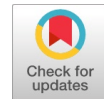


Performance Evaluation of Hybrid Electric Vehicles for Sustainable Transport System

Avanish Kumar, P. R. Thakura



Abstract: The emissions from the internal combustion (IC) engine vehicle causes pollution which increases the carbon footprints in the environment which causes global warming. In ICE vehicle only 20 % of the energy produced by it is used to run the vehicle and rest 80 % of it get wasted. The emerging technology of Hybrid Electric vehicle (HEV) has become the feasible solution for the modern world as it lessens the carbon emission and augments the fuel performance of vehicle. The role of power electronic converters is very crucial in designing the configuration of HEVs. The performance of the converter is employed for realizing the features of electric traction motor drive. The paper analyses the performance of a small car powered by gasoline based internal combustion engine, series hybrid electric vehicle (SHEV) and parallel hybrid electric vehicle (PHEV) drive train. The simulation has been performed on Advanced Vehicle Simulator (ADVISOR) platform. Different types of HEVs configuration has been analyzed by considering three different driving schedules such as CYC_UDDS, CYC_NEDC and CYC_URBAN_INDIA. The gradability and acceleration test has also been carried out in all category of test vehicles and result is demonstrated by examining vehicle emission at each driving cycle.

Index Terms: HEV; hybrid electric vehicles, PHEV; parallel hybrid electric vehicle, SHEV; series hybrid electric vehicle, traction motor drive, ADVISOR.

I INTRODUCTION

The demand for alternative energy sources is increases as fossil fuel are limited and demand for oil increases significantly due to consumption in automobile sector which grows at higher rate in comparison to any other industrial sector. Many environmental issues are directly related to emissions generated by the vehicles and in order to minimize the carbon footprints from the environment is one of the greatest concerns nowadays [1,2]. The unstable cost of gasoline, and the lower fuel-efficiency creates the demand for electric vehicles (EV) and HEV. HEVs have higher efficiency and user's suitability than pure battery operated EV and gasoline operated ICE vehicles Therefore, more attention has been given to HEV [3,4]. HEV growth have been only possible due to advancement in high power semiconductor devices and advent of high performance and high power density traction motors and these have been used to make efficient electric drive. HEV combines the two prime movers firstly the ICE and an electric motor drive. The ICE is driven by conventional fuel and the storage battery provide the energy to the electric motor drive. These two prime movers can work together or separately using different possible topologies namely series, parallel, series-

parallel or complex topology [10-15]. The control methodology for each topology is different but the complete emphasis is to increase the fuel efficiency while fulfilling the traction demand of speed and torque throughout the driving cycle. The performance analysis of series and parallel topology along with conventional vehicle is done for different driving cycle and comparison is done using ADVISOR software[6,13], so that the torque and speed demand of the vehicle can be optimized and the total efficiency and emissions of each vehicle can be determined[13]. For the test purpose typical small car type vehicle is selected.

II HYBRID ELECTRIC VEHICLES

HEVs were developed to overcome the limitations of ICE vehicles and EV although several configurations is used for HEVs power trains, the main architectures are namely the series, parallel and series-parallel architecture [1,3,10-15].

A. Series Architecture

The block diagram shown in Fig. 1 represents the SHEV drivetrain. The generator is coupled to the main power unit. The generator can supply power to either the energy storage battery pack or an electric traction motor. The energy storage batteries supply power to the electric motor and during retardation in regenerative braking mode energy storage batteries receives some fed back power from an electric motor which now act as a generator. An electric motor is connected to drivetrain which drives the wheels of the vehicle. When the vehicle is retarding in regenerative braking mode the drivetrain also fed power back to the motor.

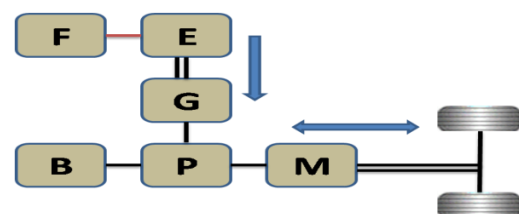


Fig. 1 SHEV Powertrain architecture

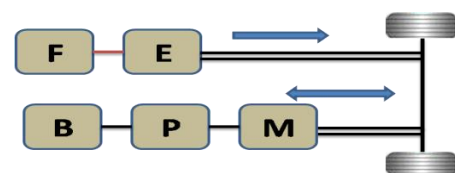


Fig. 2 PHEV Powertrain architecture

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where

B: Battery

E: ICE

F: Fuel tank

G: Generator

M: Motor

P: Power converter

— Electrical link
— Hydraulic link
— Mechanical link

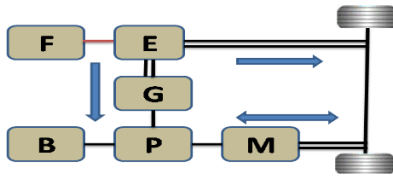


Fig. 3 SPHEV powertrain architecture

B. Parallel Architecture

The block representation of a PHEV powertrain configuration, given in Fig. 2, the ICE powertrain is coupled to an electrical powertrain by using a clutch system which allows the vehicle to be driven by electric motor or ICE separately or by both powertrain together. PHEV drivetrain consists of two independent drivetrains mechanical type and an electrical drivetrain, whose power are combined through a three-way mechanical device. Energy storage batteries provides the power demanded by an electric traction motor to drive the wheels of the vehicle. this architecture required only one electrical machine. The peak power demand for an electric motor is lower than that in SHEV since both ICE and an electric motor and provides the propulsion power to the vehicle. in this architecture the generated ICE power is directly transferred to the wheels of vehicle, which makes PHEV more efficient from other vehicles which has the two stage energy conversion.

C. Series – Parallel Architecture

Series-Parallel HEV (SPHEV) powertrain is shown in fig.3. This configuration includes the features of both the series and parallel HEVs. Electric motor, generator, ICE, and the wheels of the vehicle drivetrain can be joined together through one or multiple planetary gear sets or other

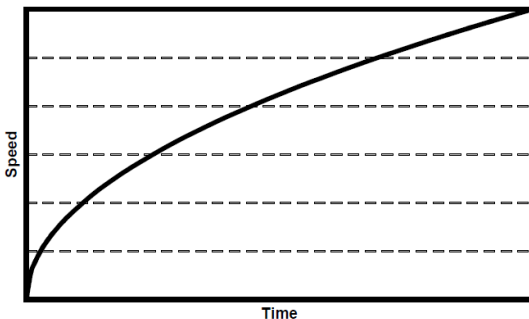


Fig. 4 Relationship between Vehicle speed and time during acceleration.

devices. In this configuration an additional electric machine is needed, the control of this configuration is complex due to planetary gear.

III VEHICLE SPECIFICATION

A HEVs consists of electric motor and storage battery which are power plant and power source of the vehicle. The motor and storage battery power must be large to satisfy the

power requirement of the vehicle during each driving schedule. Otherwise, the vehicle cannot fulfill the power demand by the driving schedule. HEVs are developed to match the performance criteria so that it can compete with IC Engine vehicles. The HEV should be designed in such a way that it is capable to avoid at least 5% possible grade at a normal speed. The first and most important conditions is the time needed to accelerate the vehicle from zero to 60 km/h range. The method described here calculates the demand of power for acceleration of the vehicle on a flat road and settle a grade angle θ at a regular speed. There is an assumption that the air density does not change, and HEV must not accelerate from speed zero to maximum up a hill. The hybrid electric vehicle having a mass M_{veh} and it constitutes 0° gradeability i.e. flat road require power P_{acc} described by the following equation: -

$$P_{acc} = M_{veh}V \frac{dv}{dt} + \frac{1}{2}\rho AC_d V^3 + M_{veh}gVC_{ro} \quad (1)$$

where,

V = Vehicle speed,

ρ = Air density,

A = Vehicle frontal area,

C_d = Coefficient of aerodynamic drag,

g = Gravity, and

C_{ro} = Coefficient of rolling resistance

The resultant power at the wheels is given in the equation 1. The acceleration power must be determined so that sizing of drive train components is possible for analyzing the losses at different levels. If the vehicle starts accelerating from zero to maximum speed V_{max} , the equation 1 can be written as integrating the first term and taking the limit from zero to maximum speed V_{max} to fulfil the conditions of acceleration power requirements of the vehicle.

$$P_a = \frac{M_v}{t_{max}} \left\{ \frac{1}{2} V_{max}^2 + C_{ro}g \int_0^{t_{max}} V dt \right\} + \frac{\rho AC_d}{2t_{max}} \int_0^{t_{max}} V^3 dt \quad (2)$$

Where, t_{max} denotes the time required to reach the vehicle to the maximum speed. In equation 2 the speed V describes the function of time t which contribute to provides smooth speed, acceleration, and time relationship and the plot is shown in Fig. 4. It is assumed that relationship between speed of the vehicle and time exhibits the hyperbolic function which is being approximated by speed variable V shown in Fig. 4 and given by

$$V = V_m \left(\frac{t}{t_m} \right)^x \quad (3)$$

The exponent x has the value of 0.5-0.66 for zero to speed 60 mph. We can determine the acceleration requirement of the vehicle by using two methods, first by integrating the equation 2 after integrating Equation 2 it consists of two terms. The first term expresses the power require to move the vehicle of certain mass and the average power obtained by the vehicle to overcome the air resistance is given by the second term and the second method by determining the equation of power between the time interval of t_{max} and $t_{max}+0.1$. The first method is used to determine the average value for the acceleration power.

Table I Physical parameters of test vehicle

Vehicle physical specifications	Value
Frontal area (m ²)	2
Coefficient of drag	0.33
Wheelbase(m)	2.6
Air Density	1.2
Vehicle Mass	
Weight of conventional vehicle(kg)	1140
Weight of Series hybrid electric vehicle(kg)	1219
Weight of Parallel hybrid electric vehicle(kg)	1248
Cargo Weight(kg)	136

Table II SHEV Drivetrain component Parameter

Parameter	Value
Fuel Converter	
Max. torque	60 Nm
Max. Power	41 kW
Peak Efficiency	34%
Converter Mass	131 kg
Motor Controller	
Peak Torque	85 Nm (0 – 2200 rpm)
Continuous Power	25 kW (2200 – 6000 rpm)
Peak Efficiency	92%
Motor Controller Mass	30 kg
Generator	
Max. power	30 kW
Peak Efficiency	95%
Mass	35
Storage Battery (Nickel – Metal Hydride)	
Capacity	28 Ah
Mass	108 kg

The acceleration power P_{acc} can be written as follows:

$$P_{acc} = a_0 M_v + b_0 \quad (4)$$

Where

$$a_0 = \frac{V_{max}^2}{2t_{max}} + \frac{C_{ro} g}{t_{max}} \int_0^{t_{max}} V dt = \frac{V_{max}^2}{2t_{max}} + \frac{1}{1+x} C_r g V_{max} \quad (5)$$

And

$$b_0 = \frac{\rho A C_d}{2t_{max}} \int_0^{t_{max}} V^3 dt = \frac{1}{2(1+x)} \rho A C_d V_{max}^3 \quad (6)$$

The acceleration power given by equation 4 have two components, one component is linear to mass of the vehicle and other is a constant which depends on the design of the vehicle. The constant a_0 depends upon the rolling resistance and acceleration. The constant b_0 is a function that depends upon frontal area and drag coefficient which exhibits the power requirement to overcome the force of aerodynamic drag.

Grade-climbing power (P_{gr}) essential for avoiding a grade at a constant speed V_{gr} is stated in equation 7

$$P_{gr} = \frac{1}{2} \rho A C_d V_{gr}^3 + M_v g V_{gr} \sin \theta + M_v g V_{gr} C_{ro} \cos \theta \quad (7)$$

Where θ is the grade angle. This equation can be written as

$$P_{gr} = a_1 M_v + b_1 \quad (8)$$

Where

$$a_1 = g V_{gr} (\sin \theta + C_{ro} \cos \theta) \quad (9)$$

And

$$b_1 = \frac{1}{2} \rho A C_d V_{gr}^3 \quad (10)$$

The above equation 8 consists of two parts, one which is linear to the vehicle mass and the other is a constant which depends on the design of the vehicle. The term a_1 denotes the action of rolling resistance and grade specifications on the vehicle while negotiating the grade, the term b_1 denotes the power necessary to overcome aerodynamic drag due to wind. For the performance analysis a small car type vehicle is selected in this paper. The main dimensions and the weight of the small car chassis are mentioned and few changes are made for the simulation purpose based on the current available small car vehicle in the developing country. The physical parameters of the tested gasoline powered ICE vehicle along with the SHEV and PHEV weight are specified in table I. The table II summaries SHEV drivetrain parameters which has used for test purpose. Nickel – Metal Hydride batteries are used as energy storing devices. Table III contains the test drivetrain parameter of PHEV.

Table III PHEV Drivetrain Component Parameter

Parameter	Value
Fuel Converter	
Max. torque	60 N m
Max. Power	41 kW
Peak Efficiency	34%
Converter Mass	131 kg
Motor Controller	
Peak Torque	85 Nm (0 – 2200 rpm)
Continuous Power	25 kW (2200 – 6000 rpm)
Peak Efficiency	92%
Motor Controller Mass	30 kg
Storage Battery (Nickel – Metal Hydride)	
Capacity	28 Ah
Mass	108 kg

A. Driving Cycle Schedule

An engine operation schedule or specified vehicle drives of varying speeds and loads which represents real driving pattern of the vehicle and engines on road. The test schedule of vehicle operation is known as driving cycle. In this paper

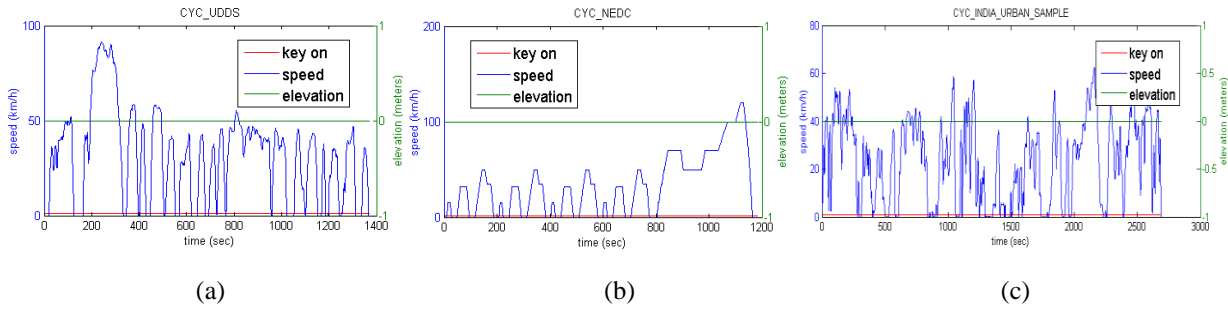


Fig. 5 different driving cycle (a) CYC_UDDS , (b) CYC_NEDC and (c) CYC_INDIA_URBAN

for test purpose of small car vehicle three driving schedule are selected namely CYC_UDDS, CYC_NEDC and CYC_INDIA_URBAN. The vehicle performance in each driving cycle and the overall efficiency of the test vehicle will be compared which are directly affected by the driving schedule. The Urban Dynamometer Driving Schedule (UDDS), constitutes the first two cycles of the Federal Test Procedure (FTP-75) driving schedule which reflects the city driving conditions where start and stops are more frequent. The New European Driving cycle (NEDC) which is used for the light duty vehicles in European countries. Fig. 5 shows the driving cycle used for the performance analysis of the test vehicle. Table IV shows different parameters and the stages of the driving schedule.

Table IV driving schedule parameters

Driving Cycle	CYC_UDDS	CYC_NEDC	CYC_INDIA_URBAN
Distance(km)	11.99	10.93	17.49
Max. Speed(km/h)	91.25	120	62.56
Avg. Speed(km/h)	31.51	33.21	23.41
Max. Acceleration(m/s ²)	1.48	1.06	1.73
No. of Stops	17	13	52
Idle time(s)	259	298	267
Time(s)	1369	1184	2689

IV. PERFORMANCE ANALYSIS AND RESULT

The performance analysis of the ICE, SHEV and PHEV is presented in this section. The electric motor-converter efficiency map, generated by using the three driving schedule which vary according to driving conditions which

includes start and stops, for two test vehicles namely SHEV and PHEV are presented and compared. In addition, the efficiency of the ICE is compared with that of the electric motor-converter, to form the source for complete efficiency analysis. Fig. 6-10 depict the electric motor-converter operating points and engine efficiency maps for CYC_UDDS, CYC_NEDC and CYC_URBAN_INDIA, respectively. The performance analysis of electric motor (EM) used in SHEV's for CYC_UDDS driving schedule is depicted in Fig. 6 the torque output must satisfy the ICE working range to deliver its torque demanded by the vehicle. The maximum torque demanded by the vehicle to meet the CYC_UDDS driving schedule is around 100kN at a speed of 2000 rpm. As the speed increases the torque demand decreases around 4000 rpm 56kN. The rated torque is 85kN at speed of 2200 rpm and the power is 25kW and this electric motor satisfy the demand of the CYC_UDDS driving schedule as the number of stops in this schedule is 17 so the vehicle has a wide range of speed and torque profile.

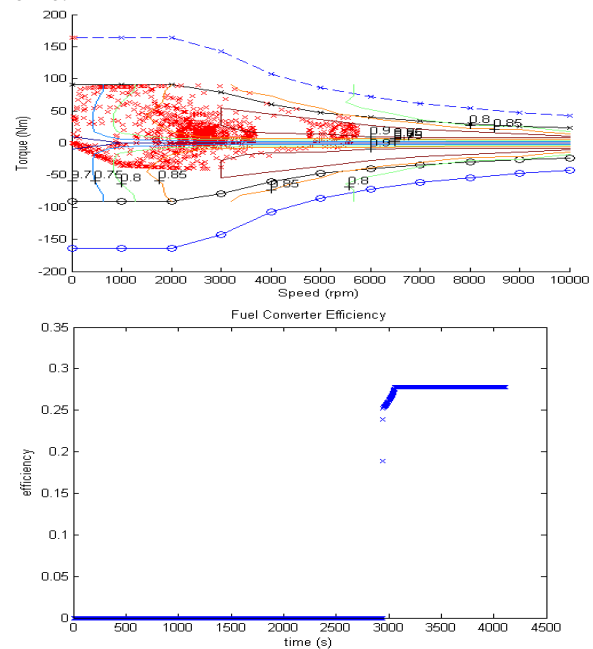


Fig. 6 Speed torque profile of traction motor-converter showing operating points in SHEV and ICE efficiency map for the CYC_UDDS driving schedule.

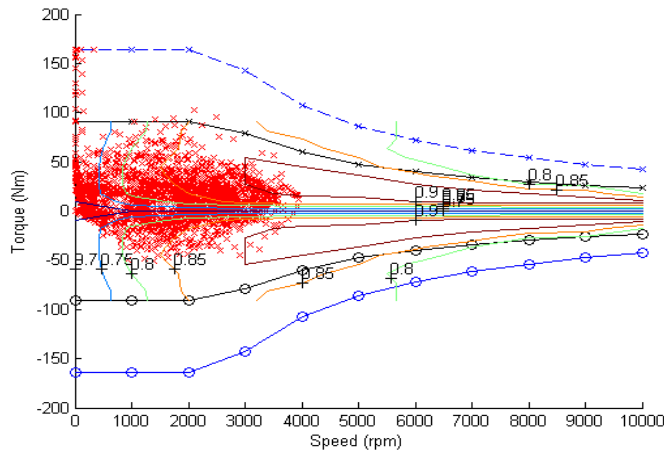


Fig. 7 Speed torque profile of EM used in SHEV during CYC_INDIA_URBAN driving schedule

The performance analysis of electric motor EM used in SHEV's for CYC_INDIA_URBAN driving schedule is depicted in Fig. 7 here also the torque output must fulfill the demand of ICE working range to deliver its torque demanded by the vehicle. As the number of stops is more around 52 the vehicle does not undergo in free run instead it has frequent acceleration and retardation the whole operation of EM lies in the speed range of 0 – 4000 rpm and the maximum torque demanded by the EM is around 45kN at 2000 rpm. EM fulfills the speed torque characteristics as demanded by the driving schedule.

The performance analysis of EM used in PHEV's for CYC_UDDS, CYC_NEDC and CYC_URBAN_INDIA driving schedules is depicted in Fig. 8-10 the torque output must satisfy the ICE working range to deliver its torque demanded by the vehicle.

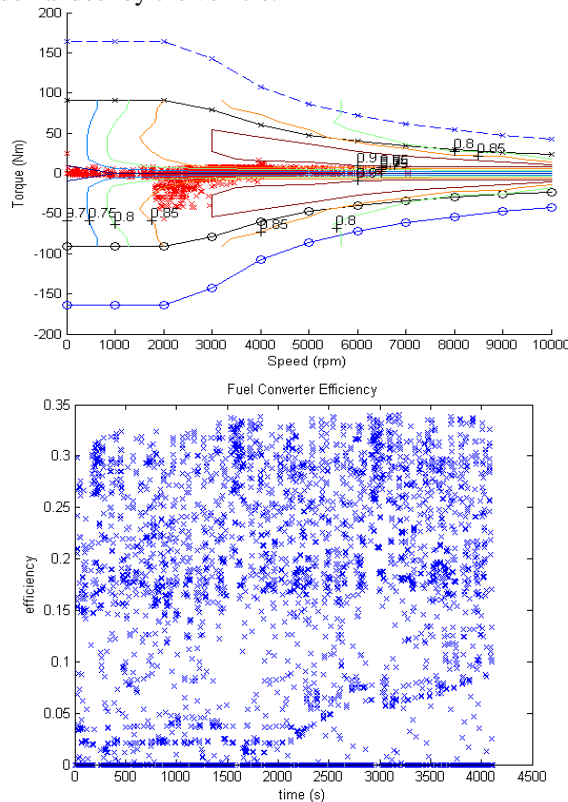


Fig. 8 Speed torque profile of traction motor-converter showing operating points in PHEV and ICE efficiency map for the CYC_UDDS driving schedule.

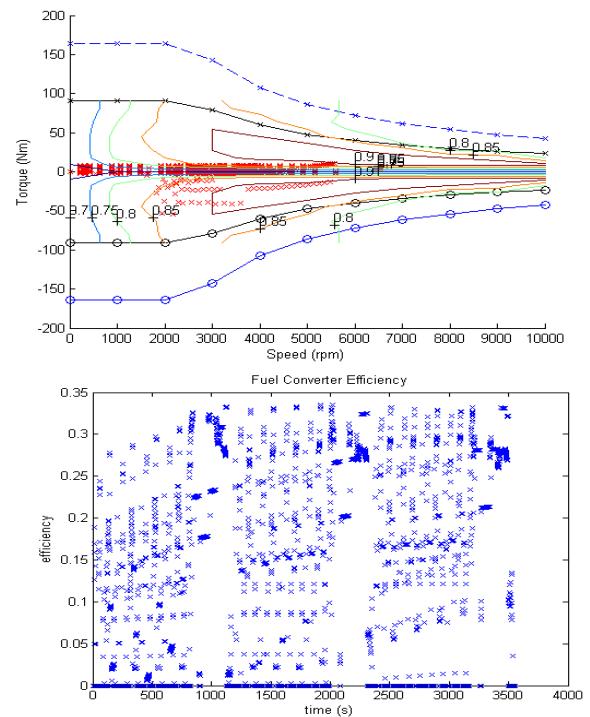


Fig. 9 Speed torque profile of traction motor-converter showing operating points in PHEV and ICE efficiency map for the CYC_NEDC driving schedule.

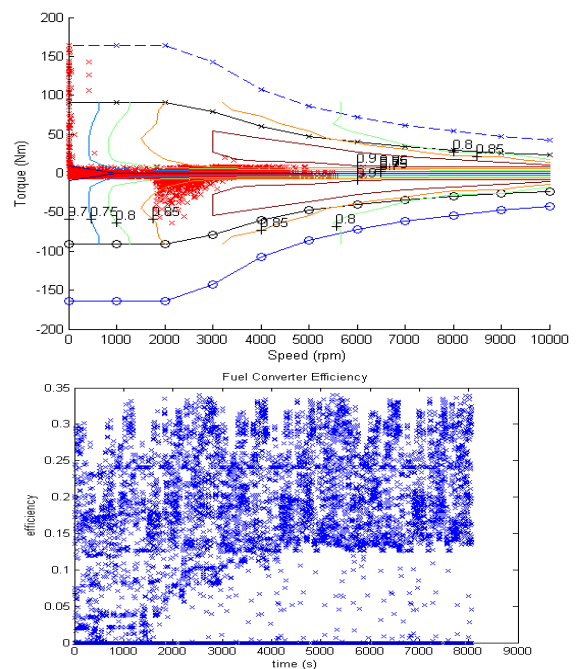


Fig. 10 Speed torque profile of traction motor-converter showing operating points in PHEV and ICE efficiency map for the CYC_URBAN_INDIA driving schedule.

The paper presents a comprehensive analysis of the effects of different driving schedule on the HEV efficiency, some other analysis was carried out to monitor the vehicle emissions, acceleration, and gradability performance. This paper mainly focuses on the acceleration performance of the CYC_URBAN_INDIA

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in the test car. Table V summarizes the vehicle acceleration performance in this time taken for the acceleration of 0-120 km/h is 12.8 second for PHEV. The performance evaluation according to different parameters is depicted in table VI.

Table V Vehicle acceleration Performance comparison for CYC_INDIA_URBAN

Vehicle	Acceleration performance(s)			Gradability at 88.5 km/h(%)
	0 – 60 km/h	40 – 100 km/h	0 – 120 km/h	
Conventional Vehicle (Gasoline)	9.7	17.6	34.7	7.4
Series hybrid vehicle	6.4	11.4	23.2	4.9
Parallel hybrid vehicle	4	6.7	12.8	22.4

Table VI Performance evaluation of each vehicles for different parameters in CYC_INDIA_URBAN driving schedule.

Vehicle Performance Parameter	Conventional Vehicle (Gasoline)	Series hybrid vehicle	Parallel hybrid vehicle
Max. Acceleration(m/s ²)	2.3	2.9	5
Distance in 6s (m)	35.5	50.8	76.7
Time in 0.5 km(s)	26.7	23.1	19
Max. Speed(km/h)	152.8	157.8	183.3

Vehicle emissions or Green House Gas (GHG) emissions in (gram/km) over different driving schedule is given in Fig. 11-12. The GHG emission of PHEV is very less as compared to SHEV and ICE vehicles.

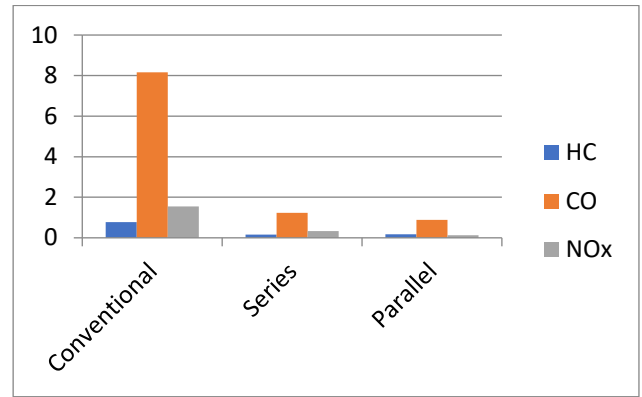
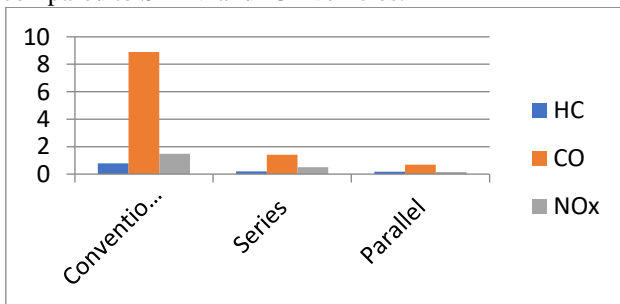


Fig. 11 GHG emissions in (gram/km) during CYC_UDDS and CYC_NEDC driving schedule.

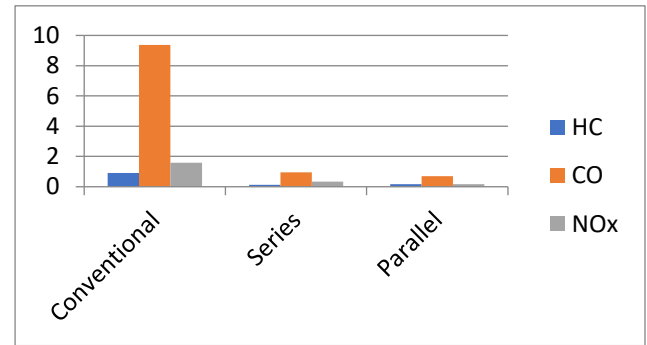


Fig. 12 GHG emissions in (gram/km) during driving schedule CYC_URBAN_INDIA

V. CONCLUSION

This paper studied the performance of small car that includes gasoline-based ICE vehicle, SHEV and PHEV. The different driving schedule have significant effects on the electric motor- converter efficiency and vehicle performance. In this paper, more emphasis is given to PHEV under CYC_INDIA_URBAN. The simulation results presented above gives acceleration and gradability performance of the vehicle, from the above results the PHEV has better performance over SHEV and conventional vehicle. The overall HEV efficiency by studying the EM operating points and ICE efficiency plots while using the PHEV drive train configuration, the overall emissions of GHG in PHEV configuration is also minimized as compared to another configuration. The overall efficiency of the drive train is low due to inefficient use of the ICE. Since all the other countries in world are more focused towards implementing environmental protection to sustain the green earth the developing countries like India should also contribute towards vehicle emissions, the minimization of vehicle emission is of paramount importance using advanced semiconductor devices improved switching techniques, efficient converter topologies and using green energy, will help to minimize HEV losses. With improvement in energy storage devices(batteries) or development of fuel cell it would be further possible to improve HEV design levels,



which will offer more flexibility to use efficient HEVs control methods, to attain higher electric drive train performance as well as motor – converter efficiencies for sustainable transport system.

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