

# Comparative Analysis of Regenerative Power and Fuel Consumption of Hybrid Electric Vehicle

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## Abstract

Hybrid Electric Vehicle (HEV) is one of the emerging environment-friendly technologies in vehicular world with improved efficiency but its main issue has been its energy management and supervisory control that ensures best energy distribution. This research analyzes the drive performances of different possible regeneration paths with standard drive cycles through hybrid powertrain model based on quasi-state model of machines. Further, the efficiency map table developed from laboratory test is utilized to estimate efficiency and energy loss in the motor. In this research, 65 kW generator and 110 kW motor of 3000 rpm with an efficiency map are utilized to develop a model in MATLAB. From the simulation result, it has been observed that fuel economy and final state of charge (SOC) of the battery improves when regeneration is done by both machines. The implementation of Rule-Based algorithm indicates that the battery charges only when Internal Combustion Engine (ICE) operates.

## Keywords

hybrid electric vehicle, electric vehicle, internal combustion engine, state of charge, drive cycle

## 1. INTRODUCTION

Hybrid Electric Vehicles (HEV) has become a promising technology for public and mass transport when compared to the low efficient conventional vehicles. Fossil fuel-based vehicles have become the main reason for the accelerated depletion of the non-renewable energy resources in an unsustainable manner. ICE based vehicle or classical vehicle has a maximum efficiency of around 40 % [Eshani et al., 2018] for a particular operating condition, but in reality, the vehicle requires a wide range of torque and speed. The output power drive thus varies and it will only have a maximum rating for a small interval of time, resulting in the requirement of the oversized engine. Electric Vehicles (EV) has high efficiency as the converter loss and machine loss are negligible and also with the implementation of the converter, the operating region can be tailored. Besides that, EV is environmentally friendly and there is the possibility of regeneration as well. Total recovered energy for EV is around 20% [Cauwer et al., 2015], but it has some limitation such as; high charging time and short mileage compared to the classical one [Wang, 2016].

The advent of permanent magnet (PM) material and Neodymium-Iron-Boron (Nd-Fe-B) with higher en-

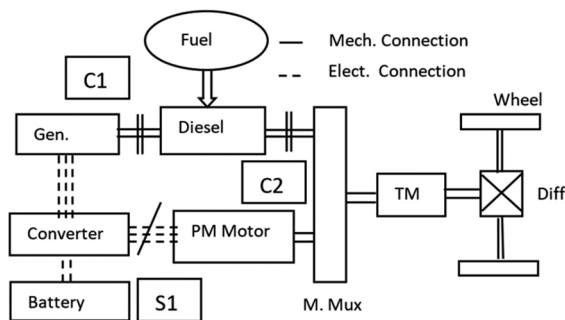
ergy product has led to the increase of its application in machine design [Husain, 2003; Mi and Masrur, 2017]. Nd-Fe-B magnet has high negative temperature coefficient compared to other available PM, so special attention needs be given when the temperature exceeds 1000 °C [Finken et al., 2008; Chau et al., 2008; Pyrhonen et al., 2013]. Direct current machines have the good technical maturity, low power electronic, low manufacturing cost and ease of controllability but due to its low power density, unreliability and high maintenance cost it is less popular the EV applications [Finken et al., 2008]. The next type of the low-cost machine is induction type but it does not meet all the requirements of EV application. Prominently, the induction type machine size for low speed will be larger, and it has low power density for same frame size [Finken et al., 2008]. In the early days, switch reluctance motor was one of the options because it had properties comparable to that of the PM synchronous motor, but it did not turn out to be a viable option due to its torque ripple and acoustic noise particularly in the low-speed range [Faid et al., 2010].

The key issue in HEV has been its energy management and supervisory control to ensure the best energy distribution in function of the global demand [Karbaschian and Söffker, 2014; Keulen, 2010]. Different power management algorithms have been devised to manage the energy of a hybrid powertrain. Salmasi et al. proposed different rule-based and optimization-

based methods for energy management [Salmasi, 2007]. The energy management strategy only uses past and current vehicle states and driver commands to calculate a proper control signal [Du, 2017]. Vehicle operator receives all the required inputs from the vehicle and road conditions, makes decisions about braking, gearing and accelerating, and executes the commands [Opila *et al.*, 2012]. The design process is initiated by interpreting driver pedal as a signal in the form of power request and according to power request, the energy management controller determines the power flow in hybrid drivetrain [Lin *et al.*, 2001]. In this study, a model for HEV has been developed and analyzed for different options of power distribution. It is focused on hybrid topologies that utilize the advantages of both conventional and hybrid vehicles. The study commences with the background of the study followed by section 2 that presents the system description and assumptions. In section 3, mathematical calculations for preliminary design are presented while section 4 elaborates the applied algorithm (i.e. Rule-Based Algorithm). Section 5 presents the analysis and the outcomes of the study and finally in section 6, the conclusion is drawn and presented based on the results of the simulation.

**2. SYSTEM DESCRIPTIONS**

The drive train under consideration is a combination of direct diesel drive and series hybrid drive with a minimum diesel dimensioning. The generator and diesel engine, both having the initial performance level of 65 kW and a maximum driving speed of 3000 rpm, form a diesel gen-set of the hybrid drive. The PM traction motor has an initial performance output of 110 kW at the rated voltage of 400 V AC. The maximum torque of 1700 Nm is reached with 300 amperes of current. Figure 1 shows the system layout. The mechanical multiplexer is a special type of clutch which provides three possible states, diesel only, electrical motor only or power from both diesel and electric motors, to the transmission shaft. Here, C1 and C2



**Fig. 1** System under consideration with electrical and mechanical links

denotes the two clutches used in the system. As shown in Table 2, dedicating C1 and C2 to engage and disengage electrical motor and diesel engines in different combinations will result in the operation of defined hybrid system in different topologies as: (a) series hybrid, (b) parallel hybrid, (c) two-electric-machines drive with a free-wheeling diesel, or (d) pure diesel drive.

Besides that, electric motor power can be isolated from the supply whenever possible to minimize total core losses. Battery isolator is used to isolate multiple batteries present in the HEV from each other. A HEV contains multiple batteries, that are used to perform various tasks. For the simulation, only the battery dedicated for electricity supply for vehicle propulsion is shown in Figure 1. But taking the whole HEV into account, it will contain at least another battery for electricity supply of the headlights, horn, etc. This battery is not designed for frequent deep charging cycles. In absence of isolator, whole system will use the charge of both the batteries regardless of the task, resulting in frequent deep cycle recharging of both batteries. Thus, the battery isolator (S1) is kept on during the simulation in the designed system as states in Table 2. This is done to isolate the battery used to supply the electric motor for frequent deep cycle recharging.

Converter is an essential part of any hybrid vehicle system. Different components of the vehicle like headlights and horn works on 12 Volts. But the 65 kW generator and 110 kW motor modelled in the MATLAB is designed for higher voltage operation. 27 Ah 12 V NiMH battery pack, as discussed in section 3.7, acts as a primary source of electricity in the designed system. With the electric components of the HEV operating on two different voltages, a DC-DC converter is used to transfer energy between the two voltage systems. With only the higher voltage system present in

**Table 1** Vehicle parameters

Parameters	Symbol	Value
Drag Coefficient	Cd	0.55
Wind Speed Coefficient	Cw	0
Rolling Resistance Coefficient	Fr	0.01
Frontal Area (m <sup>2</sup> )	Af (m <sup>2</sup> )	5
Total Weight	M(kg)	12500
Air Density	ρ	1.2
Max Velocity (km/hr)	Vm (km/h)	50
Transmission Efficiency	η1	0.85
Motor Efficiency	η2	0.9
Wheel radius (m)	r	0.5
Acceleration due to Gravity (m/sec <sup>2</sup> )	g	9.8

**Table 2** Possible operating modes

State					Topology
C1	C2	S1	M Mux.	Fuel	
Electric Motor	Diesel Engine	On	Electric Motor	On	Series
Diesel Engine	Electric Motor	On	X	On	Parallel
Electric Motor	Electric Motor	On	X	Off	EV
Diesel Engine	Electric Motor	On	Diesel Engine	On	Pure Diesel

the simulation and there is no need of power transfer between the different voltage systems, the converter is not taken into account.

The system parameters for the hybrid bus has been assumed as given in Table I, and Different possible operating modes are obtained from engaging and disengaging of clutches and isolators as shown in Table 2.

### 3. PRELIMINARY CALCULATION AND MODELING

#### 3.1 Cruising power

The maximum cruising power is the power required to drive the vehicle into the flat zone with a maximum speed which is given by equation (1) [Husain, 2003].

$$P_{Cruising} = \frac{Vm}{1000} \left( M_v g f_r + \frac{1}{2} \rho C_D A_f V m^2 (1 \pm C_w) \right) \quad (1)$$

#### 3.2 Accelerating power

Acceleration is the most demanding requirement. The aim is to evaluate  $P_{drive}$  so that the vehicle can accelerate from initial velocity to final velocity in the defined time interval on a flat road [Ehsani et al., 2018; Husain, 2003; Mi et al., 2017]. Maximum acceleration can be obtained from a typical drive cycle. Here, for London 159 drive cycle, the maximum acceleration is  $a_{max} = 1.502 \text{ m/s}^2$  with data sampling period being 1 second [Hayat et al., 2014]. For a series hybrid electric vehicle, the series motor capacity must be enough to accelerate it, and for a parallel total power of the engine, the motor must enough to accelerate.

#### 3.3 Grade-ability power

Power required to overcome slope with some speed is given in equation (2) [Husain, 2003].

$$P_{grade} = \frac{1}{1000\eta} (M_v g \sin\alpha Vm) \quad (2)$$

The average load power from the engine/ generator can be given by equation (3) [Husain, 2003].

$$P_{engine} = \frac{1}{T} \int_0^T (M_v g f_r + \frac{1}{2} \rho C_D A_f V m^2) V_m dt + \frac{1}{T} \int_0^T \delta m \frac{dVm}{dt} dt \quad (3)$$

Before motor 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 either any one source or both, which are given in equation (4) [Husain, 2003].

$$i_g \geq \frac{M_v g (f_r \cos\alpha + \sin\alpha) \times r}{T_{max} \eta_{diff}} \quad (4)$$

Where  $T_{max}$  is maximum transmission torque and for a parallel vehicle, it can be the sum of the motor as well as ice torque capacity whereas for series it represents maximum motor torque. Hence, a maximum slope that the vehicle can climb with reduced speed according to maximum gear ratio is calculated from equation (4).

The power rating of the electric motor (kW) used in the powertrain and engine power of hybrid vehicle must be able to drive the vehicle. Thus, sizing of the components to a great degree, depends on the maximum velocity, driving cycle; i.e. maximum acceleration, start-stop pattern, landscape and length of the trip. Apart from that the battery size is influenced by topology as well. Initial battery energy required is computed on the basis of energy extracted from the battery and replenished to the battery during the trip considering SOC limit of the battery. The system parameters for the hybrid bus are assumed as given in Table 1 and simulation are carried out for the standard drive cycles.

#### 3.4 Differential ratio

The differential ratio is computed by assuming the maximum cruising speed of the vehicle, and must correspond to the maximum speed of the motor given in equation (5) [Husain, 2003].

$$\zeta_{diff} = \frac{\Omega_{max\_em1} (rpm)}{\frac{30 V}{\pi r_w}} \quad (5)$$

Here  $V_{max} = 80$  km/hr,  $r_w = 0.5$  m and  $\Omega_{max} = 3000$  rpm  $\zeta \approx 7$

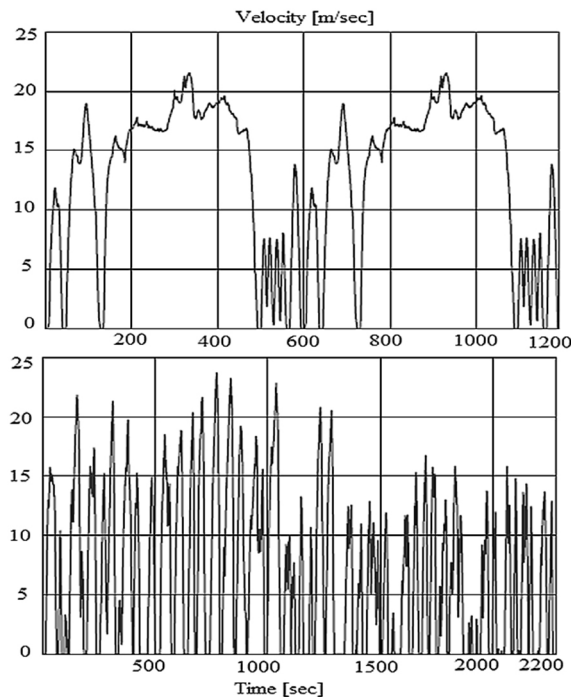
### 3.5 Transmission gear ratio

The maximum driveline speed ratio is designed to ensure that the vehicle can climb slopes from equation (4). It can be computed considering the diesel engine only, the electric motor only, and both as a drive power. The speed is adjusted as shown in Table 3.

**Table 3** Adjusted speed

S. No	Velocity in m/sec	Gear Ratio
1	$v \leq 4.4$	6.32
2	$4.4 < v \leq 8.8$	3.62
3	$8.8 < v \leq 13.2$	2.15
4	$13.2 < v \leq 17.6$	1.35
5	$17.6 < v$	1.00

When the highway drive cycle is considered, the vehicle moves with constant speed for a long time with few starts and stops at the initial and final stage of the trip. Such a cycle can be used for highway driving between cities. When the city drive cycle is considered it gives the vehicle movement has frequent start



**Fig. 2** Standard highway (US06) and city (Manhattan) drive cycle

and stoppages. Such a cycle can be used for driving within cities. Both drive cycles are used for simulation as shown in Figure 2. The standard highway (US06) drive cycle is considered for the time period of 1200 second, whereas the city (Manhattan) drive cycle for the time period of 2200 second.

### 3.6 Engine model

ICE is represented by its quasi-state model. The efficiency map table and fuel consumption map table are utilized to estimate fuel consumption and efficiency. In this research, efficiency map and fuel consumption map are used to develop a model in MATLAB.

The efficiency of ICE is given by equation (6) [Husain, 2003].

$$\eta_e = \frac{T_e(t) \omega_e(t)}{P_{fuel}(t)} \quad (6)$$

Where  $\eta_e(t)$  is the efficiency of the engine,  $P_{fuel}(t)$  is the enthalpy flow associated with the fuel mass flow, and  $T_e(t)$  and  $\omega_e(t)$  are the engine's torque and speed respectively.

### 3.7 Motor model

The electrical motor is also represented by its quasi-state model. Efficiency map table developed from laboratory test is generally utilized to estimate efficiency and energy loss in the motor. In this research 65 kW generator and 110 kW motor of 3000 rpm with an efficiency map are utilized to develop a model in MATLAB. The efficiency of the machine has been calculated from equation (7).

$$\eta = \begin{cases} \frac{T_m(t) \omega_m(t)}{P_{ele}(t)} & \text{when } P_{drive} T_m(t) \omega_m(t) > 0 \\ \frac{P_{ele}(t)}{T_g(t) \omega_g(t)} & \text{when } P_{drive} T_m(t) \omega_m(t) < 0 \end{cases} \quad (7)$$

### 3.8 Battery model

The battery model was referred from [He et al., 2010]. According to the paper, non-linear relationship for terminal voltage and resistance for 27Ah 12 V NiMH battery is given by:

$$\begin{aligned} E &= -61.805 \times k^6 + 246.72 \times k^5 - 358.34 \times k^4 + \\ & 246.03 \times k^3 - 5.24 \times k^2 + 15.389 \times k + 11.369 \\ R &= -0.75178 \times k^6 + 2.268 \times k^5 - 2.6248 \times k^4 + \\ & 1.4629 \times k^3 - 0.40259 \times k^2 + 0.04957 \times k + \\ & 0.0083927 \end{aligned} \quad (8)$$

Where  $k$  is SOC of the battery.

The system is modelled in MATLAB environment which comprises backward facing, forward facing, and both modelling approach. The model can be dynamic as well as a quasi-static model. The actual dynamic model requires lots of system parameters and experiments and gives more accurate results, whereas components like generator / engine / motor / battery and another mechanical system like transmission/ differential are replaced by a static model in the quasi-static model. which is mainly because of slow dynamics on sampling period and some of the above components utilizes their mapping table. This leads to the removal of inner subsystem control. Here, the backward facing model whose main simulation executes faster is adopted. However, limitation of the backward-facing model is that it does not deal in the quantities measurable in a vehicle. For example, control signals like throttle and brake positions are absent from the model which hinders the dynamic system simulation and control system development [Chan et al., 2010; Hou and Guo, 2008; Mierlo et al., 2004; Ade and Binder, 2009; Gong et al., 2008]. In this approach, the force required to accelerate the vehicle through the time step is 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/battery for instance. The power flow has been calculated from backward; i.e. wheel to sources considering losses in various stages. In the end, the use of fuel or electric energy is computed for the given speed trace or drive

cycle.

#### 4. RULE BASED ALGORITHM

In most of the existing HEV, the power management algorithm is rule-based due to the ease of handling switching operating modes [Sulaiman et al., 2015; Geetha and Subramani, 2017]. Chan-Chiao Lin et al implied a rule-based algorithm in the parallel hybrid truck. According to him power operation of this controller can be divided into different control modes such as: Braking Control, Power Split Control, and Recharging Control on the basis of power/torque request [Lin et al., 2001]. If the torque request is negative, braking control will be applied to decelerate the vehicle. If the torque request is positive and below the minimum torque of the engine, then the motor will give propulsion torque. Similarly, when within range of ICE, it will provide requested torque. But above the ICE range, either battery or both battery and ICE will be operated. Recharging torque will act according to a charge-sustaining policy. Whenever the SOC drops below the lower limit, the controller will switch to recharging rule until the SOC reaches the upper limit. Then the power split rule will take over [Hour and Guo, 2008; Mierlo et al., 2004; Ade and Binder, 2009; Ganji, 2010; Lin et al., 2003; Ganji and Kouzani, 2010]. The logic of the rule-based algorithm for the HV has been summarized in Table 4.

If  $SOC < SOC_{min}$ , minimum  $T_{tot} = T_{ch} + T_{req}$   
 If  $SOC > SOC_{max}$ , maximum  $T_{tot} = T_{req}$

**Table 4** Logic of rule-based algorithm

Normal Mode $T_{req} > 0$	$\text{if } T_{req} \leq T_{emin}, \begin{cases} T_e = 0 \\ T_{em} = T_{req} \end{cases}$ $\text{if } T_{emin} \leq T_{req} \leq T_{emax}, \begin{cases} T_e = T_{req} \\ T_{em1} = 0 \end{cases}$ $\text{if } T_{req} \geq T_{emax}, \begin{cases} T_e = 0 \\ T_{em} = T_{req} \end{cases}$
Charging Mode	$SOC < SOC_{min},$ $\begin{cases} T_e = T_{max} \\ T_{ch} = T_{emax} - T_{req} \end{cases}$
Braking Mode $T_{req} < 0$	$T_{req} > T_{mming},$ <p>The hydraulic braking will be activated to assist the vehicle deceleration.</p> $\text{if } T_{req} \leq T_{mmin}, T_{engine} = 0, \text{ and } P_{batt} = T_{req} \omega, P_b = 0$ $\text{if } T_{req} \leq T_{mmax}, T_{engine} = 0, \text{ and } P_{batt} = T_{mmax} \omega, T_b = T_{req} - T_{max}$



## 5. RESULT AND DISCUSSION

Energy consumption and losses have been observed for the following four cases:

- Regeneration is done via Electrical Motor (EM) without charging
- Regeneration is done via Electrical Motor (EM) with battery charging
- Regeneration is done via Electrical Motor (EM) and Internal Combustion Engine (ICE) without charging
- Regeneration is done via Electrical Motor (EM) and Internal Combustion Engine (ICE) with battery charging.

Here, charge control has been computed when SOC is lower than  $SOC_{1\_limit}$  and the engine on command is high.  $SOC_{2\_limit}$  has not been considered in this study because in all cases of the chosen drive cycle, the SOC is less than the initial values.

Simulations have been carried out for the values with the assumptions being, number of batteries =24, number of parallel paths = 2,  $SOC_{initial} = 0.7$ ,  $SOC_{1\_limit} = 0.65$  and battery will charge only when ICE is in operation, which happens when drive torque is within ICE torque limit.

The simulated output for performance parameters of the vehicle namely, the power required, the torque required, acceleration and gear ratio for vehicle load with different load cycle have been depicted in Figure 3 and 4. The positive portion of the graphs representing power, acceleration, transmission torque, accelerating power, wheel torque and the differential torque is required to be supplied by the HEV, while the negative portion would be regenerated from the wheel to the engine during the respective drive cycles. The required power, wheel torque and differential torque are frequently altered to meet the changing velocity and acceleration with an appropriate gear ratio for frequent start and stops on city drive. The changes in the performance parameters are comparatively slow due to sporadic start and stop requirement on a highway drive.

Following the powertrain for highway drive (Figure 3), the velocity of the vehicle is comparatively constant with few swift variations owing to a smaller number of start and stops made. Consequently, lesser changes in velocity with respect to the time have resulted in the vehicle to have zero acceleration for quite an extensive period of time. As the highway provides an unrestricted pathway for the ride, the vehicle is free to move at a velocity of 50km/hr or higher which is achieved by the gear ratio of 1. The gear ratio changes from 6.32 to 1 as the vehicle starts from zero to high

speed as defined in Table 3. The sporadic braking changes the power consumption of the vehicle to be negative. This torque of ICE motor utilized to charge the battery.

However, following the powertrain for city drive (Figure 4), the velocity of the vehicle is observed to be frequently changing owing to a large number of start and stops due to multiple obstacles in the road, sharp turns, traffics, etc. Consequently, more changes of velocity with respect to the time have resulted in the vehicle to accelerate and deaccelerate between the range of  $2 \text{ m/sec}^2$  to  $-2 \text{ m/sec}^2$  within short spans of time throughout the test period. The gear ratio constantly changes within the range of 1 to 6.32 as the vehicle needs to gain speed after each subsequent stop. Though more regenerative braking occurs during the city drive resulting in added charging of the battery, the charge of the battery will be immediately used up for the acceleration and torque gain after each braking.

The characteristics of SOC of the batteries for highway and city drive cycles in all the four cases with different battery charging capacities have been presented in Figures 5 and 6. With the test conducted a little over 2200 sec for city drive and 1200 sec for highway drive, the result shows abrupt fluctuation in SOC for

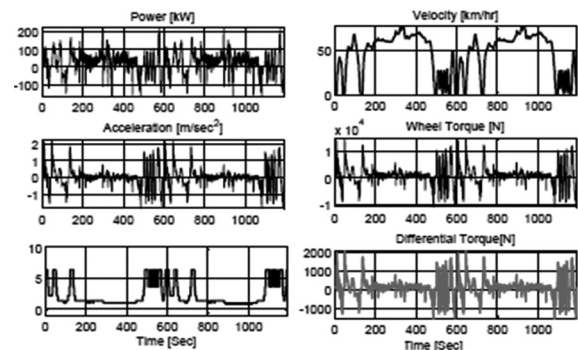


Fig. 3 Simulated outputs of powertrain for highway drive cycle

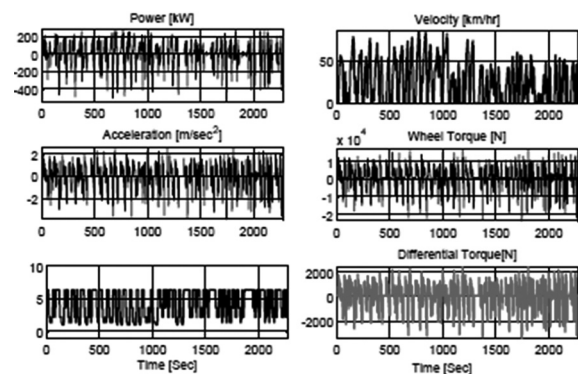


Fig. 4 Simulated outputs of powertrain for city drive cycle

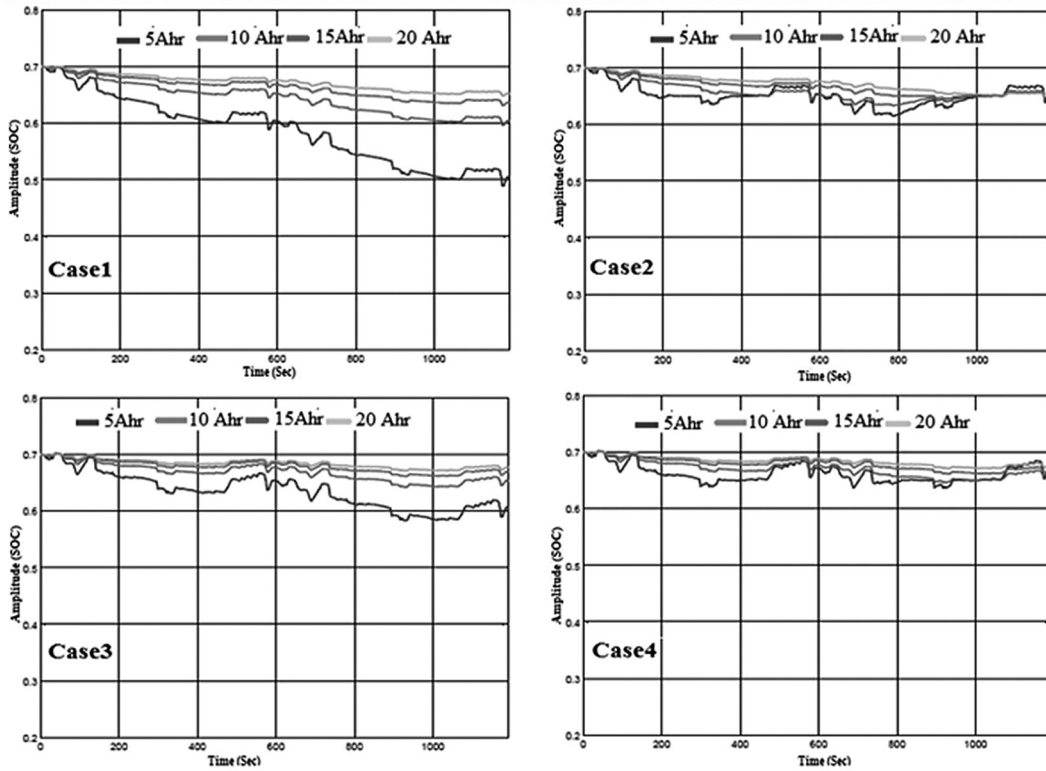


Fig. 5 SOC for different battery capacity for highway drive cycle

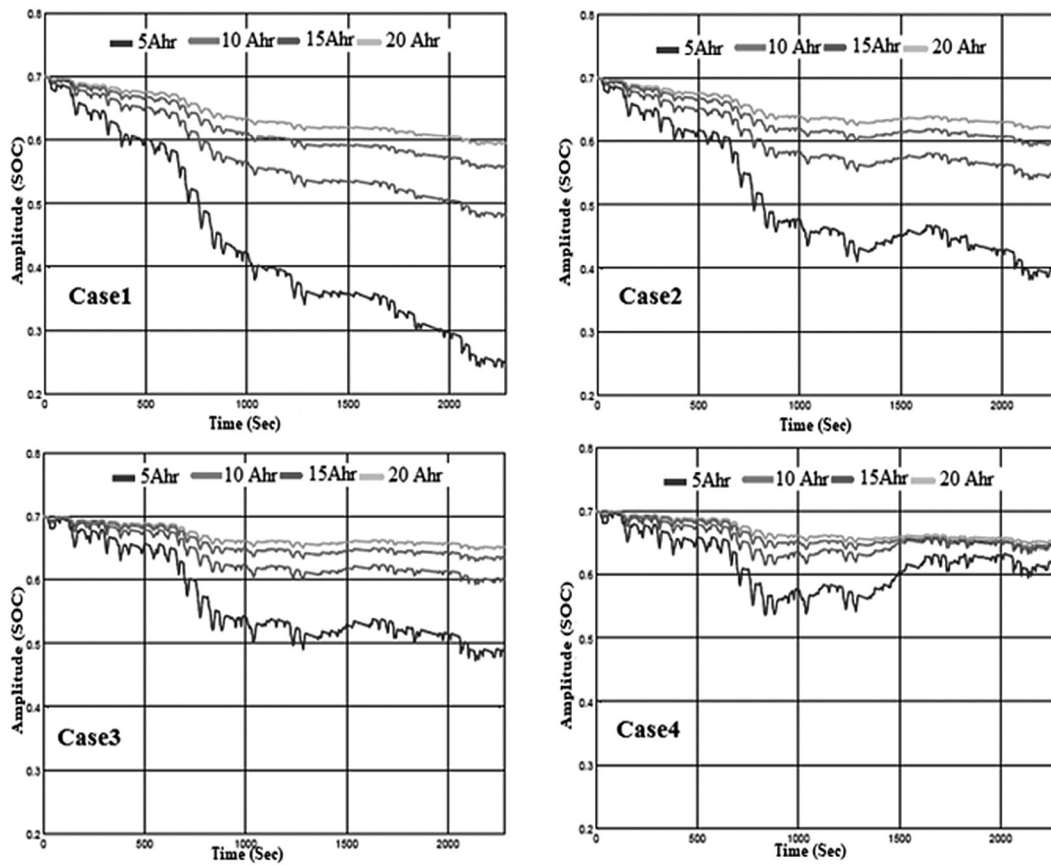


Fig. 6 SOC for different battery capacity in city drive cycle

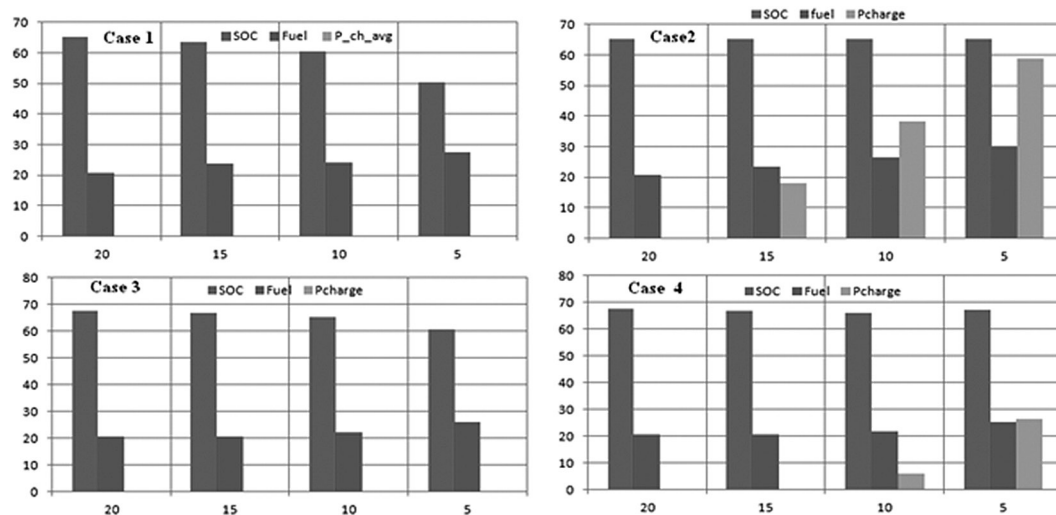


Fig. 7 Final SOC (%), Fuel consumption (kWhr), Average charging power (kW) for highway drive cycle

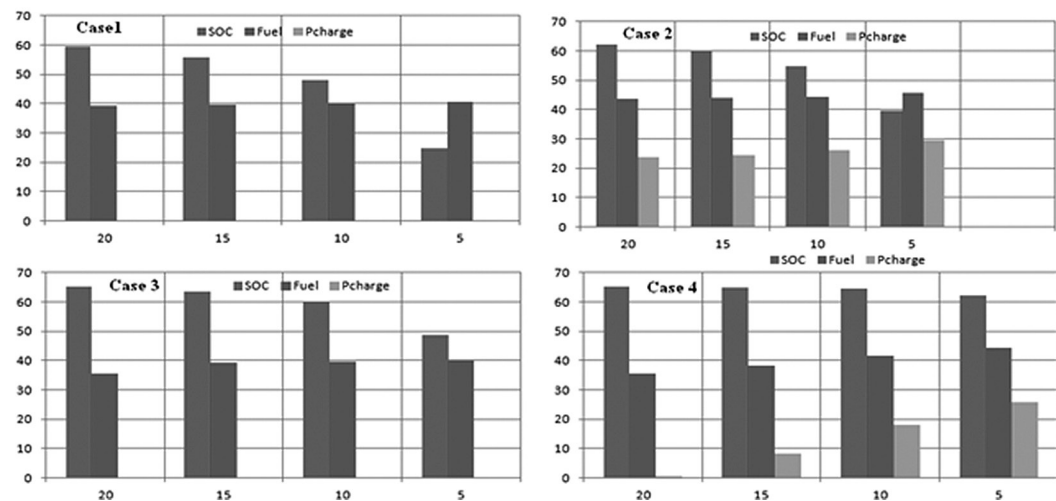


Fig. 8 Final SOC (%), Fuel Consumption (kWhr), Average charging power (kW) for City drive cycle

all four battery capacities with city drive cycle requiring frequent starting and stopping of the vehicle as compared to that of highway drive cycle. The SOC of batteries improves in Case 2 and Case 4 with the facilitation of regeneration and the possibility of battery charging option when compared to Case 1 and Case 3 with no battery charging option. The analysis illustrates that regeneration involving two motors with battery charging option for Case 4 has an improved SOC of batteries as compared to regeneration with a single motor and battery charging option for Case 2. That being the case, the 5Ahr battery has the least SOC of a little more than 24% in Case 1 of city drive cycle. The city drive's SOC output shows the inefficiency in all four cases. Case 1 and Case 3, not being provided with the battery charging option, the battery's charge is consumed by the frequent stopping of the vehicle. Further use of the battery is done to provide torque as

states in the normal mode of Table 4. Case 2 and Case 4 has been provided with the battery charging and frequent regenerative braking results in more power availability of the charging of the battery, but frequent start and stoppage result in inefficient charging of the battery. Also, more battery charge is consumed for the frequent stoppage and torque fulfillment during the start and acceleration.

Comparatively, during the Case 1 and Case 3 of the highway drive, comparatively less battery charge is consumed due to a lesser number of start and stops. And even though the cases are not provided with battery charging, final SOC is still comparatively high. With the initial SOC being 0.7, the effectiveness of the proposed hybrid model can be seen in Case 2 and Case 4 of the highway drive cycles. Comparatively though, Case 4, i.e. regeneration involving two motors with battery charging option is found to be more effec-



tive than Case 2, i.e. regeneration involving a single motor. Less number of start and stoppage in highway drive and involvement of two motors ensures the efficient transfer of negative power towards the charging of the battery.

As seen from the graphs, the selection of battery size is critical. Selecting a smaller battery size, in this case 5Ahr, will result in the frequent deep discharging of the battery that results in the battery lifespan to decrease significantly. However, selecting a battery size that is more than required, in this case 20Ahr will result in inefficient use of the total capacity of the battery. This will result in the unnecessary extra weight added to the total weight of the car.

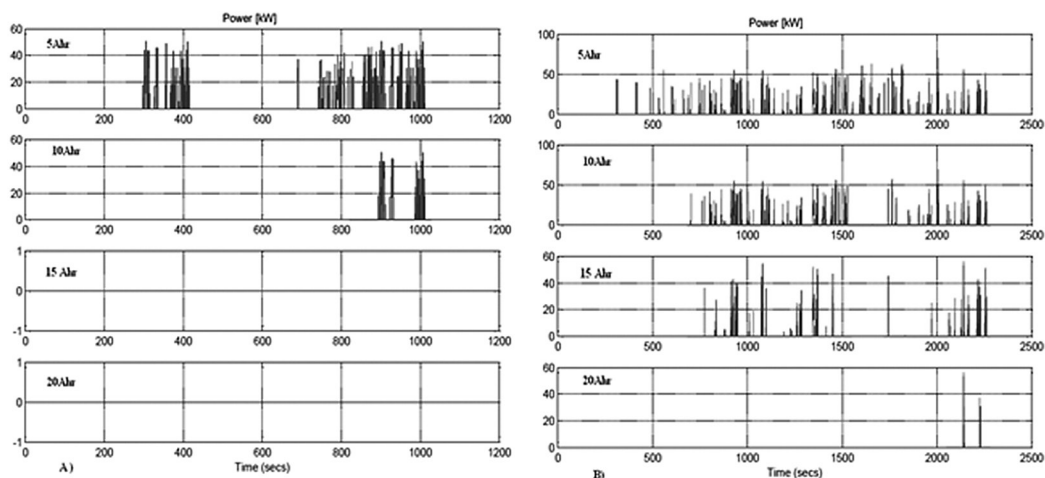
The SOC of batteries, fuel consumption pattern in kWh and average charging power in kW in percentage have been shown in Figures 7 and 8 below for both the city and highway drive cycles for all four cases. The fuel consumption patterns of the vehicle for both Case 3 and Case 4 have been found to be low when compared to Case 1 and 2. The reduced fuel consumption is due to the combined use of EM and ICE, which can regenerate the power and further utilize it to operate the motor again. The percentage SOC is noticeable in Case 2 and Case 4 with battery charging option, while in other cases with no battery charging, it is less so. The average power charged is significant in Case 2 when compared to Case 4 as the two motors operate and consume the regenerated power instantly in Case 4.

Comparing the highway and the city drives, more fuel is consumed in the city drive cycle vs the highway drive cycle within the same interval of time. Even when the vehicle moves in a slow speed, few kilometres per hour, the engine still uses quite a lot of fuel to operate the cylinders and various electrical parts of

the cars. Thereby consuming a lot of fuel for essentially covering a short distance. That is, the mileage of the car at low velocity is essentially low. But as the car's velocity increases, after a certain point a certain increase in the velocity of the car will require more power. So, in the case of city drives with the constant stoppage of the vehicles, the majority of the time is spent by the vehicle where the mileage it provides is poor. This leads to the increase in fuel consumption.

With the same amount of operating time, driving range for city drive and highway drive tends to vary a lot. When compared to highway drive, result from the simulation shows that even though driving range of city drive is lesser when compared to the highway drive for same length of operating time, the amount of fuel consumed and energy regenerated greater for city drive. And simulating the city and highway drive for the same drive range will only result in this difference of fuel consumption and energy generation to be greater. i.e., overall result of the total simulation will only in terms of energy and fuel related values rather than the conclusion itself.

Figure 9 (A) and (B) portray the regeneration from the simulated model with both motors functional at the value of  $SOC_{limit}$  of 0.65 for both drive cycles. The regenerated power is substantial for a city drive cycle for a battery capacity of 5 Ah. Further, the charging of the battery is well distributed in the city drive with the frequent start and stops of the vehicle. But the charging power in the highway drive is sporadic. No charging takes place in the 15 Ahr and 20 Ahr batteries in the highway drive and only small amount of charging takes place at the near end of the 20 Ahr battery in the city drive. These lacks of battery charging are due to the SOC limit being 0.65 for both drive cycles. That is, higher the capacity of the battery,



**Fig. 9** Charge power when  $SOC_{limit}$  is 0.65 and Regeneration is done from both motors for (A) highway drive cycle, and (B) city drive cycle.

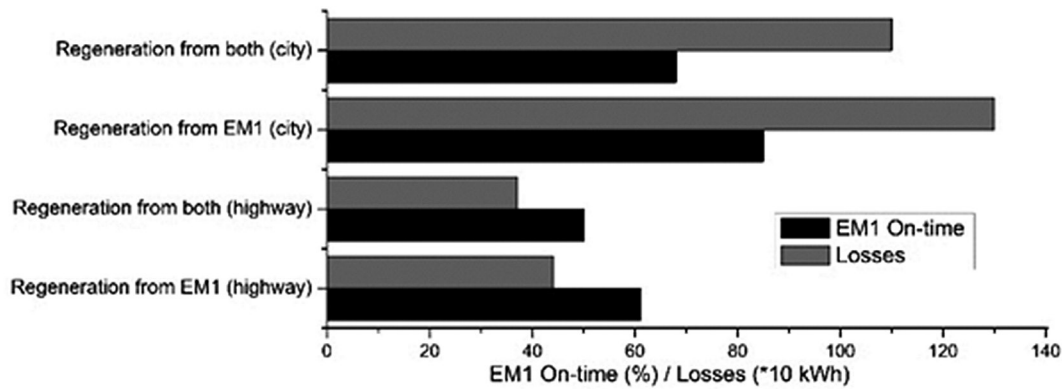


Fig. 10 EM<sub>1</sub> on time (percentage of drive cycle) and Losses of EM<sub>1</sub> ( $\times 10$  kWh)

more time it takes for the battery's SOC to go below the SOC<sub>limit</sub>.

Figure 10 presents the comparative results between losses and operating time of electric motor for different cases. The higher amount of regeneration on highway drive is resulted due to less on-time of the electric motor in both cases (regeneration from EM and regeneration from both motors). Both the losses and the operating time are also found to be less in highway drive. Whereas in case of a city drive, the percentage of on-mode of the electric motor is higher (i.e. operating as a motor) as the EM is used to gain torque and accelerate after each stoppage in accordance with the conditions defined in Table 4. Due to the frequent start and stop, there is less time to regenerate the electricity and the losses in this case is significantly higher than that in the case of the highway drive.

## 6. CONCLUSION

The analysis involves simulation of the model for city and highway drive cycles under different cases of motor operation by varying the ampere-hour capacity of the battery. It has been observed that for the chosen highway drive cycle, when both machines operate for regeneration, the final SOC as well as fuel consumptions are better in highway cycle when both machines operate for regeneration. The operational time and total losses of the HEV in highway drives are significantly less than the city drive cycle, due to the smaller number of start and stops resulting in the production of relatively high regenerative energy. Whereas, for the city drive cycle the isolation period of the main motor is quite less which might be inconvenient with respect to the cost. But still this configuration gives better SOC when compared to others. However, the battery will be depleted after fewer drive cycles.

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## References

- Ade, M. and Binder, A., Modeling the drive train for two Parallel Hybrid Electric Vehicles in MATLAB/Simulink, *IEEE Vehicle Power and Propulsion Conference*, 592-600, 2009.
- Cauwer, C. D., Mierlo, J. V., and Coosemans, T., Energy consumption prediction for electric vehicles based on real-world data, *Energies*, Vol. 8, No. 8, 8573-8593, 2015.
- Chan, C. C., Bouscayrol, A., and Chen, K., Electric, hybrid, and fuel-cell vehicles: Architectures and modeling, *IEEE Transactions on Vehicular Technology*, Vol. 59, No. 2, 589-598, 2010.
- Chau, K., Chan, C. C., and Liu, C., Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles, *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 6, 2246-2257, 2008.
- Du, Z., *The Hierarchical Control Method for Coordinating a Group of Connected Vehicles on Urban Roads*, Clemson University, 2017.
- Ehsani, M., Gao, Y., Longo, S., and Ebrahimi, K., *Modern electric, hybrid electric, and fuel cell vehicles*, CRC Press, 2018.
- Faid, S., Debal, P., and Bervoets, S., Development of a switched reluctance motor for automotive traction applications, *The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition*, 5-9, 2010.
- Finken, T., Felden, M., and Hameyer, K., Comparison and design of different electrical machine types regarding their applicability in hybrid electrical

- vehicles, *18th IEEE International Conference on Electrical Machines*, 1-5, 2008.
- Ganji, B. and Kouzani, A. Z., A study on look-ahead control and energy management strategies in hybrid electric vehicles, *Proceedings of Control and Automation (ICCA), 8th IEEE International Conference*, 388-392, 2010.
- Ganji, B., Kouzani, A. Z., and Trinh, H. M., *Drive cycle analysis of the performance of hybrid electric vehicles, Life system modeling and intelligent computing*, Springer, 2010.
- Geetha, A. and Suramani, C., A comprehensive review on energy management strategies of hybrid energy storage system for electric vehicles, *International Journal of Energy Research*, Vol. 41, No. 13, 1817-1834, 2017.
- Gong, Q., Li, Y., and Peng, Z. R., Trip-based optimal power management of plug-in hybrid electric vehicles, *IEEE Transactions on Vehicular Technology*, Vol. 57, No. 6, 3393-3401, 2008.
- Hayat, J., Copley, G., and Porter, C., Crossrail 2-Development and Application of an Appraisal Framework for Crossrail 2 in London, *European Transport Conference, Association for European Transport (AET)*, 2014.
- He, H.W., Xiong, R., and Chang, Y. H., Dynamic modeling and simulation on a hybrid power system for electric vehicle applications, *Energies*, Vol. 3, No. 11, 1821-1830, 2010.
- Hou, J. and Guo, X., Modeling and simulation of hybrid electric vehicles using HEVSIM and ADVISOR, *IEEE Vehicle Power and Propulsion Conference*, 1-5, 2008.
- Husain, I., *Electric and hybrid vehicles: Design fundamentals*, CRC Press, 2003.
- Karbaschian, M. A. and Söffker, D., Review and comparison of power management approaches for hybrid vehicles with focus on hydraulic drives, *Energies*, Vol. 7, No. 6, 3512-3536, 2014.
- Keulen, T. V., Jager, B. D., Kessels, J., and Steinbuch, M., Energy management in hybrid electric vehicles: Benefit of prediction, *IFAC Proceedings Volumes*, Vol. 43, No. 7, 264-269, 2010.
- Lin, C. C., Kang, J. M., Grizzle, J., and Peng, H., Energy management strategy for a parallel hybrid electric truck, *IEEE American Control Conference*, Vol. 4, 2878-2883, 2001.
- Lin, C.C., Peng, H., Grizzle, J.W. and Kang, J.M., Power management strategy for a parallel hybrid electric truck, *IEEE transactions on control systems technology*, vol. 11, no. 6, pp. 839-849, 2003.
- Mi, C. and Masrur, M. A., *Hybrid electric vehicles: Principles and applications with practical perspectives*, John Wiley & Sons, 2017.
- Mierlo, J. V., Maggetto, G., and Bossche, P. V., Simulation methodologies for innovative vehicle drive systems, *International Power Electronics and Motion Control Conference*, 2004.
- Opila, D. F., Wang, X., McGee, R., Gillespie, R. B., Cook, J. A., and Grizzle, J. W., An energy management controller to optimally trade off fuel economy and drivability for hybrid vehicles, *IEEE Transactions on Control Systems Technology*, Vol. 20, No. 6, 1490-1505, 2012.
- Pyrhonen, J., Jokinen, T., and Hrabovcova, V., *Design of rotating electrical machines*, John Wiley & Sons, 2013.
- Salmasi, F. R., Control strategies for hybrid electric vehicles: Evolution, classification, comparison, and future trends, *IEEE Transactions on Vehicular Technology*, Vol. 56, No. 5, 2393-2404, 2007.
- Sulaiman, N., Hannan, M., Mohamed, A., Majlan, E., and Daud, W. W, A review on energy management system for fuel cell hybrid electric vehicle: Issues and challenges, *Renewable and Sustainable Energy Reviews*, Vol. 52, 802-814, 2015.
- Wang, J., Battery electric vehicle energy consumption modelling, testing and prediction: a practical case study, PhD Thesis, Technische Universiteit Eindhoven, Netherlands, 2016.

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