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# Study on Modeling and Simulation of HEV for Optimal Fuel Economy

**Owe Israel**

Department of Electrical Power Engineering and Mechatronics
Tallinn University of Technology, 12480 Tallinn, Estonia
israelowe@yahoo.com

## ABSTRACT

Hybrid electric vehicle uses internal combustion engine (ICE) and electrical power for propulsion. This study will provide information about the series parallel hybrid vehicle architecture. The different components; which includes the electric motor, generator, internal combustion engine, control system, batteries, DC to DC converter, vehicle dynamics , planetary gear of the series parallel hybrid vehicle will be modelled using matlab simulink . Also analysis will be carried out using standard vehicle curb weight and tire rolling radius from manufacturers to optimized the series parallel hybrid vehicle for better fuel economy. Finally simulation will be run for four different drive cycles (FTP75, NYCC, HWFET, EUDC) comparing the HEV model and the optimized HEV model.

***Keywords:*** HEV, Fuel Optimal, Serial-Parallel, Internal Combustion Engine

## 1. INTRODUCTION

MA hybrid vehicle refers to a vehicle with at least two sources of power, typically one of the sources of power is provided by an electric motor. Hybrid electric vehicles (HEVs) are the type of hybrid vehicle that combines the best features of internal combustion engine (ICE) and electric motor (EM). Hybrid Vehicles can save up to 50% less fuel when compared to convectional vehicle in the same class. Hybrid electric vehicle has numerous advantages when compared to the conventional internal combustion engine vehicle, HEVs combine both ICE and EM and these allows the HEVs to operate with only the EM when driving at low speed (less that 50 Km/h) in cities and while the Hybrid vehicle operate in this mode no fuel is exhausted, when in the highway (above 50 Km/h) where a higher speed is required both the ICE and the EM can be used to drive the HEV as more power is required. This implies less few comsuption and less pollution in the environment, although the main advantage of ICEs is the higher power that it can provide to vehicles but HEVs can maintain the optimal operation in both low speed on busy roads and high speed on highways[1].

These are three main types HEVs : series type , parallel type and the series parallel type. In the series types the internal combustion engine is not connected to the vehicle powertrain, it is only used to run the generator to supply electrical power to battery and the electrical power of the battery is used to propel the wheels . In the parallel type mechnical and electrical power are both connected to the powertrain of the vehicle and different control strategies are used during motion to determine if only the EM is used (at low speed) or if only the ICE is used (at high speed) or if both the EM and ICE is used to propel the wheels of the vehicle. When both the ICE and EM is required at very high speed the the excess power is used to charge the battery . For the

Series Parallel type, it is more like the parallel type but has an additional electric motor and a planetary gear unit, this makes the control complex but more efficient as one of the electric motor acts as a generator for charging the battery while the other is used for the propelling the wheel[1][2].

In the past there have been different studies carried in reagards to optimizing the hybrid electric vehicle; this includes Dual clutch transmission for hybrid vehicles[3], Multi objective optimization of HEV fuel economy and emissions using the self-adaptive differential evolution algorithm[4], Optimization of HEV energy management strategy based on driving cycle modeling[5], Energy control of HEV based on fuzzy controller optimized by particle swarm optimization[6]. But in this study, attention will be given to the modeling of a series parallel hybrid electric vehicle using matlab simulink. The simulink model will be used to investigate the effect of fuel economy on the series parallel hybrid electric vehicle as a fucntion of vehicle weight and tire rolling radius. Analysis will be done using data from hybrid electric vehicle manufacturers and tire manufacturers to investigate the degree of effect that the tire rolling radius and vehicle weight has on the series parallel hybrid electric vehicle. Analysis of data from manufactuers will be done using Matlab cftool to find the best tire rolling radius and vehicle weight required to optimize the series parallel hybrid electric vehicle for better fuel economy.

## 2. MODELING

### 2.1. Battery

The battery is modeled as a voltage source and resistance which changes the load and power flow. A sub-block was modeled for the state of charge (SOC) taking voltage and current as input and the output voltage of the Battery is just over 200V is connected to the input of the DC to DC converter. The modeling criteria used for the for the battery model can be found in[7].

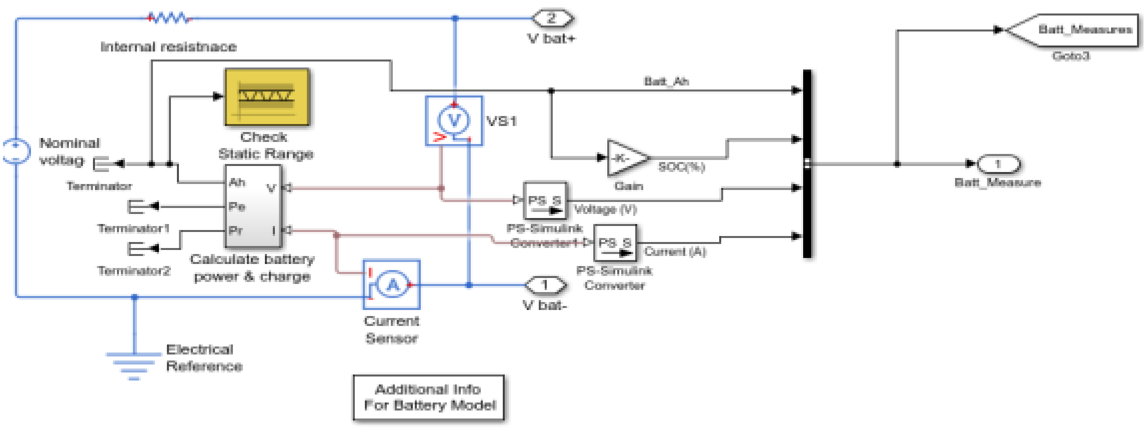


Figure 2.1: Simulink model of battery

### 2.2. DC to DC Converter

The DC to DC converter can be considered as DC equivalent to an AC transformer with a continuously turns ratio. Like a transformer, it can be used to step down or step up a DC voltage source. The criteria used for the modeling of the DC to DC converter can be found in [8][9]. For this study the DC to DC converter is used to boost the input voltage it receives from battery which is just over 200V and then step it up and gives the output voltage of 500V which is assigned to drive the motors. The Simulink model of the DC to DC converter is given below in figure 2.

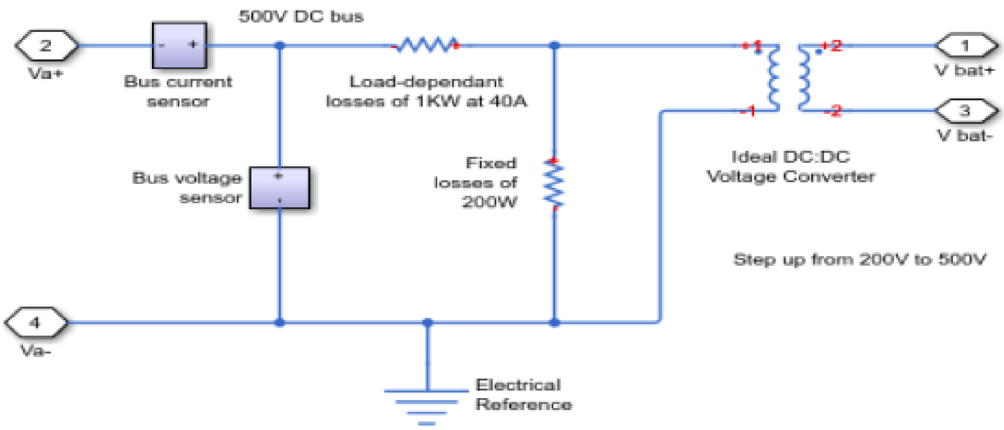


Figure 2.2: Simulink model of DC to DC converter

## 2.3. Electric Motor and Generator Model

The servomotor is used to represent the electric motor and generator, the output torque required is tracked from the torque demand reference value from the control system of the series parallel HEV model, and both the servo motor and servo generator are connected to the DC supply. The function of the motor is to provide torque to the transmission required for the propelling the vehicle while the generator is used to start the vehicle and to charge the HEV battery through regenerative braking at certain mode in the control process. Criteria used for modeling the motor can access in the reference[7], while that of the generator can be found in these references[7][10]. Figure 2.3 and 2.4 shows the Simulink model of the electric motor and generator, the blue lines in both figure indicates the electrical part of the model while the green part indicate mechanical part of the model.

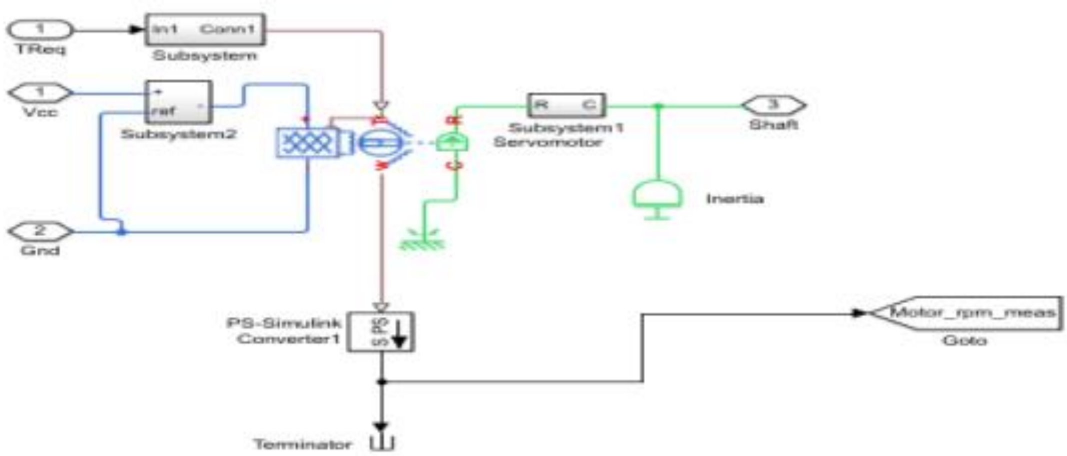


Figure 2.3 Simulink model motor

## 2.4. Planetary gear (power split)

Planetary gear is used in the series parallel HEV configuration for power split functionality between the mechanical (ICE) and the electrical link (Electrical Motor).

The planetary gear connects the gasoline engine, generator and electric motor together allowing the vehicle to operate at different mode (ICE, Motor, ICE and Motor combine). The planetary gear (Power Split) set consists of the sun gear, several pinion gears, carrier, ring gear. The criteria used for this model can be assessed in this reference[7].

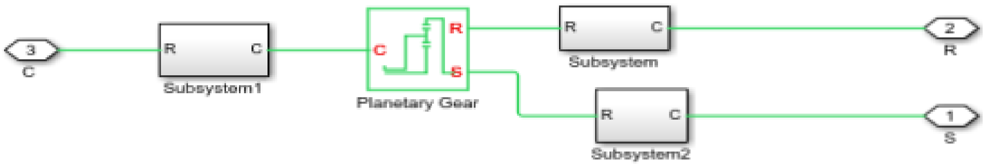


Figure 2.5 Simulink model of planetary gear

## 2.5. Vehicle Dynamics

The vehicle dynamics model is made up of gear box, differential, left and right tires, vehicle body and it was modelled using simscape driveline tool in matlab Simulink. The criteria used for the modeling can be found in the this reference[7]. The figure 2.6 below illustrates the Simulink model of the vehicles dynamics model.

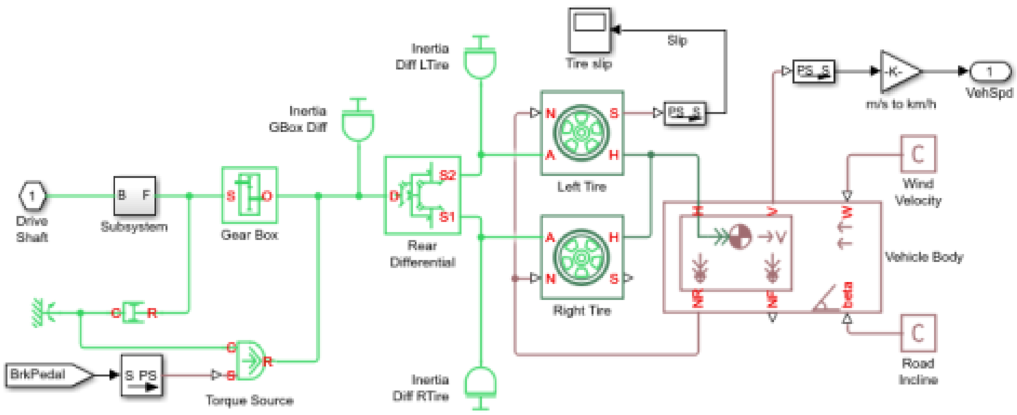


Figure 2.7 Simulink model vehicle engine block

## 2.7. Control System

The control system block is the made of five different sub blocks namely, Mode Logic Block, Battery Controller Block, Motor Controller Block , Genrator Controller Block , Engine Controller block. The system control block is where decisions required for the control of the HEV is taken. Figure 2.8 below illustrates the control system block.

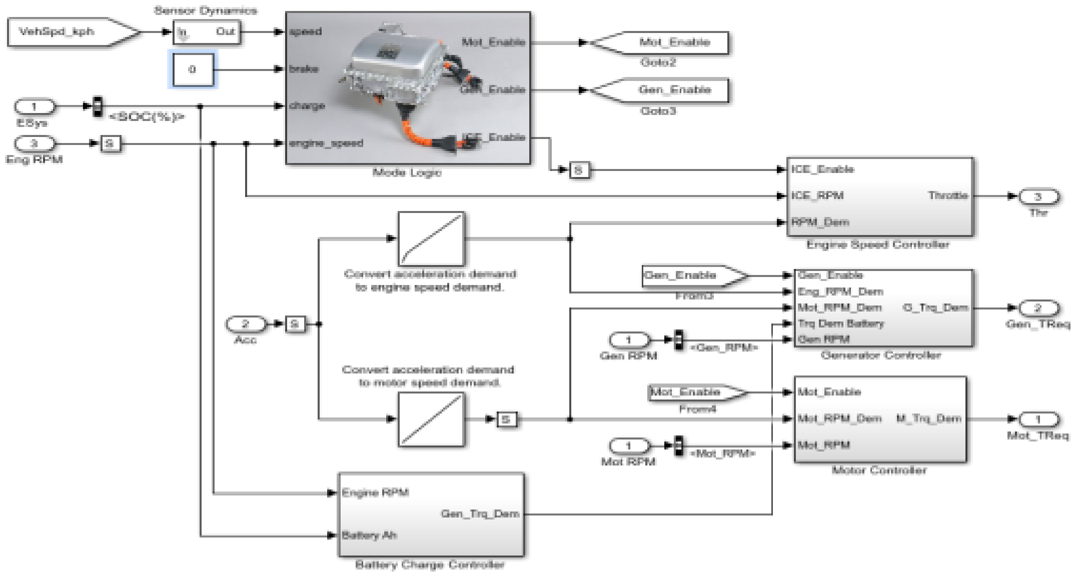


Figure 2.8 Simulink model of control system

**Mode Logic**

The mode logic block was modelled using stateflow toolbox in matlab Simulink, the mode logic block contains different states (Motion Mode, Start Mode, Normal Mode, Acceleration Mode, Cruise Mode, Brake Mode). Inside this different states actions as taken that defines the specific condition that the HEV works. The mode logic block has four inputs (vehicle speed, Brake, State of charge, engine rpm) and three outputs (motor enable, generator enable, ICE enable), the four inputs are implemented to figure out which state the vehicle must be assigned to and the decision is taken if the motor, generator, or engine should work.

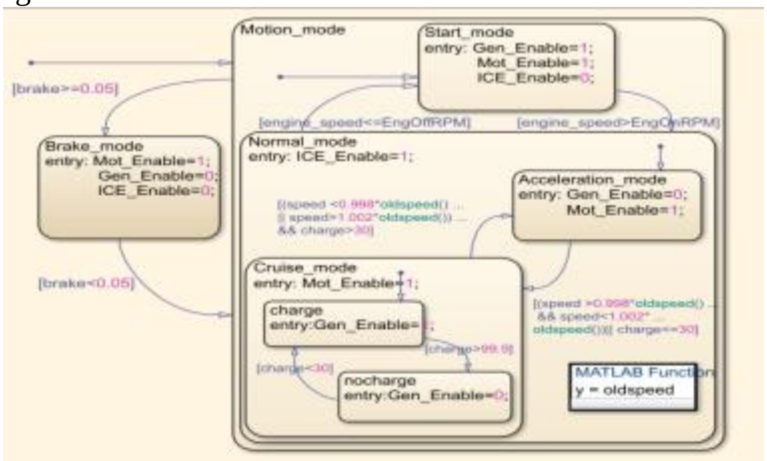


Figure 2.9 Simulink model of mode logic

**Battery charge controller block**

This block receives input signals from the engine speed and battery Ah (state of charge), both inputs signal parameter are resposible for providing the required generator torque demand to lunch the generator when there is demand from the mode logic to activate the generator.

**Motor controller block**

This block receives input signals from the motor rpm (motor speed) and motor rpm demand and motor enable signal from the mode logic and then these parameters can be controlled using a PI controller to give the output motor torque required. The maximum value of voltage allowed is 5 volts which is the equivalent to a demand of 6500 rpm.

**Generator controller block**

This block receives five input signals namely: gen_enable signal from mode logic, engine_rpm demand, motor_rpm demand, generator torque demand from battery, generator rpm. Excluding gen_enable signal and torque demand from battery signal all other signals are controlled using a PI controller. The generator torque output which is the output signal of this block is controlled by five different input parameters.

**Engine speed controller block**

The output signal of this block is throttle and it is determined by three input signals namely (ICE Enable from mode logic, engine rpm, engine rpm demand). These three input signals are controlled using the PI controller to give an output signal called throttle whenever required.

### 2.8. Integrated powertrain component (Simulink model of Series parallel HEV)

Below is the integrated powertrain components of the series parallel HEV. The electrical system contains the battery, DC to DC converter, electric motor and generator, also shown below in figure 2.10 is the vehicle engine, power split or planetary gear, vehicle engine, and control system which contain the mode logic, battery charge controller, engine speed controller, generator controller, motor controller.

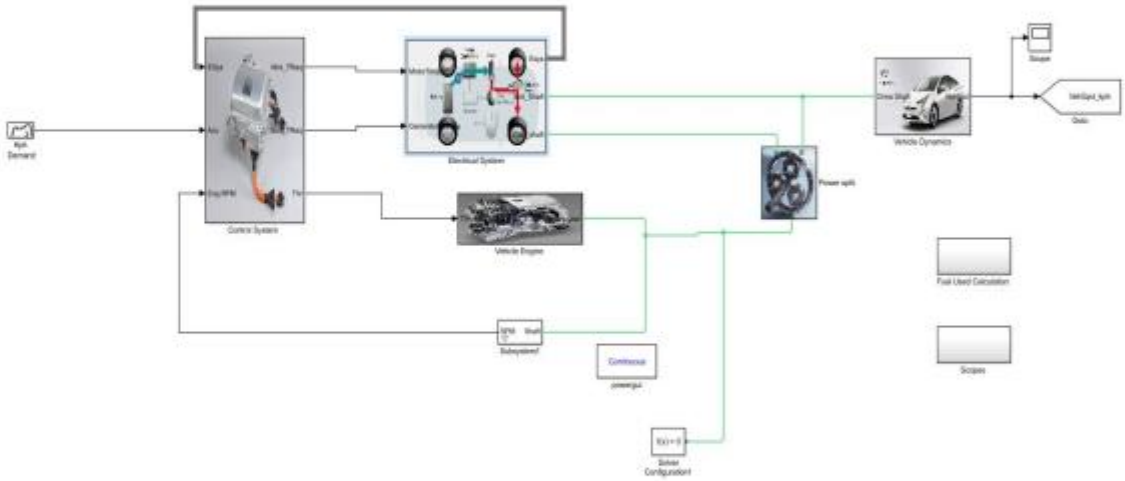

Figure 2.10 Simulink model of series parallel HEV

## 3. ANALYSIS AND SIMULATION

For this study, analysis will be based on fuel efficiency and how the vehicle weight, Rolling Resistance affect the fuel consumption of the HEV. Thus, data will be collected from vehicle and tire manufacturers that will be analysed and the results will then use for the optimization of the series parallel hybrid vehicle model.

### 3.1. Data collection

Table 4.1 and 4.2 below illustrates the data for vehicle weight and tire rolling radius collected from different manufacturers.

Table 3.1 Data for Vehicle Curb weight

| **No** | **Car model and year** | **Curb Weight Kg** |
|---|---|---|
| 1 | Toyota Prius (2009-2015) | 1325[11] |
| 2 | Honda Insight Hybrid (2009-2014) | 1237[12] |
| 3 | Kia Niro Hybrid (2016) | 1409[13] |
| 4 | Hyundai Sonata hybrid (2011-2013) | 1568[14] |
| 5 | Kia Optima Hybrid (2016) | 1585[15] |
| 6 | Hyundai Avante LPi Hybrid | 1297[16] |
| 7 | Toyota Camry Hybrid (2007) | 1649[17] |
| 8 | Honda Civic hybrid (2011-2016) | 1280[18] |

Table 3.2 standard Tire sizes from manufacturers with rolling radius [19]

| **No** | **Tires sizes** | **Loaded or Rolling Radius M** | **Recommended rim Inch** |
|---|---|---|---|
| 1 | 155/65 R13 | 0,241 | 4,5 |
| 2 | 155/80 R13 | 0,261 | 4,5 |
| 3 | 165/60 R14 | 0,251 | 5,0 |
| 4 | 165/65 R13 | 0,247 | 5,0 |
| 5 | 165/65 R14 | 0,258 | 5,0 |
| 6 | 165/70 R14 | 0,266 | 5,0 |
| 7 | 165/80 R13 | 0,269 | 4,5 |
| 8 | 175/65 R14 | 0,264 | 5,0 |
| 9 | 175/65 R15 | 0,276 | 5,0 |
| 10 | 205/50 R15 | 0,277 | 6,5 |

## 3.2. Analysis

The series parallel HEV model was simulated considering different HEV vehicle weight and rolling radius from manufacturers for 100 secs over the FTP75 drive cycle and the resulting fuel consumption was recorded and shown below in table 3.3.

Table 3.3 HEV weights vs tire radius

| Tire Rolling Radius m \ Vehicle Weight kg | 1325 | 1237 | 1409 | 1568 | 1585 | 1297 | 1649 | 1280 |
|---|---|---|---|---|---|---|---|---|
| 0,241 | 0,01984 | 0,01984 | 0,01985 | 0,01993 | 0,01995 | 0,01984 | 0,02009 | 0,01984 |
| 0,261 | 0,01961 | 0,01961 | 0,01964 | 0,02032 | 0,02052 | 0,01961 | 0,02181 | 0,01961 |
| 0,251 | 0,01973 | 0,01973 | 0,01973 | 0,0199 | 0,01995 | 0,01973 | 0,02053 | 0,01973 |
| 0,247 | 0,01977 | 0,01977 | 0,01977 | 0,01991 | 0,01993 | 0,01997 | 0,02024 | 0,01977 |
| 0,258 | 0,01966 | 0,01964 | 0,01968 | 0,01995 | 0,02025 | 0,01964 | 0,02121 | 0,01964 |
| 0,266 | 0,01956 | 0,01957 | 0,01957 | 0,02057 | 0,02088 | 0,01957 | 0,02255 | 0,01957 |
| 0,269 | 0,01953 | 0,01954 | 0,01959 | 0,02091 | 0,02129 | 0,01953 | 0,02322 | 0,01954 |
| 0,264 | 0,01958 | 0,01959 | 0,01962 | 0,02045 | 0,02063 | 0,01958 | 0,02209 | 0,01958 |
| 0,276 | 0,01948 | 0,01948 | 0,01956 | 0,02188 | 0,02238 | 0,01947 | 0,02511 | 0,01947 |
| 0,277 | 0,01962 | 0,01962 | 0,01965 | 0,02025 | 0,02046 | 0,01962 | 0,0216 | 0,01962 |

To investigate the effect of tire rolling radius and vehicle weight on fuel consumption in the series parallel HEV the curve fitting Matlab tool is utilized and based on the Goodness of fit with respect to R-square: 0.9874, the third order for weight of HEV and second order for rolling radius is obtained. Below is the 3D plot illustrating the relationship between the x = Vehicle Weight, y = Rolling Radius of Tire, z = Fuel Consumption as shown in figure 3.1.

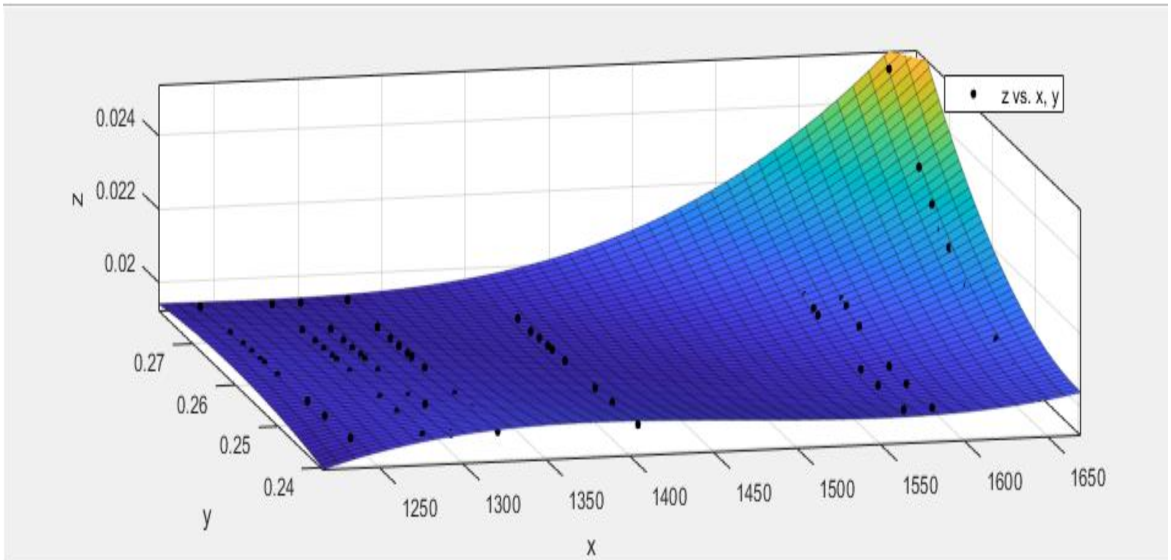


Figure 3.1 Matlab cftool 3D plot of data

$$Z = f(x,y) = P_{00} + P_{10}X + P_{01}Y + P_{20}X^2 + P_{11}XY + P_{02}Y^2 + P_{30}X^3 + P_{21}X^2Y + P_{12}XY^2 \quad (3.1)$$

Where, Z is the fuel consumption over selected drive cycle, X is the HEV weight, Y is the tire rolling radius

And the coefficient value is $p00 = -1{,}816,\ p10 = 0{,}002245,\ p01 = 9{,}824\ p20 = -7{,}502e-07,\ p11 = -0{,}009577,\ p02 = -13{,}75,\ p30 = 8{,}758e-11,\ p21 = 1{,}527e-06,\ p12 = 0{,}01062$

To get the optimum value for X and Y in the in equation 3.1 let (F) be a function of XY as shown below in equation 3.2

$$F = P_{00} + P_{10}X + P_{01}Y + P_{20}X^2 + P_{11}XY + P_{02}Y^2 + P_{30}X^3 + P_{21}X^2Y + P_{12}XY^2 \quad (3.2)$$

Then differentiate F partially with respect to XY and equate your answer to zero as shown in equation (3.3)

$$3{,}0540e^{-6}x + 0{,}0212y - 0{,}0096 = 0 \quad (3.3)$$

Since there are two variables in equation, hence there will be numerous number of possibilities and there for the sake of the simplicity we take the $y$ (corresponded to rolling radius of HEV equal to 0,261 m or 261mm) for the HEV to find the best value for vehicle weight $x$ which is called the optimized vehicle weight.

After solving the equation 3.3 with $y = 0.261$ then x way obtained to be $1220\ kg$ which is the optimized HEV weight, the OHEV vehicle weight is also used to calculate the for optimized HEV rolling radius value which is $0{,}277\ m$.

Hence the optimized model of the HEV has optimized vehicle weight and tire rolling radius of $1220\ Kg\ and\ 0{,}277\ m$ respectively.

Simulation was carried out comparing HEV and optimized HEV(OHEV) in different standard Europe and United States drive cycles (FTP75, NYCC, HWFET, EUDC), comparison between HEV and OHEV will be based on vehicle performance and fuel consumption. Table 3.4 illustrate fuel consumption over the four different drive cycle when the series parallel hybrid electric vehicle and the optimized series parallel hybrid electric vehicle were compared.

In the table below HEV indicates series parallel hybrid electric vehicle while OHEV indicates the optimized series parallel hybrid vehicle.

Table 3.4 Fuel consumption results from different drive cycle

| No | Vehicle type | Drive cycle | Vehicle weight m/kg | Tire rolling radius m | Fuel consumed L |
|---|---|---|---|---|---|
| 1 | HEV | FTP75 | 1200 | 0,261 | 0,03668 |
| | OHEV | FTP75 | 1220 | 0.277 | 0,03649 |
| 2 | HEV | NYCC | 1200 | 0,261 | 0,03295 |
| | OHEV | NYCC | 1220 | 0,277 | 0,03263 |
| 3 | HEV | HWFET | 1200 | 0,261 | 0,03969 |
| | OHEV | HWFET | 1220 | 0,277 | 0,03915 |
| 4 | HEV | EUDC | 1200 | 0,261 | 0,03715 |
| | OHEV | EUDC | 1220 | 0,277 | 0,03655 |

Figure 3.2-3.9 shows the performance and fuel consumption compares between the series parallel hybrid electric vehicle(HEV) and optimized (OHEV) over four different standard drive cycles (FTP75,NYCC,HWFET,EUDC).

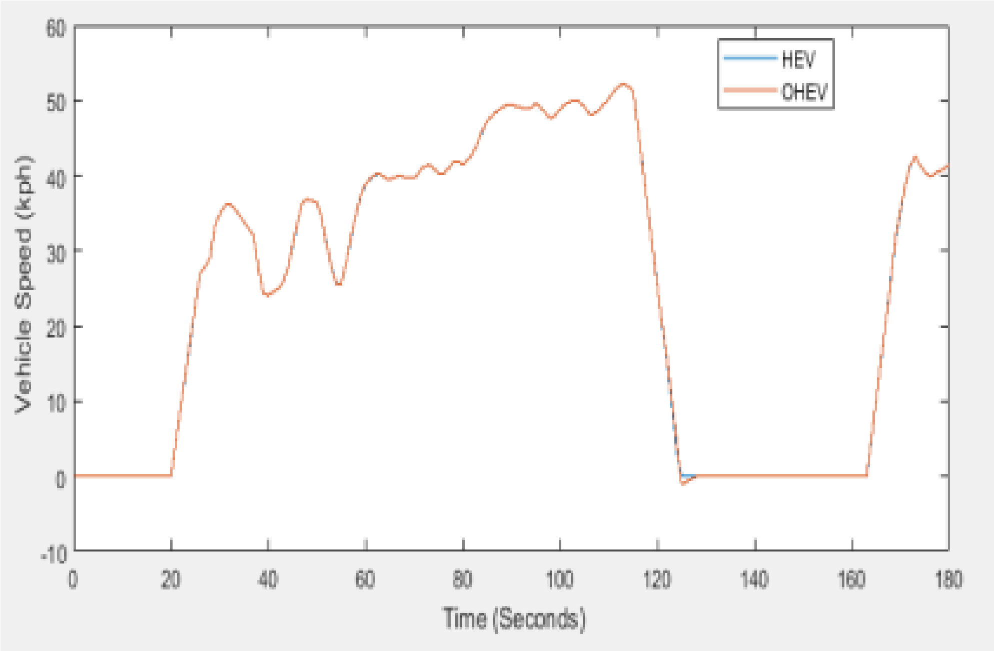


Figure 3.2 HEV and OHEV performance plot in FTP75 drive cycle

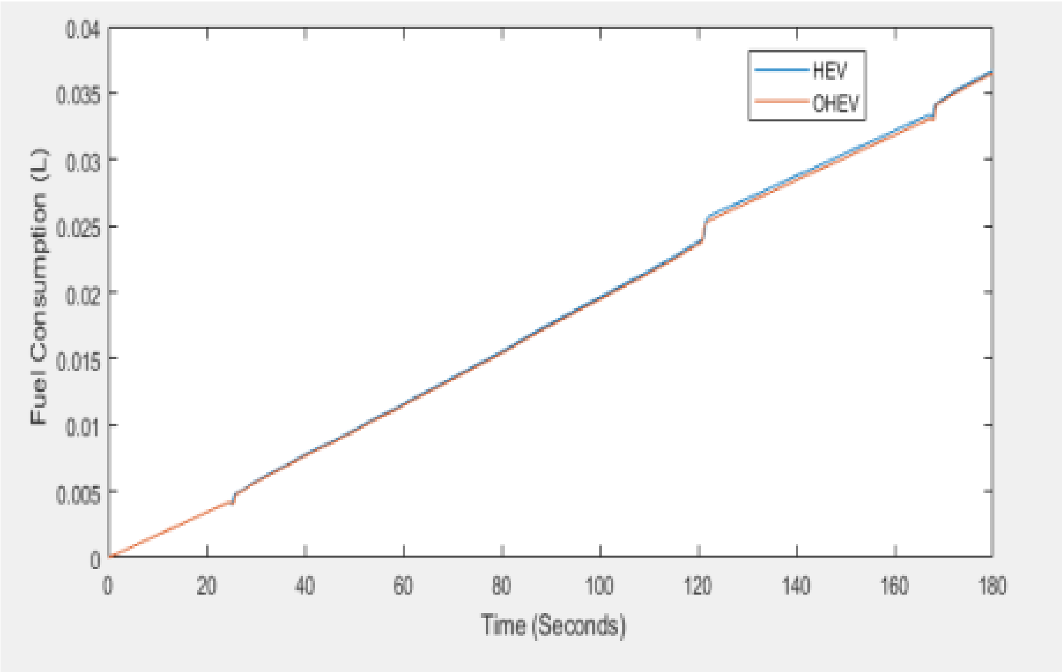


Figure 3.3 HEV and OHEV fuel consumption plot in FTP75 drive cycle

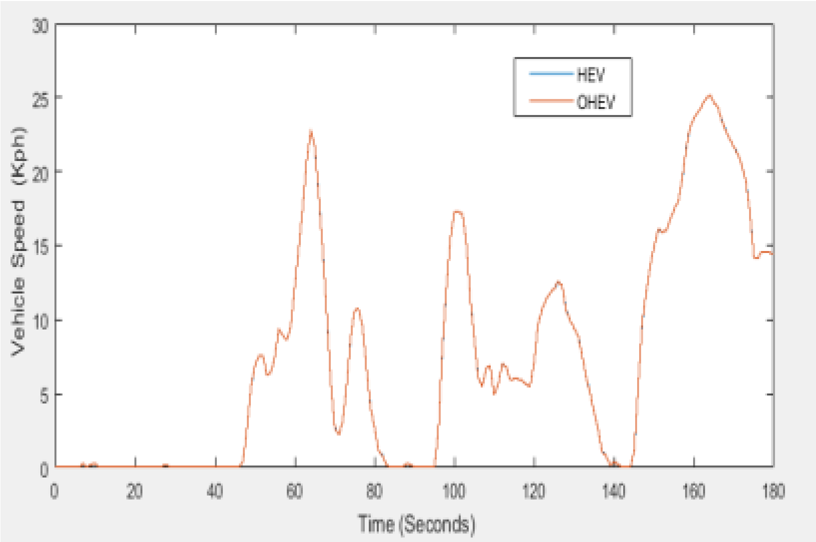


Figure 3.4 HEV and OHEV performance plot in NYCC drive cycle

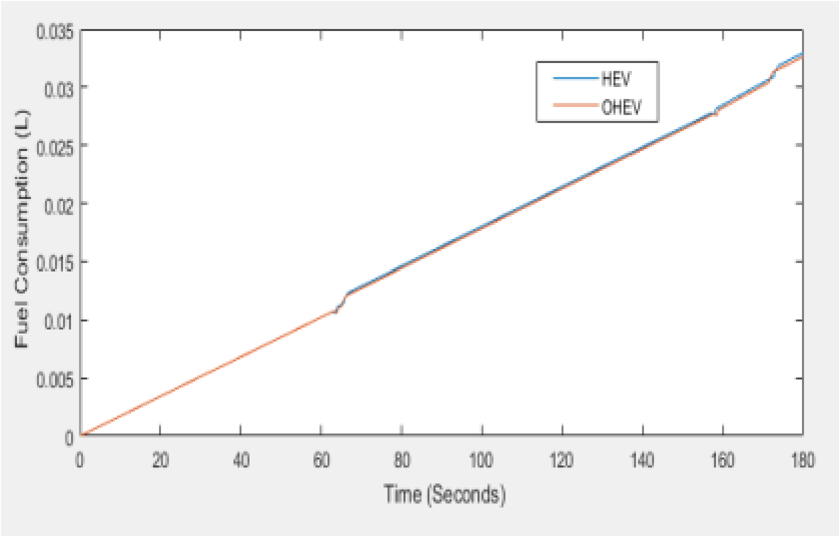


Figure 3.5 HEV and OHEV fuel consumption plot in NYCC drive cycle

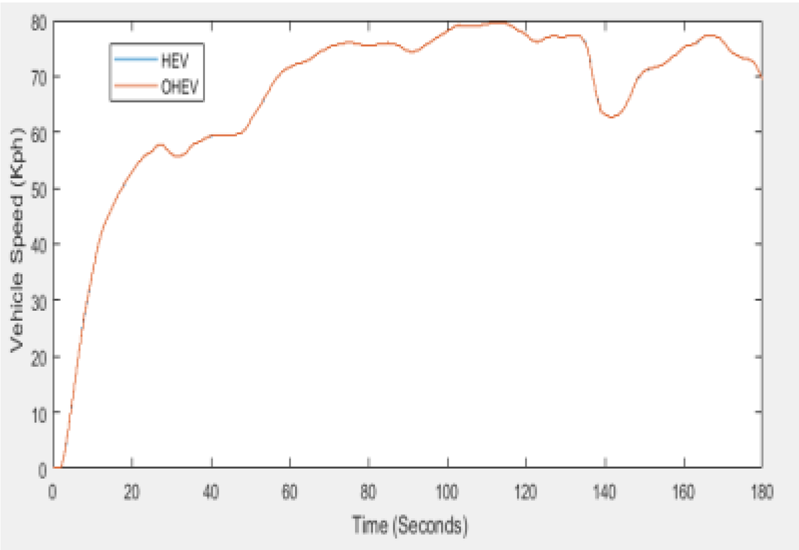


Figure 3.6 HEV and OHEV performance plot in HWFET drive cycle

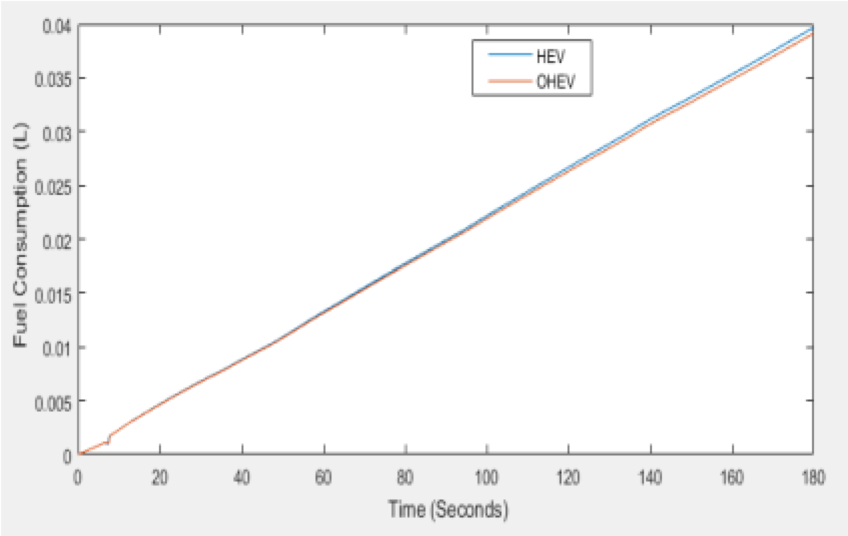


Figure 3.7 HEV and OHEV fuel consumption plot in HWFET drive cycle

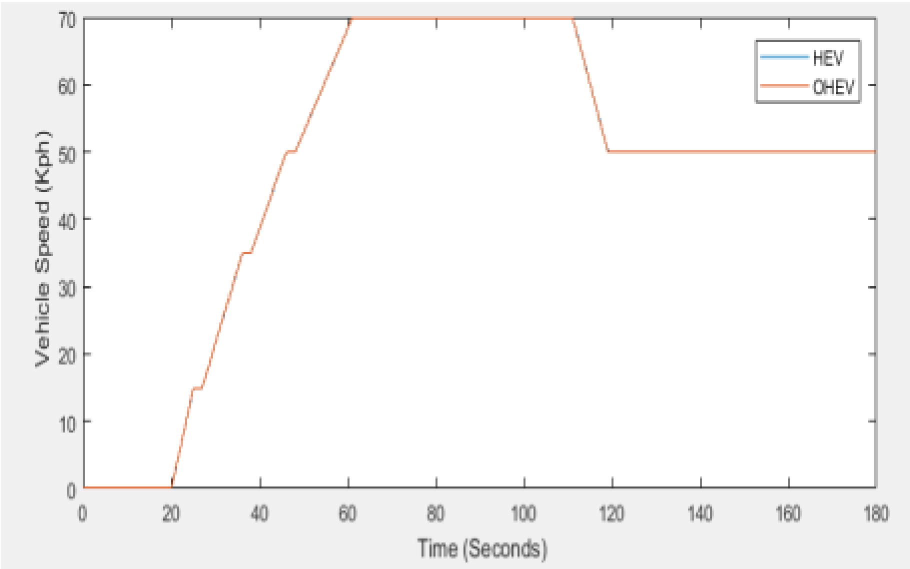


Figure 3.8 HEV and OHEV performance plot in EUDC drive cycle

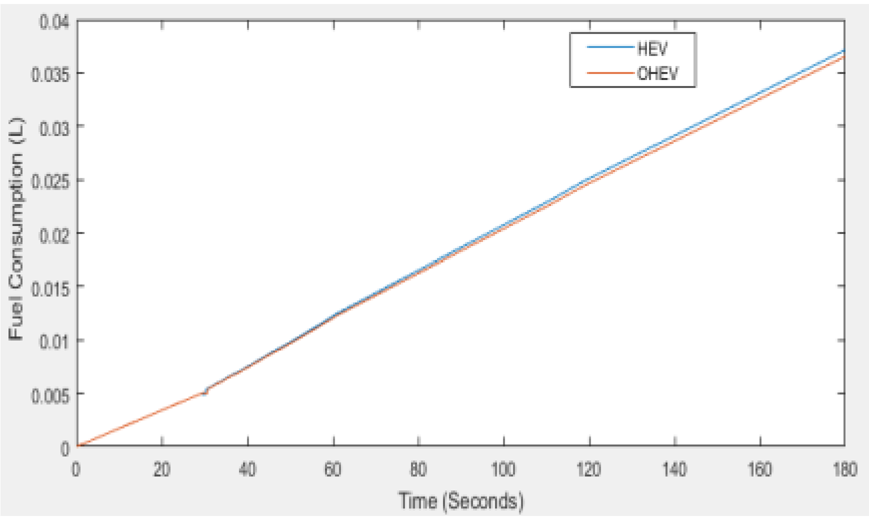


Figure 3.9 HEV and OHEV fuel consumption plot in EUDC drive cycle

## 4. CONCLUSION

The different powertrain components of the series parallel hybrid vehicle was model and integrated on matlab Simulink. The analysis for optimization was carried out considering vehicle weight and tire rolling radius and results show that the optimized HEV (OHEV) consumes less fuel when compared to the series parallel hybrid vehicle (HEV), this means that choosing the right vehicle weight and tire rolling radius during manufacturing of the HEV will go a long way in reducing the amount of fuel used by HEV and reduce the amount of emission of pollutant gases in the environment.

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## CONFLICT OF INTERESTS

The author would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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