the feedback signals and the engine map, find the best operating point and then split the power and let the engine work as near as possible to this efficient point, that can be done by controlling the motor (or generator). In the case of motor, let its torque supply the rest of the torque needed, while the engine works near its efficient point, or in the case of generator, let its torque supply an additional load to put the engine in an efficient point. 3) Control the motor to supply the transient torque demand, and keep the engine torque constant as long time as possible, this help to reduce fuel consumption. Finally simulations of a conventional and hybrid vehicle are performed using Simulink environment to check the controller and series of results will prove the effectiveness of the proposed controller and will show the advantage of hybrid powertrain over conventional one in term of fuel economy.

Keywords— Hybrid Electric Vehicle, Power management, Hybrid Controller, Simulation

1 Introduction

The research of economized fuel vehicles has taken a huge interest in recent years due to the increased price of fuel and emission stringent laws. In this way, Hybrid Electric Vehicles (HEV) seems to be the most promising short-term solution and is under enthusiastic development by many automotive companies. An HEV adds an electric power path to the conventional powertrain, which helps to improve fuel economy by engine downsizing, load leveling, and regenerative braking. A downsized engine has better fuel efficiency and smaller heat loss. The reduced engine power is compensated by an electrical machine (or machines). Compared with internal combustion engines, electric machines provide torque more quickly, especially at low vehicle speed. Therefore, launching performance can be improved even with reduced overall rated power. Load leveling can also be achieved by adding the motor; which enables the engine to operate efficiently, independent from the road load finally regenerative

braking allows the electric machine to capture part of the vehicle kinetic energy and store it in the battery.

HEVs can be assigned to either parallel hybrid, series hybrid, or their combination [1]. In the parallel hybrid configuration, the mechanical connection between the components does not allow arbitrary optimization of the engine as is the case where series hybrids are concerned. However, the parallel hybrid powertrain allows both the engine and the motor to deliver power which is good because we can use smaller engine to get good performance. Therefore, in passenger car applications, the parallel hybrid configuration has been used in many HEV that have come onto the market [2].

Power management strategies for parallel HEVs can be classified into three categories. The first type uses heuristic control techniques such as control rules [3], fuzzy logic ([4], [5]) or neural networks [6] for estimation and control algorithm development. The second approach is based on static optimization methods ([7], [8], [9]). Generally, electric power is translated into an equivalent amount of fuel rate in order to calculate the overall fuel cost. The optimization schemes and figures out the proper split between the

two energy sources using steady-state efficiency maps. Because of the simple point-wise optimization nature, it is possible to extend such optimization schemes to solve the simultaneous fuel economy and emission optimization problem [10]. The basic idea of the third type of HEV control algorithms considers the dynamic nature of the system when performing the optimization ([11], [12]). Furthermore, the optimization is with respect to a time horizon, rather than for an instant in time. In general, power split algorithms resulting from dynamic optimization are more accurate under transient conditions, but are computationally more intensive.

In this paper we first made simulations for conventional and parallel hybrid vehicle and then we used the first category of power management strategy to make a model for the parallel HEV hybrid controller, the goal of this hybrid controller is first to estimate the power demand using the driver commands, second the controller is tuned to get a suitable HEV performance and finally it efficiently splits the power between the diesel engine and the electric motor in order to improve the fuel economy over the conventional vehicle with the same characteristics.

2 System Simulation

Nomenclature and parameter used

J1: Sum of inertia running at the same speed of the engine ($0.52 \text{ kg}\cdot\text{m}^2$)
 J2: Sum of inertia running at the same speed of the transmission ($0.32 \text{ kg}\cdot\text{m}^2$)
 J3: Sum of inertia running at the same speed of the wheels ($3.1 \text{ kg}\cdot\text{m}^2$)
 W, W_e , W_t : Wheel, Engine and transmission angular speed respectively
 V: Vehicle speed
 Mv: Vehicle mass (1200 kg)
 Acc: Vehicle acceleration
 Ft, Ftr: Traction and equivalent resistance force
 Faer, Froll: Aerodynamic and rolling resistance
 Fgrad: Grade resistance
 Af: Frontal area of the vehicle (2.2 m^2)
 Cd: Aerodynamic coefficient (0.31)
 Vwind: Axial wind speed
 α : Road angle
 (cr1=0.08) and (cr2=0.03): Rolling coefficient.
 (it, if): Transmission and differential ratio respectively
 Tt: Torque applied in the wheels
 Vac: Actual vehicle speed
 Tac: Actual torque demand
 S: Pedal signal
 Vr: Speed reference (drive cycle)
 Ves: Estimated speed
 Tes: Estimated torque
 Vmax: Vehicle maximum speed
 E0: Battery open circuit voltage (100.8V)
 R0, R1, C1: Battery interne resistors and capacitor
 Battery capacity 5.75Ah
 Power electronics efficiency 0.97

2.1 System simulation (the hybrid vehicle)

Using the models described below a simulation was performed using the Simulink environment, this simulation is forward looking that is why we simulated an automatic driver (PI controller). The simulation is presented in Fig 1 and its results have been validated by the 'Advanced vehicle simulator' (ADVISOR) developed by the National Renewable Energy Laboratory

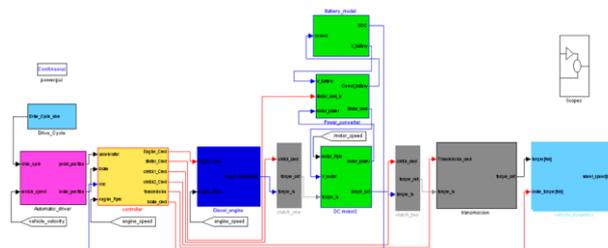


Figure 1: Top level simulation model for the hybrid vehicle implemented in Simulink

3 System Modeling

3.1 Power flow modeling

The hybrid vehicle structure considered in this article is a parallel single shaft topology, which utilizes a PMSM motor placed before the transmission and coupled with the engine via clutch Fig 2.

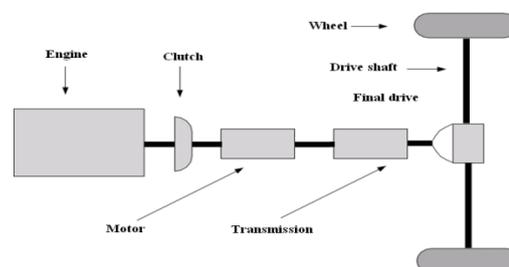


Figure 2: Powertrain structure considered

The power flows from the engine and motor to the wheels through the gearbox, the final drive and the drive shaft; thus the energy will be divided into a lot of quantities; the first quantity will be used to rotate the different inertia at different speed (kinetic energy or rotation energy), the second one will be used to overcome resistance forces (aerodynamic and rolling resistances), the third quantity will be used to accelerate the vehicle (kinetic energy or translation energy) and the last quantity will be lost inside the powertrain components as friction and damping losses (lost energy) which we neglect in this study due to the fact that this energy is small (if the powertrain is new) and don't have a big effect in our study.

The energy (E_s) of the power sources (engine and motor, knowing that ($W_e=W_m$) at positive power demand) is described by:

$$E_s = \int (T_e + T_m) \cdot \omega_e \cdot dt \quad (1)$$

Energy of rotation of different inertia (kinetic energy)

$$E_{k1} = \frac{1}{2} J_1 \cdot \omega_e^2 + \frac{1}{2} J_2 \cdot \omega_t^2 + \frac{1}{2} J_3 \cdot \omega^2 \quad (2)$$

Energy of translation of the vehicle (kinetic energy)

$$E_{k2} = \frac{1}{2} M \cdot V^2 \quad (3)$$

Energy to overcome resistant forces

$$E_r = \int F_{aer} \cdot V \cdot dt + \int F_{roll} \cdot V \cdot dt \quad (4)$$

Knowing that:

$$\left(F_{aer} = \frac{1}{2} C_d \cdot \rho \cdot A \cdot V^2 \right) \text{ and } \left(F_{roll} = M \cdot (C_{r1} + C_{r2} \cdot V) \right)$$

So we have:

$$E_s = E_{k1} + E_{k2} + E_r \quad (5)$$

Then after derivation by time we get this equation

$$\frac{d}{dt} \left(\int (T_e + T_m) \cdot \omega_e \cdot dt \right) = \left[\begin{aligned} & \frac{1}{2} J_1 \cdot \omega_e^2 + \frac{1}{2} J_2 \cdot \omega_t^2 + \frac{1}{2} J_3 \cdot \omega^2 \\ & + \int \left(\frac{1}{2} C_d \cdot \rho \cdot A \cdot V^2 \right) \cdot V \cdot dt \\ & + \int M (C_{r1} + C_{r2} \cdot V) \cdot V \cdot dt + \frac{1}{2} M \cdot V^2 \end{aligned} \right] \quad (6)$$

After derivation and arrangement and knowing that:

$$\omega_e = (it) \cdot \omega_t = (if \cdot it) \cdot \omega \quad (7)$$

We get this last differential equation:

$$\frac{d\omega}{dt} = \left\{ \begin{aligned} & \frac{it \cdot if (T_e + T_m) - M \cdot C_{r2} \cdot R^2 \cdot \omega}{(J_3 + M \cdot R^2 + if^2 \cdot J_2 + it^2 \cdot if^2 \cdot J_1)} \\ & \frac{\frac{1}{2} C_d \cdot A \cdot \rho \cdot R^3 \cdot \omega^2 + R \cdot M \cdot C_{r1}}{(J_3 + M \cdot R^2 + if^2 \cdot J_2 + it^2 \cdot if^2 \cdot J_1)} \end{aligned} \right\} \quad (8)$$

The equation (8) gives a relation (nonlinear differential equation) between wheel angular speed (ω) and power-source torque ($T_e + T_m$).

3.1 The Engine

The engine is modeled statically using the fuel consumption map Fig 4. A set of data in terms of torque and speed of the engine and the corresponded fuel consumption in each operating point obtained from the diesel engine in the Low Emission Vehicle Research Laboratory test bench Fig 3. Using interpolation/extrapolation the fuel consumption in other operating points is found and using appropriate MATLAB program the specific fuel consumption is then deduced Fig 5.



Figure 3: Low Emission Vehicle Research Laboratory test bench

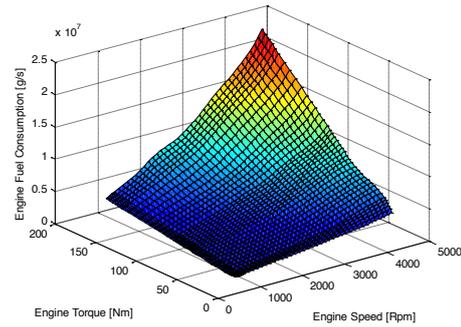


Figure 4: Engine fuel consumption rate [g/s] as function of engine speed and its torque from test bench

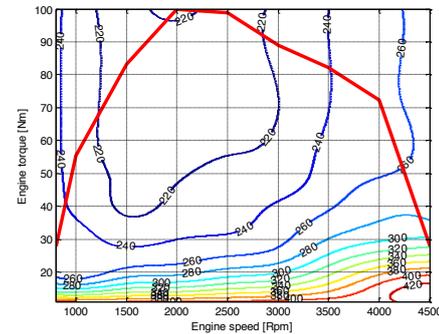


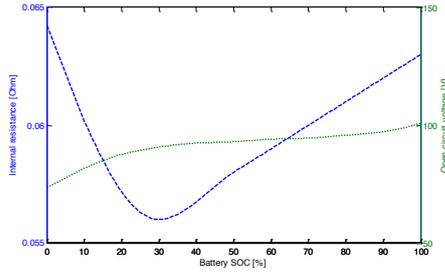
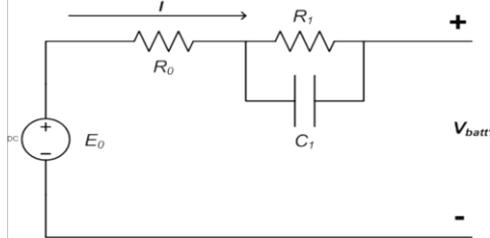
Figure 5: Engine maximum torque and specific fuel consumption [g/KWh]

3.2 The Battery

Once all the parameters including charging and discharging resistances (R_0), open circuit voltage (E_0) of the battery versus state of charge (SOC) were measured by experiments, those values are used as look up tables Fig 6. The model consists of two parts: SOC calculation block and voltage calculation block

In each time step the parameters are updated according to the battery state of charge. The maximum charging and discharging power, terminal voltage and current is limited in the model.

To obtain an electrical model that accurately reproduces the battery's voltage response over time; a dynamic model is used (Randle First order where (R_1) and (C_1) are assumed to be constant) Fig 7.

Figure 6: Battery resistance (R_0) and open circuit voltageFigure 7: Randle first order battery electrical model. (E_0) versus SOC

$$\frac{dV_c}{dt} = \frac{1}{R_1 \cdot C_1} \cdot V_c + \frac{1}{C_1} \cdot I$$

$$V_{batt} = E_0 - V_c - R_0 \cdot I$$

3.3 The Motor/ Generator

The electric motor utilized in this research is PMSM. Similar to the engine, the motor/generator is modeled using lookup tables, where the maximum torque of the motor/generator is indexed by the motor speed. And its efficiency is indexed by the operating torque range and the motor speed Fig 8.

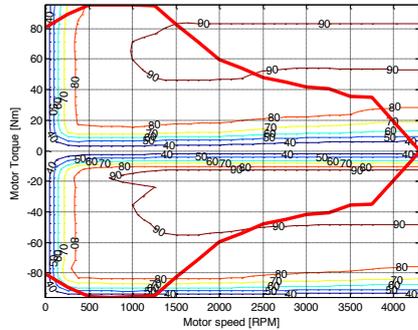


Figure 8: Motor/Generator efficiency and maximum torque

3.4 The Hybrid Controller

The hybrid controller is a block that estimates and splits the power demand; it also controls the different powertrain components like engine, electric motor and clutch; to perform such a task a block to estimate the torque demand; another one for the power split and other blocks for subsystem controls are needed see Figure 11.

3.4.1 Power Demand Estimation

For power demand estimation, we use longitudinal vehicle dynamics equations [13].

The Newton's law is written as:

$$Mv \cdot acc = Ft - Ftr$$

$$Ftr = Faer + Froll + Fgrad$$

$$Faer = 0.5 \cdot \rho \cdot Af \cdot Cd \cdot (V + Vwind)^2$$

$$Froll = Mv \cdot (cr1 + cr2 \cdot V)$$

$$Fgrad = Mv \cdot g \cdot \sin(\alpha)$$

The Newton's equation becomes:

$$Mv \cdot acc = Ft - (Faer + Froll + Fgrad)$$

$$\text{So: } Ft = Mv \cdot acc + (Faer + Froll + Fgrad)$$

The force (Ft) is applied to the wheels with radius (R), so the wheel torque (Tt) is found as: $Tt = Ft \cdot R$

By the same logic the resistive torque (Tr) is found as:

$$Tr = Ftr \cdot R \quad (10)$$

The traction power in the wheels comes from the engine and motor so assuming no losses:

$$T \cdot We = Tt \cdot Ww \quad \text{So: } T = Tt \cdot \left(\frac{Ww}{We}\right) = \frac{Tt}{it \cdot if}$$

Where: (T , We) are respectively torque demand and engine angular speed (which equal to motor angular speed in our case), (W) is wheel angular speed and (it , if) are respectively transmission and differential ratios. By replacing (Tt):

$$(it \cdot if) \cdot T = (Mv \cdot acc + (Faer + Froll + Fgrad)) \cdot R$$

So if the actual vehicle speed is (Vac) and the driver wants to accelerate the vehicle, we can estimate the torque demand taking care of transmission ratio which could be changed, (Tac) is the torque demand when the vehicle is coasting at constant speed ($V=Vac$) so no acceleration is done and the torque demand is only to overcome the resistive torques, assuming wind speed is zero and replacing resistance forces:

$$(it \cdot if) \cdot Tac = ((0.5 \cdot \rho \cdot Af \cdot Cd \cdot (Vac)^2 + Mv \cdot (cr1 + cr2 \cdot Vac) + Mv \cdot g \cdot \sin(\alpha))) \cdot R$$

The signal (S) coming from the Automatic Driver block can be used to find the speed reference (Vr), and so we can find the torque that must be provide by the power system to satisfy this command, that means that an estimated speed wanted (Ves) and estimated torque demand (Tes) are found using driver command (S), and maximum speed ($Vmax$: is the maximum speed the vehicle can reach when $S=1$):

$$Ves = Vac + Vmax \cdot S$$

$$Tes = \left(\frac{\left(\frac{1}{2} \cdot \rho \cdot Af \cdot Cd \cdot (Vac + Vmax \cdot S)^2 \right)}{it \cdot if} + \frac{\left(Mv \cdot (cr1 + cr2 \cdot (Vac + Vmax \cdot S)) \right)}{it \cdot if} + \frac{\left(Mv \cdot g \cdot \sin(\alpha) \right)}{it \cdot if} \right) \cdot R \quad (9)$$

So the power demand estimated is: $Pes = Tes \cdot We$

So now we established estimation between engine power demand and driver signal since the values like

V_{max} , C_d , A_f .etc, are constant and actual speed (V_{ac}) is a feedback signal.

3.4.2 Hybrid Controller Tuning

Since we estimated the power demand only in coasting (no acceleration) situation, (in reality the vehicle have a response time to accelerate from (V_{ac}) to (V_r), for that we have to tune our PID controller (inside the Hybrid Controller block) to give us the response time we wish, the tuning can be performed manually (time consuming), or using MATLAB (quickly).

For a performance of acceleration from (0 km/h) to (60 km/h) in 13 seconds; see Figure 9, the PID controller parameter after tuning with MATLAB are:

$$P=1.13; I=0.02; D=0.0$$

So a PI controller is enough to obtain this performance.

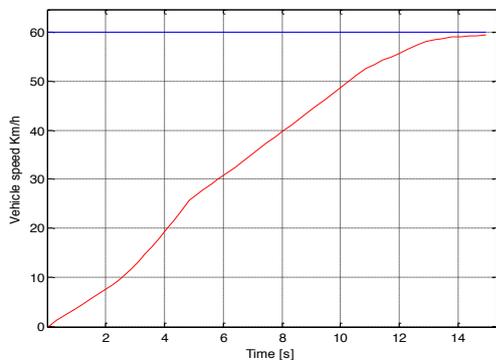


Figure 9: Acceleration performance [from 0 to 60 km/h, in 13 seconds]

3.4.3 Hybrid Controller Modeling

The Hybrid controller that is used is a rule-based controller. The energy management will only use current and past vehicle states and driver commands to calculate a close to optimal control signal. The design analysis starts from interpreting the driver pedal signal as a power demand. According to this power demand, the operation of this controller is divided into three modes, braking control, power split control and charging control. If the power demand is negative, braking Control will be applied to decelerate the vehicle (regenerative braking or mechanic braking depends on braking pedal position). If the power demand is positive either Power Split Control or Recharging Control will be applied according to the battery state of charge (SOC). Some controller use the charge sustaining policy which assure that the (SOC) stay within preset lower (SOCmin) and upper (SOCmax) bounds. This policy is chosen for efficient battery operation as well as to prevent battery depletion or damage

Power Split Strategy

The various Engine Operating modes are selected based on the following set of rules:

- 1- If state of charge of the battery is greater than the lower limit (SOCmin) and power demand

can be provided by battery then the vehicle is only operated in Electric mode.

- 2- If the state of charge of battery is above the lower limit (SOCmin) and the use of engine alone cannot be in efficient operating point, then Engine and Motor both provide the requested power in a way that the engine is as near as possible of best operating point imposed by the transmission and the motor supply the rest of torque demand.
- 3- If the state of charge of the battery goes below the lower limit (SOCmin) then the Engine provides the extra power to charge the battery and also powers the vehicle (the electric motor becomes generator and provide negative torque to charge the battery, in this controller the generator torque is controlled to put the engine in a best operating point when charging the battery).
- 4- If the power demanded by the driver is negative (the driver is decelerating the vehicle) and the state of charge of the battery is not maximal and power demanded is less than the maximal generator power then the power is stored in the battery using the Regenerative braking.
- 5- If the Power demanded by the driver is negative, the state of charge of the battery is not maximal and power demanded is greater than the maximal generator power then a part of the power is stored in the battery using the Regenerative braking and the other part is lost in the mechanical brakes.
- 6- If the Power demanded by the driver is negative, the state of charge of the battery is maximal then the mechanical braking is engaged.

The controller state machine is implemented using Simulink/Stateflow (figure 10)

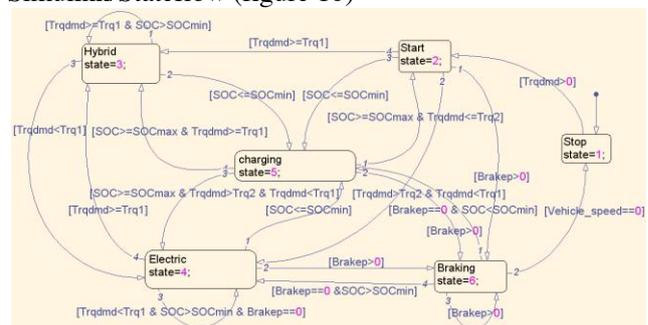


Figure 10: Controller state machine; (Trqdmd is estimated torque demand, Brake is the brake position)

State 1: the vehicle is stopping so both the electric motor and engine are switch off.

State 2: the vehicle starts only the electric motor is switch on and will drag the engine.

State 3: In this state there is a hard acceleration and the electric motor cannot supply all the power so there is

hybrid traction, this controller will control the torque of the motor to always put the engine in an efficient operating point.

State 4: In this state the motor can supply the power demand so the engine is shut down.

State 5: in this state the battery state of charge is not enough ($SOC < SOC_{min}$) so the engine will power the vehicle and charge the battery, the electric motor become generator and will provide a negative torque. In this controller when we are in this state the generator torque is controlled to put the engine in a best operating point (using engine map to find the correspondent generator torque for the best operating point possible).

State 6: This is the state of braking, the controller decides either uses the regenerative braking [4], the mechanical braking or a blending between mechanical and regenerative braking.

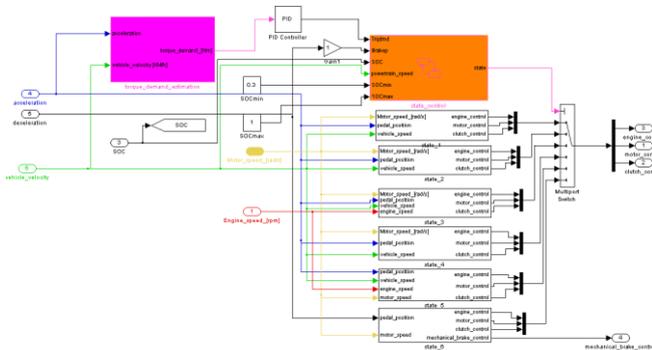


Figure 11: Top level simulation model of the Hybrid Controller implemented in Simulink

4 Results and Discussion

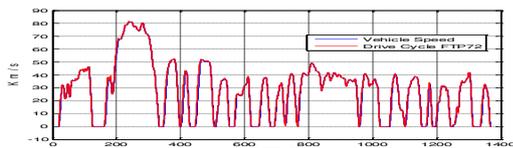


Figure 12: Conventional vehicle speed profile using FTP72 as reference (km/h)

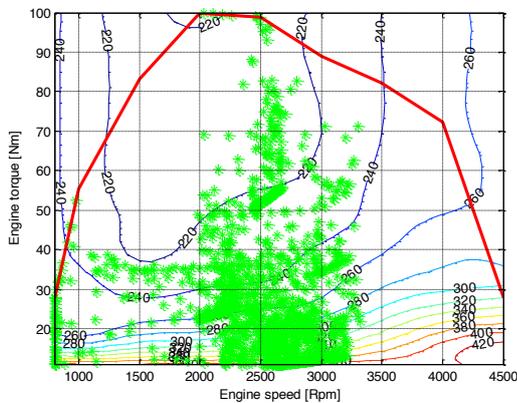


Figure 13: Engine operating point over FTP72 cycle (Conventional vehicle).

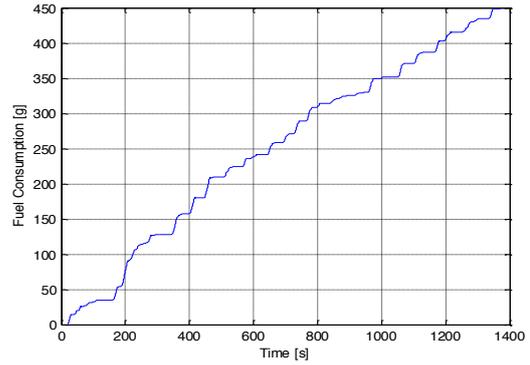


Figure 14: Fuel Consumption (Conventional vehicle)

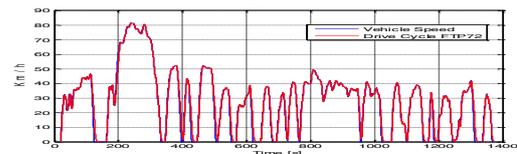


Figure 15: Hybrid vehicle speed profile using FTP72 as reference (km/h)

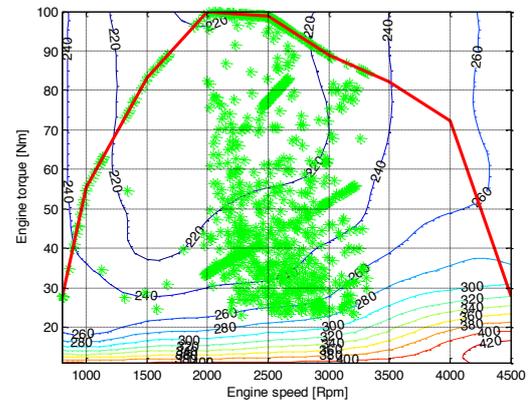


Figure 16: Engine operating point over FTP72 cycle (Hybrid vehicle).

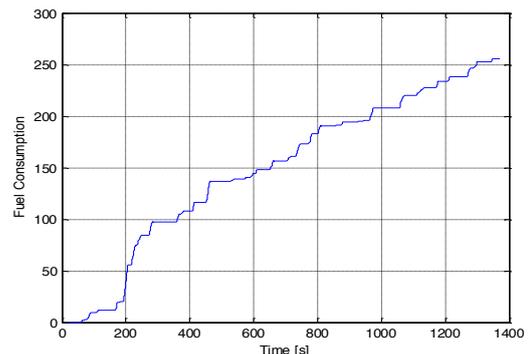


Figure 17: Fuel Consumption (Hybrid vehicle)

Using FTP72 cycle, it can be seen Fig 12 and Fig 15, that both the hybrid and the conventional vehicle model followed the desired drive cycle speed very well.

- Fuel consumption

The two figures Fig 14 and Fig 17 depict the fuel consumption of the conventional and the hybrid vehicle models over the FTP72. As expected, the equivalent fuel [2] consumed by the conventional vehicle is higher than that of the hybrid vehicle. In table 1 we can see the

improvement of a hybrid vehicle compared to the conventional vehicle is 24%.

Table 1: Fuel consumption comparison

Powertrain Model	Total Fuel Consumption (with SOC correction) (g)	Distance Traveled (km)
Conventional	450	11.9893
Hybrid	342	11.9893
Improvement	$(450-342)/450=0.24=24\%$	

Another advantage for the Hybrid vehicle is that we can control the motor not only to make the engine work efficiently but also to make it work long time in a fixed torque, which can be done, by letting the motor torque supply the transient torque demand. The operating points for the two configurations show that in the conventional vehicle Fig 13 the points are not efficiently distributed, but in the case of a hybrid vehicle Fig 16, the engine operating points are near the efficient region.

Conclusion

This article introduced a method for modeling a parallel HEV hybrid controller for power management using MATLAB/Simulink; first we estimated the power demand from the pedal position and then we chose how to split this power between the two power sources to obtain better fuel economy. Using such controller, we have demonstrated that a HEV can make a good fuel economy compared with a conventional vehicle with the same characteristics by using the engine in more efficient way and also using generative braking.

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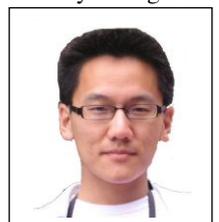


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