Design and performance evaluation of series hybrid electric vehicle using backward model

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Abstract: Hybrid electric vehicles (HEVs) are becoming a more promising means of transportation mainly because of environmental issues and depletion of fossil fuel resources. This study deals with the basic theoretical knowledge for describing their behaviour in acceleration, cruising, deceleration and control strategies. Preliminary design calculations for a series HEV bus are carried out in MATLAB environment using a backward model. In addition to this, the rule-based algorithm is implemented to compare fuel consumption, battery's state of charge (SOC) and energy-saving possibilities. The model is firstly tested for highway and city drive cycles for SOC limits of 0.6 and 0.7. Further, prolonged simulations are conducted for both the highway and city drive cycles for four different SOC limits and three parameters of the hybrid vehicle (SOC of battery, fuel power and average charging power) are observed and compared with each other. The performance indexes of both drive cycles are estimated and it is found that higher performance indexes are obtained using power-split mode and greater SOC lower limit as internal combustion engine is more efficient when operated in this mode.

1 Introduction

The widely used fossil fuel-based vehicles are one of the major causes of accelerated extraction of fossil fuel resources in an unsustainable way [1, 2]. With the overall trend of the automotive industry moving towards a more efficient and electric system of the motor drive for vehicles, there is a growing demand for an electric vehicle that is capable of running in a real-world scenario. A sudden and majority share of the transport market opting to directly switch from petroleum-based vehicles to electricity-based vehicles will overwhelm the total electricity distribution network. This paper will look at the possibility of an alternative, i.e. hybrid electric vehicles (HEVs). During regeneration, the energy storage facility is utilised to minimise fuel consumption when high torque is in demand. The internal combustion engine (ICE)-based vehicles or classic vehicles have a maximum efficiency of around 40% for pre-specified operating conditions, but in reality, the vehicle requires a wide range of torque and speed [3–5]. In addition to this, the output power of drive will vary with time and state of operation of the vehicle and will only be maximum for a short period which leads to the requirement of engine oversizing [6]. Besides this, emission of greenhouse gases, significant loss of energy during braking, depletion of natural resources of fossil fuel and unexpected rise in the price of fossil fuel have led to electric vehicle (EV)/HEV becoming more promising means of public transportation [7, 8]. Thiel et al. [9] and Bishop et al. [10] studied the cost effectiveness of avoiding the carbon dioxide (CO2) emissions and concluded that advanced internal combustion technologies and hybridisation with parallel topology reduce fossil fuel consumption and CO2 emissions. EV has higher efficiency because of the negligible converter and machine losses. With the help of a converter, its operating region can be tailored [11, 12]. Environment-friendly EV has the advantage of regeneration, which can recover around 20% of energy spent [13]. However, there are some challenges in HEV and EV like long duration of battery charging time and small mileage compared to fossil fuel-based vehicles [3–5].

Currently, the power-split configuration is dominating the electric vehicle market as this configuration enables the vehicle to drive in series as well as in parallel configuration. Various recent researches [14, 15] followed the powertrain system of Toyota Prius 2010 as the reference model for verifying the model in different drive cycles and the planetary gear with two degrees of freedom has been used for splitting the engine power to operate in different modes [16, 17]. The fuel economy has been increased in HEVs by the addition of clutches and transmission system which eases the operation of a vehicle in different operating modes [18, 19]. Integrated state of charge (SOC) planning and vehicle velocity prediction to control the power split and velocity of HEV, fuel consumption and driving safety should be balanced [20].

In this study, different topologies of HEV and basic theories describing their behaviour in acceleration, cruising, deceleration and control strategies are discussed. A rule-based algorithm is implemented, a model is developed in the MATLAB environment for series HEV and it is analysed using backwards facing and quasi-state modelling. This research is focused on analysing the characteristics and flexible structure of series HEV in different operation modes with energy management strategy and simulation results are obtained and verified for both highway and city drive cycle for optimum energy use. This study begins with the introduction of the background of the study. In Section 2, mathematical calculations for preliminary design and assumptions made are presented. Section 3 elaborates on the applied algorithm. Section 4 presents the component modelling in MATLAB environment while Section 5 presents the analysis, their outcomes and discussions. Finally, in Section 6, the conclusion is made and presented based on the results and discussions. Although it is described in more detail in the further sections, the novelty and the major contributions of this paper are related to:

(a) detailed comparison of the performance of the HEV between a highway drive cycle and city drive cycle;
(b) a detailed study of the battery performance in both drive cycles in various settings of SOC limits.

J. Eng., 2020, Vol. 2020 Iss. 11, pp. 1095-1102
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Vehicles are classified into different categories based on power sources such as thermal, electric, hybrid etc. Among them, HEV is the one in which propulsion energy is available from two or more kinds of energy stores, sources or converters with at least one of them delivering electrical energy. Hybrid-type vehicles further divided into several categories such as series, parallel and mixed. Among these configurations, series drivetrains are considered to be the simplest and highly adopted one [12]. The power train of series hybridisation is shown in Fig. 1 with the following possible operating states [21]:

- **Pure electric mode**: Engine is turned off and the vehicle is propelled only by batteries. This mode will start the vehicle since the efficiency of the diesel system at low speed is poor.
- **Pure engine mode**: The vehicle traction power is derived from the engine-generator only, while the batteries neither supply nor draw any power from the drive train.
- **Power-split mode**: Traction power is drawn from both engine-generator and the batteries.
- **Battery charging mode**: Engine generator supplies power to charge the batteries and to propel the vehicle.
- **Regenerative braking mode**: The engine generator is turned off and the traction motor is operated as a generator. The power generated will charge the batteries.

### 2.1 Cruising power

Cruising power is the maximum power required to drive the vehicle in a flat zone during maximum speed and it is given by [3]

\[
P_{\text{cruising}} = \frac{V_m}{1000} \times \eta (M \cdot g f_1 + \frac{1}{2} \rho C_D A_V V_m^2 (1 \pm C_w))
\]  

(1)

### 2.2 Accelerating power

Acceleration of the vehicle is one of the important components in vehicle drive. It is important to evaluate \( P_{\text{drive}} \) in such a manner that the vehicle can accelerate from initial to final velocity in a specified period of time on normal road conditions [22]. From a typical drive cycle (i.e. city or highway), data of maximum acceleration can be obtained.

### 2.3 Grade-ability power

Power required to overcome the slope with speed is grade-ability power and it is given by [3]

\[
P_{\text{grade}} = \frac{1}{1000} \times \eta (M \cdot g \sin \alpha V_m)
\]

For the constant speed, the power generated (kW) from the engine can be determined by using the following equation [3]:

\[
P_{\text{engine}} = \frac{V_m}{1000} \times \eta \left( \frac{1}{3} M_\text{g} g f_1 (\cos \alpha + \sin \alpha) + \frac{1}{2} \rho C_D A_V V_m^2 \right)
\]

### 2.4 Differential ratio

The differential ratio (\( \xi_{\text{diff}} \)) is computed by assuming the maximum cruising speed of the vehicle that must correspond to the maximum speed of the motor as shown in the given equation [3]:

\[
\eta_1 \cdot \frac{V_m}{1000} \times \left( \frac{1}{3} M_\text{g} g f_1 (\cos \alpha + \sin \alpha) + \frac{1}{2} \rho C_D A_V V_m^2 \right)
\]  

where \( V_m \) is the base speed of the vehicle; therefore, for a series drive, the battery size in kW is preliminary based on the difference between drive power evaluated from (6) and engine's size from (4). Besides this, the required energy supply by the battery depends on the total distance of the trip and the SOC limit. Hence, the sizing of the component is extremely dependent on the maximum velocity, driving cycle, maximum acceleration, driving cycle pattern, landscape and a total distance of the trip. Initial battery energy required is computed based on energy extracted from the battery and replenished to the battery during the trip considering the SOC limit of the battery [3, 4, 23]. The system parameters of HEV assumed for simulations of standard driving cycles are given in Table 1.

| Table 1 Vehicle parameters |
|-----------------------------|
| Parameters and coefficient  | Symbol | Value   |
| drag coefficient            | \( C_d \) | 0.55    |
| wind speed coefficient      | \( C_w \) | 0       |
| rolling resistance coefficient | \( f_1 \) | 0.01   |
| frontal area (m\(^2\))      | \( A_f \) | 5      |
| total weight (kg)           | \( M_\text{g} \) | 12,500 |
| air density                 | \( \rho \) | 1.2    |
| max velocity (km/h)         | \( V_m \) | 50     |
| transmission efficiency     | \( \eta_1 \) | 0.85   |
| motor efficiency            | \( \eta_2 \) | 0.9    |
| wheel radius (m)            | \( r_w \) | 0.5    |
| acceleration due to gravity (m/s\(^2\)) | \( g \) | 9.8    |

However, when the vehicle stops and follows the urban area's pattern, generated power by the engine should be equal to or slightly greater than the average load power to maintain the peak power system balance. Average load power can be calculated using the following equation [3]:

\[
P_{\text{engine}} = \frac{1}{T \int_0^T} \left( \frac{M \cdot g f_1 + \frac{1}{2} \rho C_D A_V V_m^2}{1 \pm C_w} V_m \, dt \right)
\]

Before the motor's determination, the maximum driveline speed ratio is designed to ensure that the vehicle can climb a maximum slope with reduced speed when it is driven by anyone of either source or both, which is given by [3]

\[
i_\text{b} = \frac{\frac{M_\text{g} g (f_1 \cos \alpha + \sin \alpha) \cdot r}{T_{\text{max}} \cdot \eta_{\text{diff}}}} \text{ where } T_{\text{max}} \text{ is the maximum transmission torque, which in the case of series-type vehicle represents the maximum motor torque. According to the highest gear ratio, the maximum slope that the vehicle can climb with reduced speed is calculated from (5). The power rating of an electric motor (kW) used in the series HEV must be able to drive the vehicle. Hence, the power rating must be greater or equal to the maximum accelerating power. The resistive power for the flat road is computed from (4) |
When the highway drive cycle is considered, vehicle movements consist of constant speed for a long time with few starts and stops. Such a cycle can be used for highway driving between cities. However when the city drive cycle is considered, vehicle movements consist of frequent starts and stops. Such a cycle can be used for driving within a city. The system can be modelled in ADVISOR (Advanced Vehicle Simulator) MATLAB Environment, which comprises backwards facing, forward facing, and both modellings approach. Here, Standard Highway (US06) and City (Manhattan) drive cycles with a data sampling period of 1 s are taken for simulation of the drive cycles.

2.5 Transmission

The maximum drive speed ratio is selected to ensure that the vehicle can climb slopes obtained from (5). It can be computed considering engine only, motor only, and both engine and motor. The gearbox used for the modelling is from Toyota Prius 2010. The Prius uses an electronic continuously variable transmission unit which uses planetary differential gear sets. This combines the power from two electric motors and a gasoline engine [24]. Further, the planetary gears are used for speed reduction and power split to control the two motors MG1 and MG2 of the Prius 2010. MG1 controls the rotor with MG2 controls the sun gear [25].

2.6 Drive cycle

When the highway drive cycle is considered, vehicle movements consist of constant speed for a long time with few starts and stops. Such a cycle can be used for highway driving between cities. However when the city drive cycle is considered, vehicle movements consist of frequent starts and stops. Such a cycle can be used for driving within a city. The system can be modelled in ADVISOR (Advanced Vehicle Simulator) MATLAB Environment, which comprises backwards facing, forward facing, and both modellings approach. Here, Standard Highway (US06) and City (Manhattan) drive cycles with a data sampling period of 1 s are taken for simulation of the drive cycles.

2.7 Backward-facing model

In the backward-facing model, the driver model is not required but the force is required to accelerate the vehicle through time step which can be calculated directly from the required speed trace (drive cycles). The required power is then translated into torque and speed that goes upstream to find the power required from the power source, an ICE and/or battery for instance. The power flow is calculated from backward, i.e. wheel to sources considering losses at various stages. In the end, fuel usage and/or electric energy consumption is computed for the driven cycle. The main advantage of the backward-facing model is the fast execution of the simulation. However, the limitation of the backward-facing model is that it does not deal in quantities measurable in a vehicle. For example, control signals like throttle and brake position are absent from the model, further hindering dynamic system simulation and control system development [26–28] (Fig. 2).

3 Energy management algorithms

The energy management and supervisory control is a slow subsystem which generates control signals as per the input provided by the driver. The objective is to ensure the best energy distribution as a function of global demand or to determine how power should be routed through available power consumers and producers to achieve a stated goal or set of goals. However, in the quasi-state model, the components like generator, engine, motor, battery and other mechanical systems like transmission and differential are replaced by state model mainly because of slow dynamics on sampling period and some of the above components that utilise their mapping table. This leads to the removal of the inner subsystem controls [29, 30].

Different power management algorithms are available to manage the energy of a hybrid power train. Salmasi [31] proposed different methods for energy management, mainly either rule based or optimisation based. The energy management strategy will only use current and past vehicle states and driver commands to calculate a proper control signal. The driver gets all the inputs from the vehicle and road conditions, which makes decisions about braking, gearing and accelerating, and executes the commands. The design process starts by interpreting the driver pedal’s position, and signal as the power request. Based on such a power request, the energy management controller determines power flow in a hybrid drive train [32] (Table 2).

In many of the existing HEV, the power management algorithm is rule based because of ease in handling and controlling the operation modes. Lin et al. [33] implied the rule-based algorithm for parallel hybrid trucks, in which they concluded that the operating power can be divided into different control modes such as braking control, power split control, and recharging control based on power request. If a power request is negative, braking control will be applied to decelerate the vehicle. Similarly, if a power request is positive, either power-split control or recharging control will be applied according to the charge-sustaining policy. Whenever SOC drops below the lower limit, the controller will switch to recharge the system until the SOC reaches the upper limit then power splinted. The logic of the rule-based algorithm for a parallel hybrid vehicle is summarised as follows [33–40].

4 Component modelling

4.1 Engine model

For the simulation, the engine from Toyota Prius 2010 has been used. This model of Prius is equipped with a 1.8L 16-valve engine and electric motor [25]. This ICE engine is represented by its quasi-state model. Focusing on the characteristics of speed, torque output and efficiency, the ICE model developed is as shown in Fig. 3. The efficiency map table and fuel consumption map table are utilised to estimate the fuel consumption and efficiency of the

\[ \xi_{diff} = \frac{\Omega_{max\_em}(rpm)}{30(\pi V_{\text{max}})} \]

Here \( V_{\text{max}} = 80 \text{ km/h}, r_{w} = 0.5 \text{ m} \) and \( \Omega_{max} = 3000 \text{ rpm} \).

![Image](http://creativecommons.org/licenses/by/3.0/)

Table 2 Logic of the rule-based algorithm

| Mode | P_{req} | P_{e} | P_{bat} | P_{ch} |
|------|---------|-------|---------|--------|
| normal mode, \( P_{req} > 0 \) | \( P_{req} \leq P_{min} \text{max} \) | \( P_{e} = 0 \) | \( P_{bat} = P_{req} \) | \( P_{ch} = P_{min} \text{max} \) |
| normal mode, \( P_{req} \leq 0 \) | \( P_{eve} \leq P_{req} \leq P_{min} \text{max} \) | \( P_{e} = P_{req} \) | \( P_{bat} = 0 \) | \( P_{ch} = 0 \) |
| charging mode, \( P_{req} < P_{min} \text{max} \) | \( P_{eve} \leq P_{req} \leq P_{min} \text{max} \) | \( P_{e} = P_{req} \) | \( P_{bat} = P_{req} - P_{min} \text{max} \) | \( P_{ch} = P_{min} \text{max} - P_{req} \) |
| braking mode, \( P_{req} < 0 \) | \( P_{eve} \geq P_{min} \text{max} \) | \( P_{e} = 0 \) | \( P_{bat} = 0 \) | \( P_{ch} = P_{min} \text{max} \) | \( P_{ch} = P_{req} - P_{min} \text{max} \) |
vehicle. The efficiency map and fuel consumption map are developed in MATLAB environment and shown in Figs. 4a and b. The estimation of fuel consumption of the engine is carried out by using the fuel consumption map for which torque and speed are extracted from an efficiency map for the given engine efficiency from Fig. 4a.

4.2 Motor model

The electrical machine is also represented from its quasi-state model as shown in Fig. 5. The efficiency map table developed from laboratory tests is generally utilised to estimate efficiency and energy loss in the motor. A 65 kW generator and 110 kW rated 3000 rpm motor with an efficiency map are utilised to develop the model in MATLAB.

5 Result and discussion

After the complete modelling of HEV in MATLAB using backwards modelling, the driving simulation of the HEV is conducted for highway and city drive cycles with the use of a power management algorithm and rule-based algorithm. The relevant vehicle parameters like power, torque, velocity, acceleration and other relevant parameters of the vehicle at different stages of the simulation for highway and city drive cycles are shown in Figs. 6 and 7, respectively. The positive portion of the power graph represents power supplied by HEV and the negative portion represents the power regenerated from wheel to the engine while the acceleration graph shows acceleration and deceleration of the HEV during the drive cycles. With the higher gear ratio (for velocity ≥17.6 m/s) to lower ratio (for velocity ≤4.4 m/s), a variation of the continuously variable transmission (CVT) during the highway and city drive cycles.

In the simulation for the highway condition drive cycle, the vehicle maintains a speed of 50 km/h or higher for a prolonged duration (cruising) with fewer stops, with the majority of the time spent by the vehicle in the higher ratio of the CVT (higher speed and low torque). Results of the highway drive cycle simulation of the HEV indicated less variation in CVT (interpreted from gear ratio versus time graph) implying fewer and slower accelerations and decelerations. The slower and infrequent accelerations indicate that less energy was pumped back into the battery as a result of fewer cases of regenerative braking. The simulation also shows less variation in the torque experienced by the vehicle during...
different stages of the drive train requiring less amount of acceleration power (evident from acceleration power versus time graph). The slow and steady accelerations and decelerations resulted in steady discharging and effective charging of the battery.

The lower number of starts and stops of the vehicle also results in less radical changes in wheel, transmission and differential torques. While on the other hand, the constant starting and stopping of the vehicle in city drive require the vehicle to move in slow speed and high torque for frequent accelerations. This consequently results in the high rate of changes of differential torque.

While on the other hand, in the simulation for the city drive cycle, the repeated starts and stops of the vehicle in city drive require the vehicle to move in slower and varying speeds. A higher number of stops resulted in the production of high regenerative power that can be transferred to the battery. The frequent accelerations after each stoppage showed a frequent change in the torque experienced by the vehicle during the drive train. A higher acceleration power requirement negated the regenerative braking power to charge the battery.

For the performance analysis of the battery system installed in the HEV, different battery parameters were observed for both highway cycle and city drive cycle which can be seen in Figs. 8 and 9, respectively. These parameters are taken as indicators to compare the performance of the designed HEV at various operating conditions. The SOC for drive cycle, charging power and braking power for different SOC lower limits are thus observed. The simulation results of the highway driving cycle for the SOC lower limit of 0.7 and 0.6 are shown in Figs. 8a and 8b, whereas the same for the city driving cycle are shown in Figs. 9a and 9b. Owing to the initial SOC of the battery being 0.7 and SOC lower limit of 0.7 in Fig. 8a, the vehicle's SOC frequently drops below the lower SOC limit prompting the battery charging to initiate and the prolonged duration of a relatively constant velocity of the vehicle effectively charges the battery.

The SOC lower limit of 0.6 in Fig. 8b results in the SOC of the battery never dropping below 0.6 limits the whole duration of the simulation (nearly equal to 1200 s or 20 min) for the highway drive cycle, the lowest SOC of battery dropping to around 0.65. Here, for the total duration of the simulation, no battery charging takes place from regeneration. However, on a longer duration drive cycle the HEV may require to switch to ICE as the SOC value drops. On account of fewer starts and stops of the vehicle, there is less amount of braking required and consequently, the battery's charge is not consumed for the stoppage of the vehicle.

However, the city drive cycle yields different results. In Fig. 9a, which showcases SOC of battery, charging power and the brake power, SOC of the battery falls below the SOC lower limit from the get-go. Consequently, this initiates the charging of batteries but is limited by the frequent state changes of the vehicle. Further, due to the frequent starts and stops of the vehicle, the battery is frequently switched between charging and discharging states on account of regenerative braking and higher acceleration power requirement. The same is for the case of brake power for the city drive with a lower level of SOC, i.e. 0.6 in Fig. 9b. However, in the city drive cycle case, as the SOC of the battery falls below 0.6
The consumed energy to be −1.5 kWh is; consequently, charging the battery, enhances when the lower limit of SOC is higher. Comparing the final SOC is better with a higher value of the lower limit of SOC the battery initiates.

If the lower limit of SOC is set to be 0.6 in Fig. 11, the simulation is more charging and discharging of the battery occurs. Further, more SOC lower limits are shown in the form of a bar graph in Fig. 10. It is observed that the final SOC is better with a higher value of the lower limit of SOC with fewer expenses on fuel energy as the efficiency of the ICE enhances when the lower limit of SOC is higher. Comparing the two outputs of the city drives, the final SOCs of the battery are close to one another. With the higher number of starts and stops, more charging and discharging of the battery occurs. Further, more fuel is consumed by the ICE to produce the required torque and acceleration. This results in greater average energy consumed in contrast to the high way drive cycle. On the other hand, the sporadic vehicle stops in the highway drive cycle have resulted in lower fuel and battery charge consumptions. The setting of SOC lower limit to be 0.7, resulted in average battery energy consumption to be −1.5 kWh; consequently, charging the battery, resulting in the final SOC of the battery (0.71) being greater than the initial value of 0.7.

The prolonged stimulation of the highway drive cycle is shown in Fig. 11. Here, the charging power is found to be zero for a highway drive cycle, but the results will only be valid for a similar size of battery used. Here, when 10.9 kWh battery is used and SOC lower limit is set to 0.6, battery charging starts after the first drive cycle as shown in Fig. 11. This can be interpreted as, lower the value of SOC lower limit, greater the time until that lower limit is crossed and longer the time for charging of the battery to be initiated. The charging occurs only after the around 1300 s. Setting the value of the lower limit of SOC as too low may result in an insufficient cushion for the battery charge which may result in discharging the battery to a dangerously low level during the drive. As no battery charging occurred for the highway drive cycle when the lower limit of SOC is set to be 0.6 in Fig. 11, the simulation is run for a longer period to see the HEV's SOC of the battery and its charging characteristics.

![Fig. 9 SOC charging power and braking power for city drive cycle when SOC lower limits are](http://creativecommons.org/licenses/by/3.0/)

(a) 0.7, (b) 0.6

(after around 1200 s), the HEV switches to ICE and the charging of the battery initiates.

Compiling the results from both Figs. 8 and 9 and measuring the consumed fuel energy during both drive cycles, the results are shown in the form of a bar graph in Fig. 10. It is observed that the final SOC is better with a higher value of the lower limit of SOC with fewer expenses on fuel energy as the efficiency of the ICE enhances when the lower limit of SOC is higher. Comparing the two outputs of the city drives, the final SOCs of the battery are close to one another. With the higher number of starts and stops, more charging and discharging of the battery occurs. Further, more fuel is consumed by the ICE to produce the required torque and acceleration. This results in greater average energy consumed in contrast to the high way drive cycle.

Further, it is also observed that the SOC of the battery in the highway drive cycle oscillated mostly around the lower limit of SOC due to fewer starts and stops and the ICE taking over after a certain speed.

To understand the working of the HEV even more, further simulations are then conducted at even more operating conditions. Simulation results for series highway and city drive cycles with different characteristics are illustrated in Figs. 12a and b (when SOC_Low = 0.55, 0.6, 0.65, 0.7), SOC_initial = 0.7, battery capacity = 9 Amp-hr, number of batteries 38 and number of parallel paths = 2). In this case, the charging is provided by the engine only.

Subjecting to multiple drive cycles, the SOC of the battery throughout the drive cycle is plotted along with the velocity of the vehicle for both drive cycles in Figs. 12a and b. In the highway drive cycle, the lower limit of the SOC directly affected the final SOC of the battery. Defining 0.7 to be the lower limit of SOC results in the final SOC of the battery to be > 0.7 while lowering the lower limit of the SOC directly affects the final SOC of the battery. It is also observed that having a lower limit of the SOC resulted in a longer time taken for the initiation of battery charging. Further, it is also observed that the SOC of the battery in the highway drive cycle oscillated mostly around the lower limit of SOC due to fewer starts and stops and the ICE taking over after a certain speed.

Meanwhile, observing the city drive cycle, SOC of the battery lowers as the drive cycle continues. Additional power required to brake and accelerate short duration of battery charging conditions and greater torque requirements during the city drive cycle consumes the battery's charge and the SOC of the battery cannot be maintained at the desired level. The final SOC of the battery is not maintained in the level of the lower limit of SOC but rather the final SOC in all the cases of city drive cycles is lower compared to the highway drive cycle. The final SOCs of the battery for a different level of SOC lie in close range to each other.

This detailed and comprehensive simulation results comply with the total amount of fuel consumption and the comparison between the characteristics is made and shown in Fig. 13. The average charging power for the battery is relatively constant for the city drive cycles, varying between 10 kW/10 and 20 kW/10, while the average charging power for the battery varies with the SOC lower limit in the case of the highway drive cycles, varying between 0 to around 40 kW/10. Similarly, the fuel consumption in the city drive cycles in different cases is relatively constant while it slightly is more in the case of highway drive cycles with an increase in fuel consumption as the SOC lower limit is increased.

### 6 Conclusions

A preliminary design calculation was conducted for series HEV and it was developed in MATLAB environment using a backward
model. The developed hybrid bus was then run through highway (US06) and city (Manhattan) drive cycles using a rule-based algorithm. Parameters such as power, velocity, acceleration and wheel torque were monitored throughout the simulations. Further, setting the SOC lower limit to 0.6 and 0.7, the battery's SOC, fuel energy consumed during the two drive cycles and battery's energy consumptions were monitored. It was observed that setting a higher lower limit of SOC resulted in less consumption of fuel energy and higher efficiency of the ICE. It was also observed that a series of hybrid buses resulted in better output when driven in a highway drive cycle.

The prolonged simulations were conducted for both drive cycles, setting the lower limits of SOC to 0.55, 0.6, 0.65 and 0.7. During these simulations, SOC of battery, fuel power and average charging power were observed. Changing the SOC limit did not result in much difference in average charging power during the drive cycle while changing the SOC limit resulted in the average charging power to range from 0 to 40 kW.

From the discussion, the following conclusions were drawn based on the results of the simulations:
(a) During the highway drive cycle, average charging power greatly depends on the SOC limit.

(b) During the city drive cycle, average charging power varies slightly with the change in the SOC limit.

(c) When SOC lower limit is more, the performance index will be enhanced with power split mode because the efficiency of ICE will be better when it will be operated in power split mode.

With these conclusions drawn, a combination of HEV with power-split mode and battery with lower SOC lower limit can be recommended for use as it displays a considerable performance boost. This is thus proven true in the highway drive cycle. With larger percentages of the world's distribution still unable to handle a full fledge EV fast charging. A totally EV-driven transportation sector is still unattainable. However, with the use of an HEV (especially for the long-distance highway travel) and an overwhelming increase in the electric energy demand from the transport industry can be avoided while still implementing a more sustainable and efficient form of a mixture of energies. This will slow down the consumption rate of petroleum products and enough time for the electric distribution sector for necessary upgrade without overhauling the entire network with rampant increase in demand. Further, with these simulations being based on a real-world engine and drive cycles the obtained results can be applied to further understand the relevancy of the HEV in these real-world scenarios; one is that is not capable of handling a sharp growth in the electricity demand of the EVs.

Furthermore, simulations conducted in this paper along with the results obtained can be complimented and furthered with the future researches addressing the following points:

(a) Comparison with the other types of hybrid vehicles. Simulating other types of hybrid vehicles and comparing the result with the results obtained in this paper should be done to clarify the efficiency of HEV discussed above.

(b) Distinct charge depleting mode and charge sustaining mode. Charge sustaining mode should be introduced to further develop the concept of HEV discussed in this paper.

(c) Inclusion of emission performance. Simulations will have to be conducted to evaluate the emission performance of the HEV to broaden the scope and better evaluate the HEV's performance.

(d) Combination of city and highway cycle. Simulations can be done for a combined city and highway drive cycles to evaluate the HEV's performance in a diverse drive cycle.

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