DESIGN OF MODULAR ARCHITECTURE FOR EV AND HEV FOR PASSENGER CARS

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ABSTRACT

Hybridization is important to obtain the advantages of both the engine and motor as the sources of propulsion. This paper discusses the effect of hybridization of powertrain on vehicle performance. The Hybrid architectures are differentiated on the basis percentage of power dependency on the engine and motor. Passenger car with hybridization ratios of 20%, 40%, 60%, 80% and 100% are modelled on MATLAB/Simulink using the backward facing approach with the engine and motor specifications remaining constant. The hybridizations ratios and the energy consumption in terms of fuel and battery energy are obtained from the model and compared. Neural network is implemented to determine the fuel consumption. The outputs can be used by a system designer to determine a desirable hybridization factor based on the requirements dictated by the specific application.

Key words: Vehicle Architecture, Hybrid Electric Vehicle, Hybridization factor, Drive cycle

INTRODUCTION

With the increasing focus on electrification in the mobility space, a decreased reliance on the internal combustion engine is evident. This is coherent through the rise in the number of hybrid and electric vehicles in the market and also observed in the aftermarket solutions which are available to convert existing internal combustion engine vehicles into hybrids or electric vehicles using retro fitment concepts (ARAI, 2019). For all these applications, deciding the hybridization factor is important based on the requirements. The different values of hybridization factor help in distinguishing the vehicles into different classes such as micro, mild, medium, full hybrid vehicles (Damiano Lanzaratto et al., 2018). The other basis for classifying hybrid vehicles is based on the architecture as series, parallel, power split configurations as shown in Figure 1, Figure 2 and Figure 3

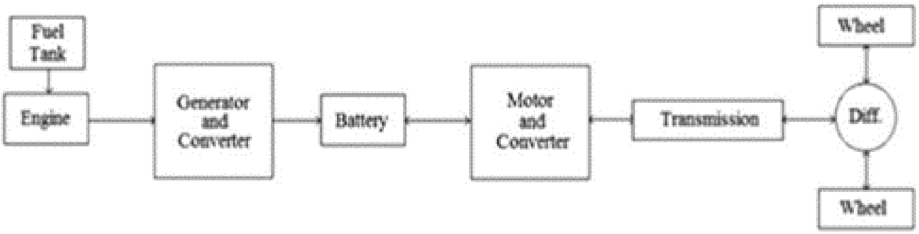


Figure 1 Series HEV (Iqbal Hussain et al., 1999)

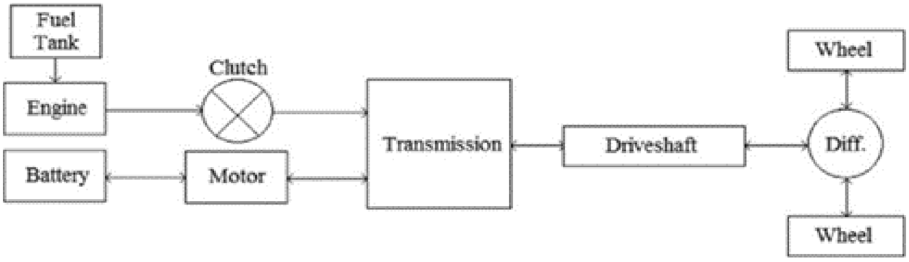


Figure 2 Parallel HEV (Iqbal Hussain et al., 1999)

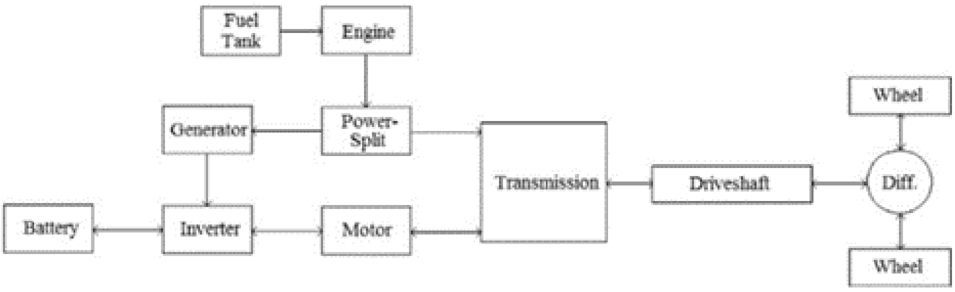


Figure 3 Series- Parallel (Power Split) HEV (Iqbal Hussain et al., 1999)

VEHICLE PARAMETERIZATION AND MODELING

Before getting into the modeling of the vehicle, it is good to acquaint with the two basic modeling methodologies typically used. One being the 'Forward facing Modeling' and the other is the 'Reverse' or 'Backward facing Modeling'. Both have numerous advantages and disadvantages to themselves, but it is observed that the 'Backward facing Modeling' is employed very often in powertrain component sizing for its quicker simulation times although the obvious downside is neglecting the transient behavior of the vehicle. (Chan, 2010, David Wenzhong Gao et al., 2007) In this paper, the model has been developed using the 'Backward facing modeling approach.

Data selection for reference vehicle:

Based on the values obtained for the physical vehicle parameters for a passenger car was chosen for a typical sedan and are shown in Table 1.

Table 1 Data corresponding to physical parameters of vehicle

Data	Constants
Mass of vehicle (ULW) (kg): 1500	
Coefficient of aerodynamic drag (C_d): 0.27	
Frontal area of the vehicle (A) (m^2): 2.15	
Coefficient of rolling resistance (μ_{rr}): 0.02	
Wheel radius I (m): 0.25	

The data taken from Table 1 is used to calculate the tractive effort required by the vehicle. The expression used for determining this value is shown in eqn. (1)

$$\boldsymbol{\Sigma F = F_{IN} + F_{AD} + F_G + F_{RR}} \qquad (1)$$

Here, $\boldsymbol{F_{IN}}$ represents the inertial force which contributes in the acceleration of the vehicle in moving forward and is determined using the Newtonian eqn. (2) where, 'm' is the mass of the vehicle, i.e., its GVW (Gross Vehicle Weight) and 'a' is the linear acceleration of the vehicle:

$$\boldsymbol{F_{IN} = m \times a} \qquad (2)$$

The next component is $\boldsymbol{F_{AD}}$ which is the resistance experienced due to aerodynamic drag. This force is calculated using eqn. (3) along with the Data taken from Table 1 and 'V' is the instantaneous linear velocity of the vehicle:

$$\boldsymbol{F_{AD} = \frac{1}{2} \times \rho \times C_d \times A \times V^2} \qquad (3)$$

F_G is the additional force which is required to overcome gradients. The expression to compute this force is given in eqn. (4) and here, 'θ' corresponds to the angle of the gradient:

$$F_G = m \times g \times \sin\theta \qquad (4)$$

Finally, F_{RR} represents the force required to overcome the rolling resistance. This is a concept which arises at the road – tire interface and is dependent on both of these mediums being a material property. From the data above and from eqn. (5), F_{RR} can be calculated as follows:

$$F_{RR} = \mu \times m \times g \qquad (5)$$

Calculation of different forces

As discussed in the previous subsection with the equations, implementing them into the 'Backward modelling' concept yields the following subsystem in SIMULINK environment, as shown in Figure 4.

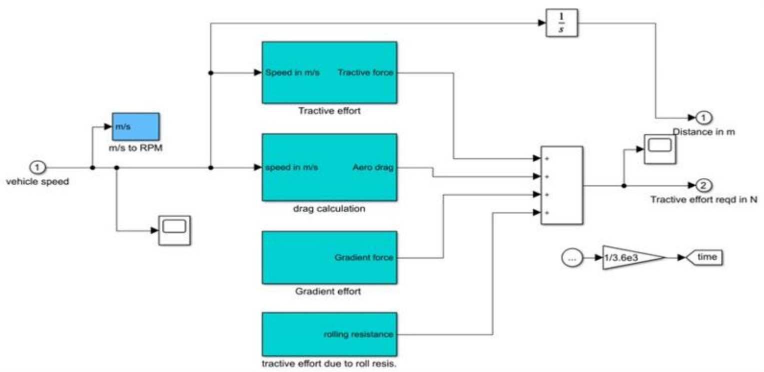


Figure 4 Subsystem for calculation of various forces

This subsystem can be termed as the 'Glider' model as this represents the physical parameters of the vehicle considering variables associated with the design of the vehicle body. Here, 'Glider' refers to the stripped-down vehicle body without the powertrain components inside.

ELECTRIC VEHICLE MODEL

The electric vehicle model will essentially consist of the 'Glider' model discussed above along with the pure electric drivetrain. The electric drivetrain can be split into various other subsystems, which can be simplified into the transmission, the motor, and the battery pack. The data used in modeling all these subsystems are shown in Table 2.

Table 2 Data used for Electric Vehicle model

Transmission Data	Motor Data	Battery Data
Single speed transmission	Permanent Magnet Synchronous Motor (PMSM)	$LiCoNiAlO_2$ cell chemistry
Fixed gear reduction ratio of 4:1		21700, cylindrical cell packaging
Transmission efficiency of 90 %		Nominal voltage: 3.6 V Nominal capacity: 4500 mAh @ 1C discharge rate Max discharge rate: 3C Weight per cell: 70 g

Transmission subsystem

Transmission subsystem has been modeled based on the data provided in Table 2. The gear reduction ratio has been selected based on the speed rating of the motor. The transmission subsystem is shown in Figure 5. The torque and speed of the motor is obtained by dividing and multiplying the torque and speed received from the Glider model respectively. It is to be noted that this, being a backward facing model, is the reason for the reversed logic being true in this case.

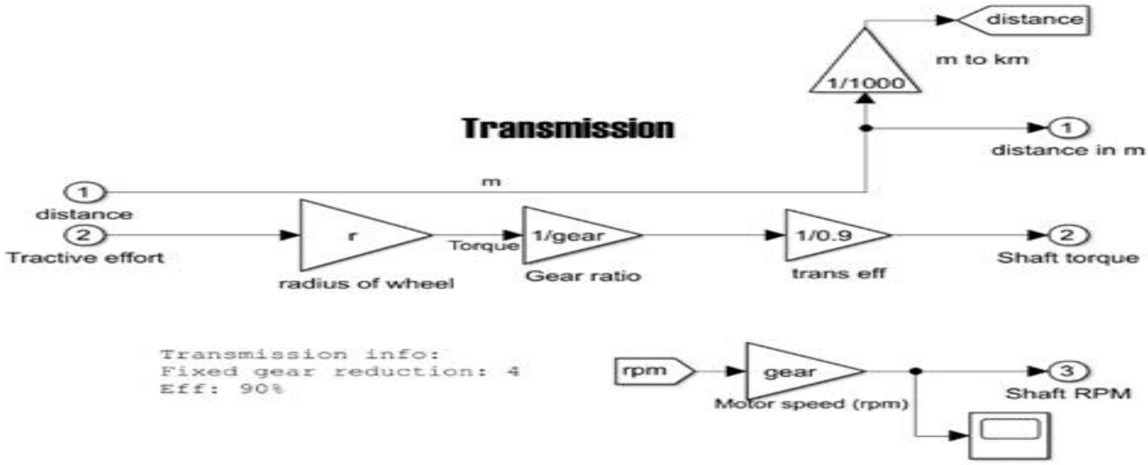


Figure 5 Transmission subsystem for Electric Vehicle Model

Motor subsystem

The PMSM (Permanent Magnet Synchronous Motor) is modeled as shown in Figure 6 using a 2-D lookup table which represents a trend of efficiency vs speed and torque of the motor (Saiful A. Zulkifli, 2013). Motor torque output is limited based on the maximum permissible torque output which is dependent on the power output of the motor.

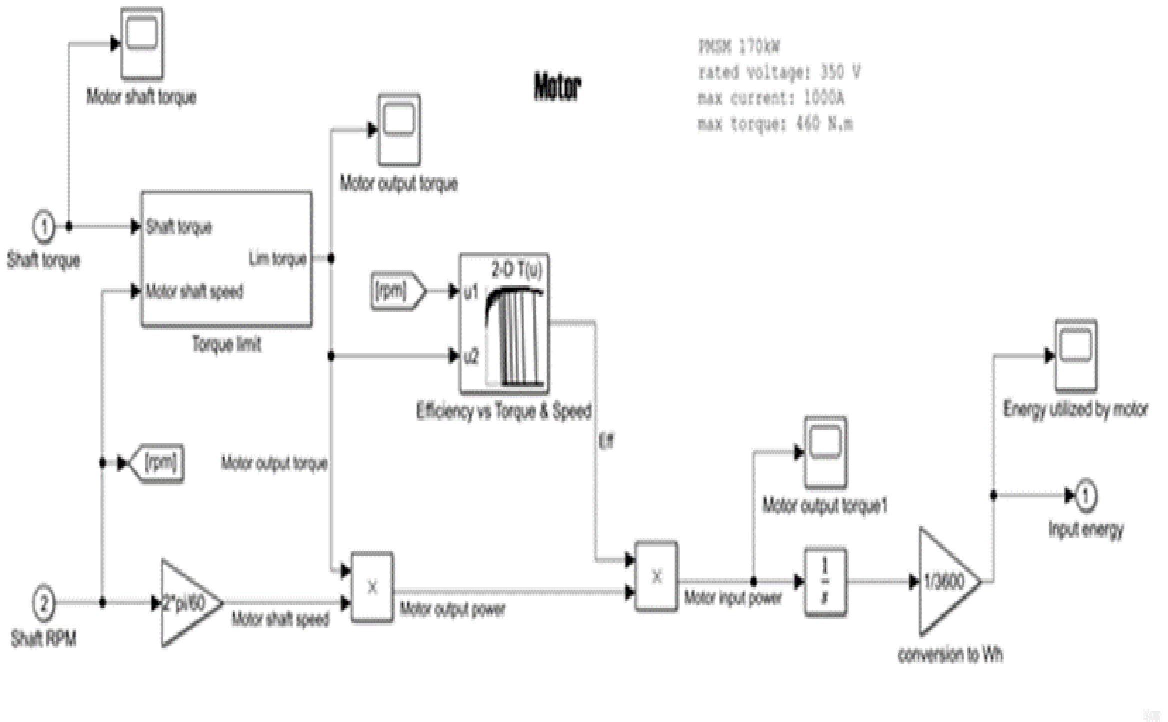


Figure 6 PMSM Motor Subsystem

Battery subsystem

The battery subsystem consists of two parts, one to determine the sizing of the battery pack, which is calculated using the estimated range of the vehicle, and second is the introduction of data related to the cell chemistry, which can then be used to calculate the cell configuration and the estimated weight of the overall battery pack. The subsystems used to achieve these are shown in Figure 7 and 8.

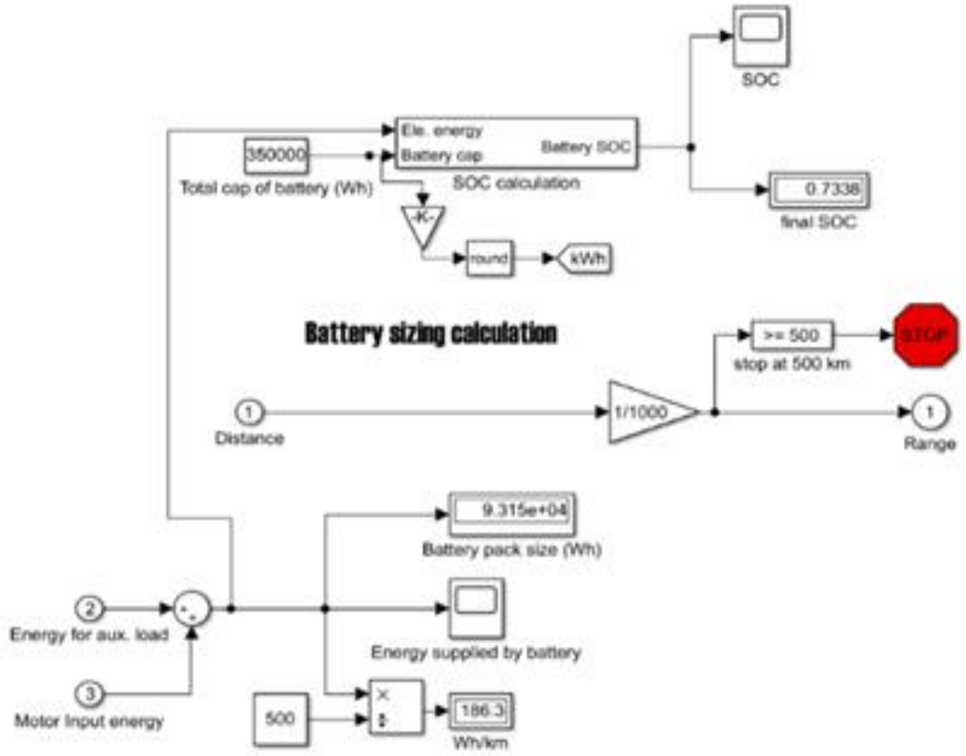


Figure 7 Subsystem for determination of battery size for a specified range

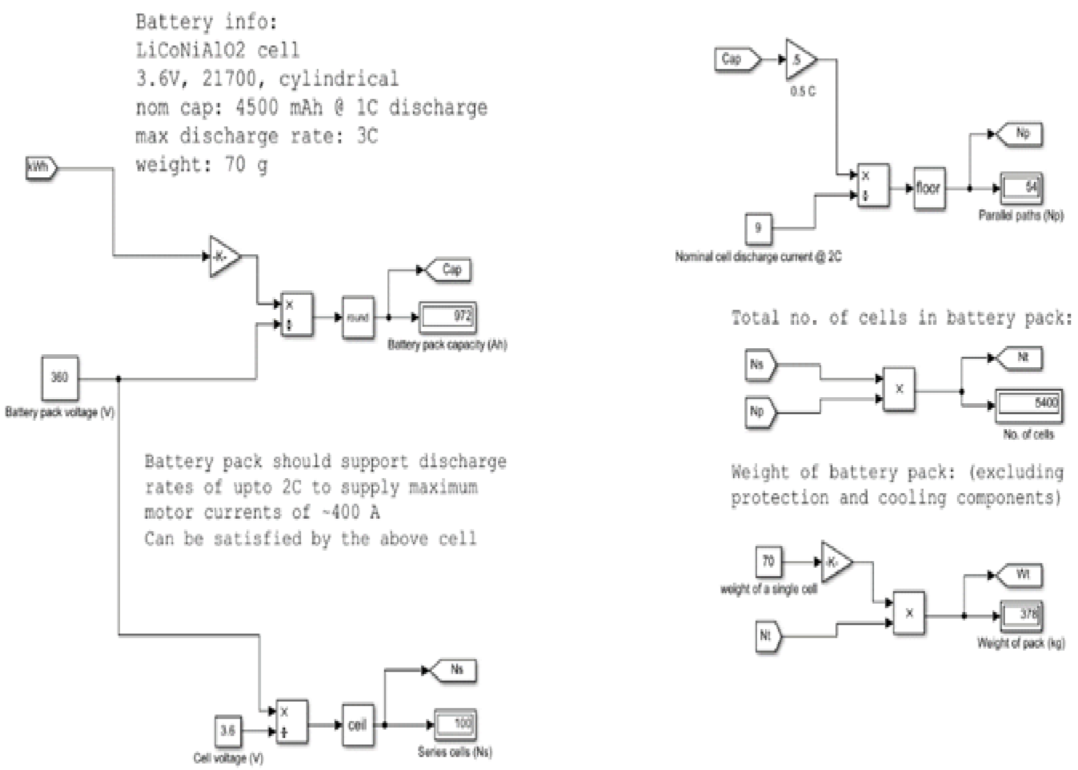


Figure 8 Subsystem for calculating the battery pack parameters

The battery pack parameters can be determined using the following expressions:

Based on the Energy rating of the battery in kWh which has been determined in the battery sizing subsystem as shown in Figure 7 and considering a predetermined battery pack voltage (which is considered as 360 V in this paper), it is possible to calculate the battery pack capacity in Ah, using the expression (6) (Tom Denton, 2004).

$$\boldsymbol{Battery\ pack\ capacity\ (Ah)} = \frac{\boldsymbol{Battery\ Energy\ Rating\ (Wh)}}{\boldsymbol{Battery\ voltage\ (V)}} \qquad (6)$$

Given the Battery voltage and the individual cell voltage, the minimum no. of cells in the battery pack required in series configuration can be determined as in the equation 7.[7]

$$\boldsymbol{No.of\ cells\ in\ series\ (N_S)} = \frac{\boldsymbol{Battery\ pack\ voltage\ (V)}}{\boldsymbol{Cell\ terminal\ voltage\ (V)}} \qquad (7)$$

From the battery pack capacity calculated previously, for a given battery discharge rate (which has to be kept under the max. cell discharge rate), the no. of parallel paths required in the battery pack can be calculated using the equation 8 (Tom Denton, 2004).

$$\boldsymbol{No.of\ parallel\ paths\ (N_P)} = \frac{\boldsymbol{Battery\ pack\ capacity\ (Ah)} \times \boldsymbol{Battery\ pack\ discharge\ rate}}{\boldsymbol{Battery\ voltage\ (V)} \times \boldsymbol{Cell\ discharge\ rate}} \qquad (8)$$

Total number of cells in the battery pack can be calculated as given in the equation

$$\boldsymbol{Total\ no.of\ cells\ in\ battery\ pack\ (N)} = (\boldsymbol{N_S}) \times (\boldsymbol{N_P}) \qquad (9)$$

Finally, the estimated battery pack weight can be determined using the equation. It is to be noted that this weight is devoid of the additional weight of other components such as the battery cooling requirements, the enclosure, etc, but can give a close estimate of the weight.

$$\boldsymbol{Estimated\ weight\ of\ the\ entire\ battery\ pack} = \boldsymbol{N} \times \boldsymbol{wt.of\ cell} \qquad (10)$$

Overall Electric Vehicle Model

Combining the individual subsystems discussed in the previous subsections, leads to the completed Electric Vehicle Model as shown in Figure 9. The additional component here is the auxiliary power which represents the additional power drawn from the battery to run auxiliary component such as HVAC (Heating, Ventilation, Air conditioning), lighting, etc. This power has been assumed to be 500 W. The drive cycle is initialized as Northern European Driving Cycle (NEDC) (Shingeru Onoda, 2004).

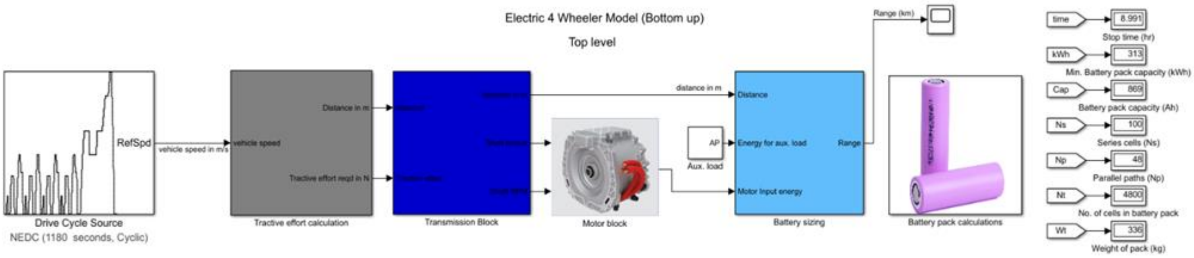


Figure 9 Electric Vehicle Top Level Subsystem

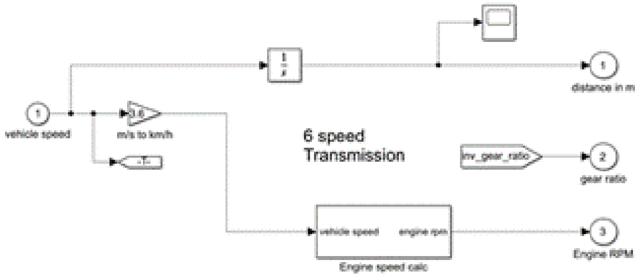
HYBRID ELECTRIC VEHICLE MODEL

In similar methodology, the simulation model of Hybrid Electric Vehicle is also developed to emulate the hybridization concept considering different hybridization ratios such as 20%, 40%, 60%, 80% and 100%. The motor power can be limited to different levels to achieve a certain hybridization ratio (Harun Turker, 2015; Courtney Holder et al., 2016). A 6-speed automatic transmission model is used based on data of vehicle as summarized in Table 3.

Table 3 Data used for Hybrid Electric Vehicle model

Transmission Data	Engine Data	Motor Data	Battery Data
Six speed automatic transmission	SI Engine	Permanent Magnet Synchronous Motor (PMSM)	$LiCoNiAlO_2$ cell chemistry
	Engine Output Power: 120 kW, 90 kW, 60 kW, 30 kW		21700, cylindrical cell packaging
	Maximum Engine Torque: 220 N.m (torque limited based on max. permissible power)		Nominal voltage: 3.6 V Nominal capacity: 4500 mAh @ 1C discharge rate Max discharge rate: 3C Weight per cell: 70 g

Engine and Transmission subsystem



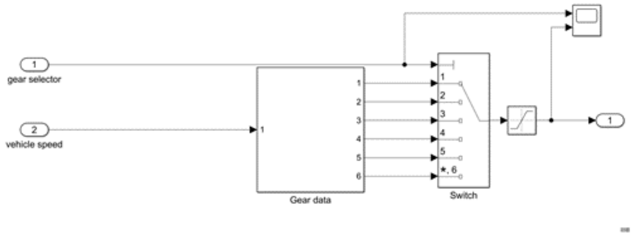


Figure 10 Transmission Subsystem **Figure 11** Gear Shift Subsystem

The Transmission Subsystem has been modeled as shown in Figure 10. A gear shift logic is developed in MATLAB to switch between the gears based on the vehicle speed and the individual gear ratios to determine the engine speed. Engine subsystem is created using a reference BSFC (Brake specific fuel consumption plot) as shown in Figure 12, which can be used to calculate the fuel consumed per unit km (U.S EPA, 2018). This plot also shows the maximum power line locus which is then used to create individual models for the engines with different maximum power outputs. The Neural network model is used to determine the BSFC value for a given Speed and Torque input as shown in Figure 13 and 14.

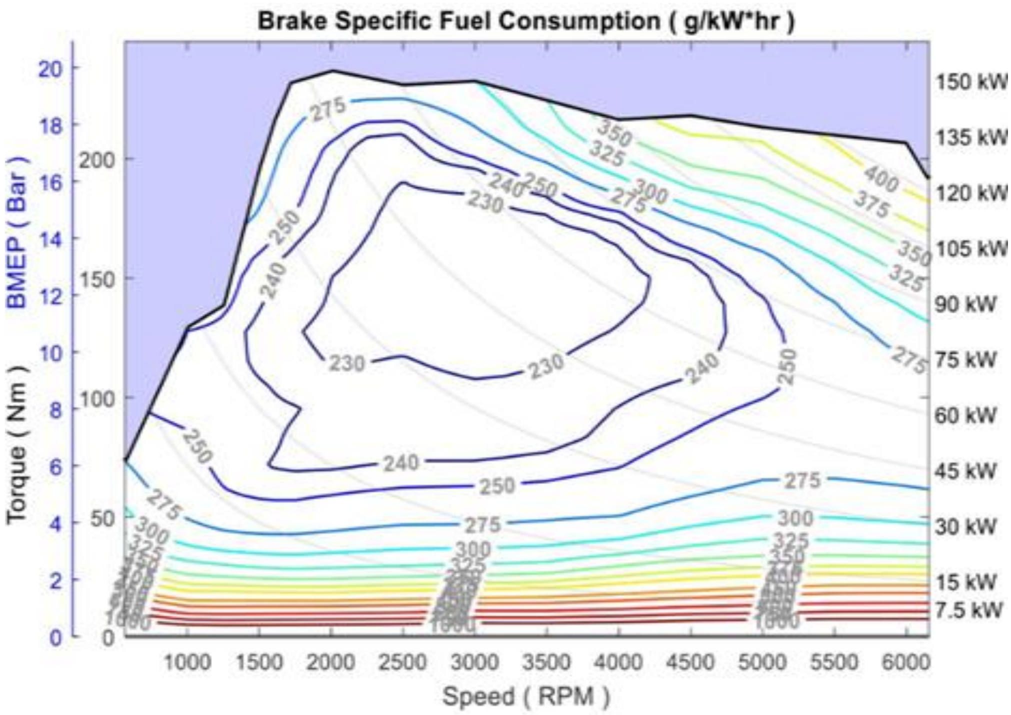


Figure 12 Brake Specific Fuel Consumption vs. Engine Speed and Engine Torque [11]

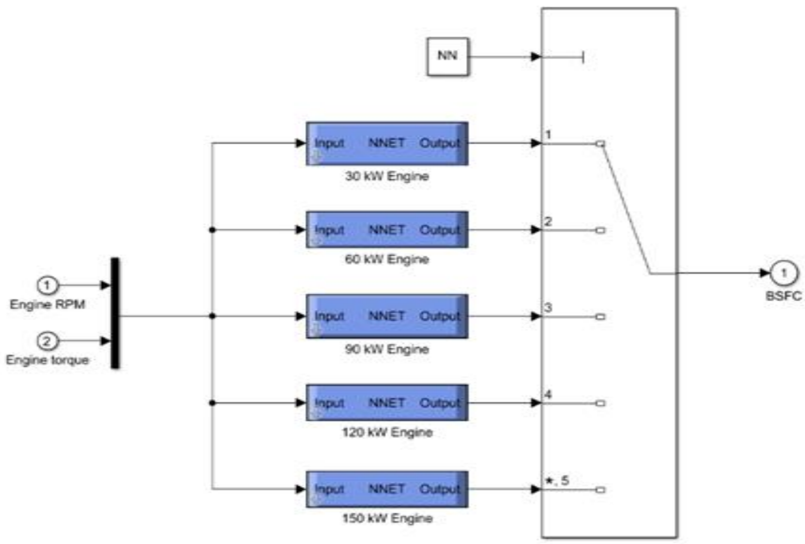


Figure 13 Neural network used to determine BSFC

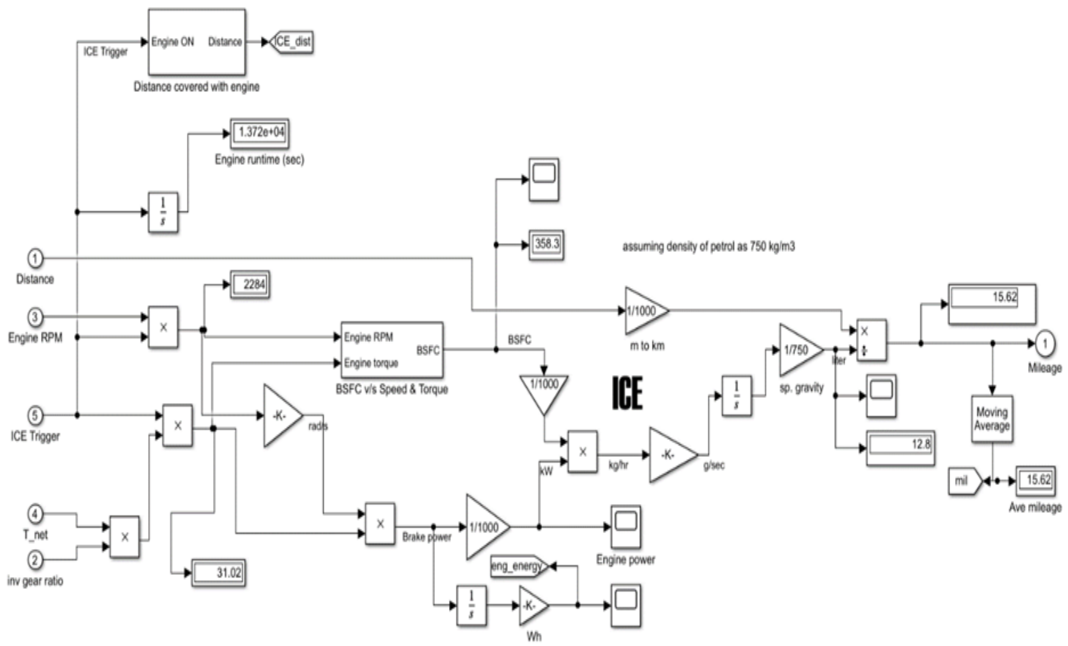


Figure 14 Engine Subsystem Top Level

Overall Hybrid Electric Vehicle Model

Combining the subsystems discussed above along with the subsystems used for the Electric Vehicle Model in Section II, gives the overall Hybrid Electric Vehicle Model. The resulting top-level model is shown in Figure 15.

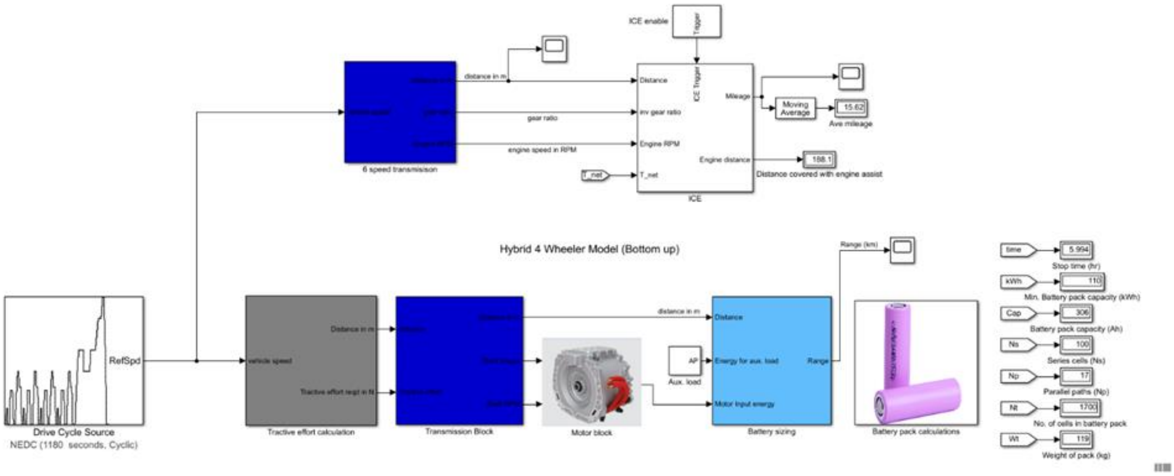


Figure 15 Hybrid Electric Vehicle Top Level

It is to be noted that in this model, the configuration developed is for the 'Parallel' HEV model. Based on the torque requirement of the vehicle, the engine acts in a 'engine assist' mode where the engine satisfies the additional torque requirement of the vehicle, if the torque requirement exceeds the permissible torque of the motor.

RESULTS

The results obtained from the models used above can be summarized as shown in Table 4.

Table 4 Summary of results obtained from the SIMULINK model

Hybridization percentage	20 %	40 %	60 %	80 %	100 %
Battery rating	110 kWh	200 kWh	250 kWh	275 kWh	280 kWh
Battery capacity	306 Ah	556 Ah	694 Ah	764 Ah	778 Ah
Ns	100	100	100	100	100
Np	34	61	77	84	86

Total no. of cells	3400	6100	7700	8400	8600
Weight of battery pack	238 kg	427 kg	539 kg	588 kg	602 kg
Total range using battery power	200 km	200 km	200 km	200 km	200 km
Range covered in engine assist mode	188.1 km	120.1 km	80.57 km	44.85 km	-

From the results in Table 4, a clear trend is observed which shows the increase in the battery capacity required as the hybridization percentage increases given that the range has to be maintained constant. It's also seen that as the hybridization percentage increases, it shows only diminished increase in the battery parameters. This is because, as the motor rating increases, the utilization of the motor is essentially decreasing after a certain point which in this model is seen beyond 80 % hybridization. This utilization is based on the drive cycle requirements, as for NEDC cycle, the maximum speed is restricted to 120 km/h.

CONCLUSION

This paper proposes a vehicle architecture in which the vehicle body is kept the same, but with different drivetrains, differentiated based on the percentage of hybridization used and it can be inferred from this model, how the change in this value causes a respective change in the engine as well as the battery performance parameters. Based on the results obtained in the previous section, it is seen that for the given vehicle parameters, the suitable value for hybridization would like between 40 and 60 %. This is because based on the given motor and engine ratings, the gains observed in the fuel economy with respect to the range and the utilization of the engine and motor proves to be a good balance between each other. This value will of course depend on the type of vehicle and also the configuration opted for, as in this paper the engine is assumed to be in an engine- assisted configuration of parallel hybrid.

Further, for improving modularity of the hybrid model, it would be better to implement other hybrid configurations such as series, and power- split hybrids which can aid the designer in an even better way with how the selection of one configuration over another would impact the results.

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