Dynamic performance analysis of front-wheel drive hybrid electric vehicle architectures under different real-time operating conditions

B. Raja Siddharth, D. John Pradeep and
Y.V. Pavan Kumar*

School of Electronics Engineering,
VIT-AP University,
Amaravati-522237, Andhra Pradesh, India
Email: siddharth.18bec7098@vitap.ac.in
Email: john.darsy@vitap.ac.in
Email: pavankumar.yv@vitap.ac.in
*Corresponding author

Ch. Pradeep Reddy

School of Computer Science and Engineering,
VIT-AP University,
Amaravati-522237, Andhra Pradesh, India
Email: pradeep.ch@vitap.ac.in

Aymen Flah

Energy Processes Environment and Electrical Systems Unit,
National Engineering School of Gabes,
University of Gabes, Tunisia
Email: flahaymen@outlook.fr

Abstract: Hybrid electric vehicle technology (HEVT) is emerging as a reliable alternative to lessen the limitations of pure electric vehicles. HEVT uses an electric motor as well as an internal combustion engine, which uses battery power and fossil fuels respectively for vehicle mobility. HEVT shifts vehicle power from fuel-to-battery, battery-to-fuel, or both based on user requirements, terrain conditions, etc. The HEVT can be realised by four architectures, which commonly use front-wheel-based two-wheel-drive systems due to their simple architecture and less-cost when compared to rear-wheel drive systems. For finding an effective architecture under dynamic operating conditions (continuous, pulse-type, and step-up type accelerations), a comprehensive analysis of all architectures is presented in this paper by testing various functionalities, viz., speed (vehicle, engine, motor), power (engine, battery), battery electrical losses, charge patterns, and fuel consumption. The modelling/simulation is done in Simulink and various recommendations are proposed using these comparative results.

Keywords: hybrid electric vehicle; HEV; HEV architectures; powertrain; vehicle operation and control; front-wheel drive; FWD; dynamic performance.

Reference to this paper should be made as follows: Siddharth, B.R., Pradeep, D.J., Kumar, Y.V.P., Reddy, C.P. and Flah, A. (2022) ‘Dynamic performance analysis of front-wheel drive hybrid electric vehicle architectures under different real-time operating conditions’, *Int. J. Powertrains*, Vol. 11, No. 1, pp.62–89.

Biographical notes: B. Raja Siddharth is pursuing his BTech in Electronics and Communication Engineering at the School of Electronics Engineering, VIT-AP University, Amaravati, Andhra Pradesh, India. His research areas include hybrid electric vehicles, power converters, and control systems.

D. John Pradeep received his Bachelor’s in Electronics and Communication Engineering from the JNTU Anantapur in 2005, Master’s in Signal Processing from the IIT Guwahati in 2009 and PhD in Electronics and Communication Engineering in the field of intelligent controls from the VIT, Vellore in 2020. He has an overall experience of 14 years as a teacher. Currently, he is working as an Associate Professor in the School of Electronics Engineering at VIT-AP University, Amaravati, Andhra Pradesh, India. He has authored several research papers for national and international reputed publishers. His research areas include communication technology, machine learning, nonlinear control, electric vehicle technology and signal processing.

Y.V. Pavan Kumar received his PhD in 2018 in Electrical Engineering from the IIT Hyderabad, India, MTech in 2011 in Instrumentation and Control Systems from the JNTUK University, India, and BTech in 2007 in Electrical and Electronics Engineering from the JNTUH University, India. He has 10+ years of experience including both industry and academia. Currently, he is working as an Associate Professor in School of Electronics Engineering at the VIT-AP University, Amaravati, Andhra Pradesh, India. His research areas include microgrids, smart grids, self-healing grids, hybrid electric vehicles, and power converters. He has authored 120 papers for reputed journal/conferences, 18 patents, and three books.

Ch. Pradeep Reddy is currently working as a Professor of Computer Science and Engineering, VIT-AP University, Amaravati, India. He has 14+ years of experience in both teaching and research. He received his BTech in 2004 in Computer Science and Engineering from the PBRVITS, JNTU, Andhra Pradesh, India, MTech in 2007 in Computer Science and Engineering and PhD in 2014 in Computer Science and Engineering both from the VIT University, Vellore, India. His research interests include IoT, sensor networks, wireless systems, and open source technologies. He has guided five research scholars towards their PhD and four more scholars are working with him currently.

Aymen Flah received his PhD in 2012 from the National School of Engineering of Gabes, specialising in Electrical Engineering. He is currently working as an Assistant Professor of Electrical Engineering. His courses are power systems, power converters and motor control which are given at the National School of Engineering of Gabes. He is selected as an associate editor and reviewer in more than 30 high indexed journals. He is an active member in the research unit of photovoltaic, wind and geothermal. His research field is related to electric vehicle, motor control, smart applications, and others.

1 Introduction

Vehicles are run on fossil fuels that are at a rapidly depleting trend all over the world. Internal combustion engines (ICE) dominated the vehicular technology and are used for the mobility of the masses and material for almost a century. Due to continuous innovations and refinement, the technology used in ICE's has almost reached its steady state (Siddharth et al., 2020). Today, there is a shift observed in the technology used in vehicles, from ICE's to electrical motors (EM), due to the reasons such as cost, demand, pollution, and efficiency. There are no known innovations of today that can cut the emanations of carbon dioxide from the ignition, however, the total power that is delivered is basically reliant on the fuel that is utilised.

1.1 Rationale of hybrid electric vehicles

Electric vehicle (EV) has EMs, which are driven by batteries, so this technology aims at zero pollution levels as suggested by Magnussen (2004). EV's are the future for the transport industry thereby reducing the usage of fossil fuels. Presently, EV infrastructure demands high initial investments which may be a problem, and this gives rise to a transitionary technology that avoids the high initial establishment cost of EV technology. Hydrogen fuel cell-based EVs (Chan et al., 2009; Chowdhury et al., 2016), super capacitor-based EVs, and flywheel-based EVs are alternate forms of EVs that suffer from the same problems as that of EVs, if not, with additional drawbacks and constraints. Hybrid electric vehicle (HEV) technology is an intermediator between EV and ICE technologies, which involves a reasonable investment cost when compared to EV technology (Frieske et al., 2013; Boschert, 2006; Zhou et al., 2014). HEV is fit to utilise two power sources, viz., an essential power source and an optional power source, which equips the vehicle to have the benefits of ICE and EM drives (Eshani et al., 2005). HEVs reduce dependency on fossil fuels and decrease the pollution and emissions created by ordinary fuel-based vehicles. Further, better fuel economy can be realised with the functions, viz., regenerative braking, idle start-stop, etc.

1.2 Challenges in HEVs implementation

There are many challenges that have to be addressed while designing the HEVs. The key challenges are:

1.2.1 Storage of electrical energy

The level of hybridisation in HEV is dependent on the capability of the EM used in the vehicle. If the EM used is of large power, then the HEV is predominantly battery-driven, and if the capacity of the EM is smaller, then it is ICE driven. The use of supercapacitors or batteries to store energy is limited by the size and weight of the units used. To increase the energy storage capacity of the battery, research should be directed towards developing lightweight, high energy density, and cheaper batteries. The larger the EM, the bigger is the requirement of the battery bank. Besides, supercapacitors are used to give the required boost to the engine, which increases the cost of the HEV (Emadi et al., 2005).

1.2.2 Power performance management

A HEV comprise of more than one type of sources of energy. So a power management system helps in monitoring power quality, power transfer to the EM, battery charging during regenerative braking and optimal utilisation of the power converters (Assadian, 2010). Control algorithms that can effectively perform the power measurement, management, and disbursal of power to different components of the HEV are of interest (Zheng, 2011; Reddy et al., 2012, Kumar and Bhimasingu, 2015). Recently, machine learning-based intelligent algorithms are developed for the proper power related administration.

1.2.3 Architectural challenges

Available HEV architectures use a combination of ICE and EM along with two types of electric energy sources – batteries and supercapacitors. The components of HEV such as, alternator, battery packs, bidirectional power converter, transmissions and drive trains are essential for power generation and vehicular movement (Zia, 2016). Seamless interchanging between the mechanical and electrical power to provide vehicular movement is very important and at the same time very tedious. The way in which ICE and electric motor are integrated has given rise to different architectures which are complex. Traditionally developed architectures are series, parallel, and hybrid architectures. The main challenge faced is related to the scaling of HEV for different applications and uses. In present work, a comparative assessment of different HEV configurations when subjected to different accelerating conditions is done and presented.

1.2.4 Electric component design and development

HEV uses electric components such as bi-directional power converters, electric motors, control and instrument related equipment. Developing EMs should consider parameters such as speed, torque, rpm and should be mechanically sturdy and rugged. Improvement of efficiency of the motor is also a point to be considered when developing motors. Similarly, the development of efficient power converters with higher power ratings and lower switching losses are of interest (Kumar and Ravikumar, 2016). In addition, the development of cost-effective and efficient charging infrastructure for HEVs is also of paramount importance.

1.3 Literature review on HEV architectures

Basically, there are four HEV architectures given in literature based on how the energy of ICE and EM are coupled and used to drive vehicles. Different literature described below have considered these architectures and implemented various strategies for a successful HEV design. The study on hybrid vehicles has shown that the combination of the powers of engine and battery sources in various ways lead to design of different types of HEVs. The performance of the hybrid architectures usually depends on the components present in it, like energy storage source (battery), converters (DC-DC bi-directional), electric motor, etc. The four HEV models of interest are series HEV, parallel HEV, series-parallel HEV and complex HEV. A review of these four types of architectures is given in Section 2.

Apart from the types of HEVs mentioned above, another type of HEV's, of interest are photovoltaic HEV's (PVHEV) and plug-in hybrid system (PHEV) which uses solar power to charge the batteries. For any type of HEV, the energy storage system plays a major role because, the larger the storage capacity, the better is the vehicle's performance (Singh et al., 2019). Besides, it has been stated that the EV and PHEVs charging architectures are available into two categories: on-board (semi-fast or slow charging with AC connectivity) and off-board (speed charging with DC connectivity) as the battery storage unit is one of the most critical parts in a PHEV with characteristics of a battery charger like charging time and lifetime is strongly considered because they can run over a long-range due to high capacity batteries (Rivera et al., 2017). In the HEV architectures, to satisfy the high power demands, the battery behaviour is considered as a key factor, mainly depends on the energy storage system (ESS) of the vehicle. The management scheme of the ESS in the hybrid vehicle is pivotal in maintaining an energy-efficient powertrain that can handle the battery state of charge conservation, fuel economy, and drivability. The strategy which was developed to manage the energy is called energy management strategy (EMS), which plays a crucial role in EVs, PHEVs, and HEV's architecture. The EMS involve a broad spectrum of optimisation techniques and various algorithms, which attracts HEV research community (Mocera et al., 2019; Tran et al., 2020).

Fuel cell vehicles (FCV) energy management by proton exchange membrane (PEM) to use the unsought thermal energy produced during the operating condition is another direction in which research is directed. In FCV, PEM increases the efficiency by generating/storing the hydrogen for later use. FCV uses fuel cells to generate power from air and hydrogen, with water vapour as by-product. This electric energy can be stored or used to operate the vehicle (Gong et al., 2020). In FCV's the energy storage systems are hydrogen tank, battery, or supercapacitor while in HEV the hydrogen tank is replaced by the fossil fuel tank as FCV runs entirely on electricity. The EMS helps to optimise and control the energy sources with high efficiency and also improves the dynamic performance of the vehicle (Trovao et al., 2014). A real-time control strategy was developed for fuel cell HEVs with an objective of controlling and reducing the number of hydrogen consumptions in FCEV by using a power-sharing scheme between energy buffer and the fuel cell system. The real-time-based control scheme was realised from a non-causal optimisation-based approach using optimal control concepts (Bernard et al., 2010).

1.4 Literature review on HEV components

A brief discussion on research in realm of HEV powertrains, drivetrains and two-wheel drive systems is given in this section. The general hybrid technology is developed to utilise two power sources which are supplied to the powertrain for propulsion.

An algorithm was to choose one among electric motor and ICE to minimise fuel consumption in a HEV architecture and the results achieved 17.5% of fuel reduction when CEN standard speed cycle was used as input (Paganelli et al., 2002). It proved that the CAE tool permits complex visualisation and optimisation routines to be used with extra effort on power trains (Guzzella and Amstutz, 1999). It is shown that when simulation tools are combined with analytical approaches, gives a good understanding of developing power efficient hybrid powertrains.

A series HEV powertrain is capable of handling only lower fuel efficiencies (Katrasnik et al., 2007). Parallel hybrid electric powertrain promises better fuel economy over series HEV powertrain because of the short energy converted form. It is also observed that a drive cycle can significantly influence the fuel economy in series and parallel hybrid powertrains. Parallel hybrid powertrains also perform well with low average load with respect to the test cycles. A mild hybrid, which has a parallel hybrid drive train comprising of induction motor and the permanent magnet synchronous motor was reported which gave satisfactory results for load wise usage (de Jager et al., 2008).

A dynamic programming approach to solve the optimal power split between the electric motors and IC engine in parallel hybrid powertrains, which provided a good approximation of the optimal control trajectory (Johannesson and Egardt, 2008, Bucherl et al., 2008). A sub-optimal control strategy was developed to create EMS for the HEVT for heavy vehicles, which showed a considerable reduction in fuel consumptions (Rizzoni et al., 1999). A triple-planetary-gear powertrain is suitable for SUVs, pick-up trucks or buses are reported in Zhuang et al. (2016). Energy and power flow-based design of drive trains to derive a framework for the design, analysis, and control of optimum HEVs was reported in Lajunen et al. (2018).

The electric traction force is one of the important in vehicle performance which gives higher energy utilisation efficiency, and lower polluting emissions. Temperature also plays an important role in the working and efficiency of a HEV. An effective way of temperature management in the powertrains of hybrid versions is discussed in Lenzo et al. (2018). An emphasis on the traction force of the powertrain is important to meet power demands and also in the functioning of a permanent magnet synchronous machine (PMSM) with short power range (Ehasani et al., 2007). In powertrain design schemes designed for four-wheel-drive HEV torque distribution requirement are presented in Zhou et al. (2018).

In research related to HEVs, vehicle control and energy management of powertrain are of huge interest. The management and control of the powertrain is based on the power demand arising from vehicle control requirement, which restricts fuel saving. So a flexible power demand architecture to provide a better fuel economy is proposed in Ghasemi and Song (2018). Further, the generic model and mathematical information of the HEV powertrain is integrated to automatically generate algorithms for various powertrain architectures in view of control and power management is provided by Zhou et al. (2020).

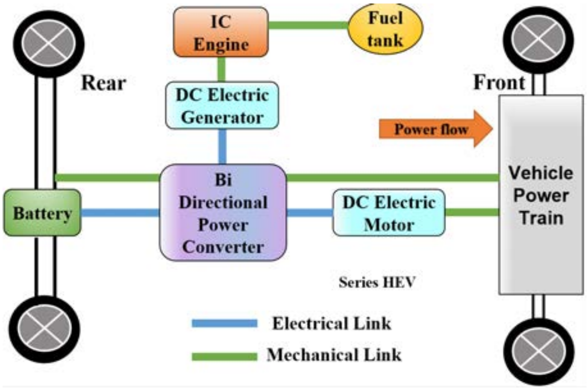
- From the above mentioned state-of-the-art literature, it is understood that most of the researchers focus on optimisation of fuel, power and other parameters in a HEV operation. Further, dynamic behavioural analysis on all the architectures, which gives real insight into the performance of HEVs is not conducted so far.
- With this intent, this paper provides an extensive performance analysis of four types of HEV architectures which use FWD system, to propel the vehicle

subjected to various dynamic operating conditions, as mentioned in Section 3. Further, from the comparative analysis, a suggestion on how to choose an architecture based on desired outcomes, is presented.

2 HEV architectures, components and operation

Traditionally, there are several hybrid architectures in which ICE and EM are integrated. They are series, parallel, series-parallel and the complex hybrid architectures, which have their own merits and limitations and thus are under constant development. In the four main architectures of hybrid technology, the simplest architecture is the series hybrid vehicle whose schematic is shown in Figure 1. The term series refers to the way components are connected to the propulsion of the vehicle. The electrical power and mechanical power are coupled to the powertrain in series, to provide power flow to front wheels. The second architecture is the parallel hybrid whose schematic is shown in Figure 2. The term parallel is used to indicate that all the components are connected in a parallel to propel the vehicle. The electrical power and mechanical power is provided in a parallel way to the powertrain and the power flow is driven into the front wheels. In the parallel hybrid vehicle, there is a coordinated control between motor and ICE when they are working simultaneously. This demands for an energy-oriented torque in parallel hybrid vehicle. Further, an input allocator is required for parallel HEV to achieve best fuel economy and drivability (Cordiner et al., 2014). The dynamic performance of the parallel hybrid vehicle was inspected majorly in the view of stability and suspension is discussed in Yamin et al. (2016).

Figure 1 Series HEV architecture model (see online version for colours)



The third architecture is the series-parallel hybrid vehicle which is shown in Figure 3. The term series-parallel is used to indicate the way all the components are connected to the propulsion of the vehicle. The electrical power and mechanical power are both coupled to the power train in a series as well as in a parallel way via a planetary gearbox, with power flow into the front wheels. In series-parallel hybrids, model-based control rule was proposed to coordinate engine, motor, and clutch torques, to have reduced vehicle jerks, low torque interruptions, and small friction loss when compared to the ordinary vehicle (Chen et al., 2012).

The fourth architecture is the complex hybrid vehicle which is shown in Figure 4. In this architecture, the electrical and mechanical power is fed to the power train both in series and parallel mechanism ensuring that power flow is driven into the front wheels. All these hybrids are developed and are designed to propel FWD vehicles. The torque distribution among the drivetrains in FWDs is discussed in detail in Zhaoj et al. (2016). Battery management plays an important role in working of HEV. It is observed that the state of charge, injecting currents, and the other constraints of the battery when managed properly, increase the effectiveness of power management in a HEV (Zhu et al., 2020).

Figure 2 Parallel HEV architecture model (see online version for colours)

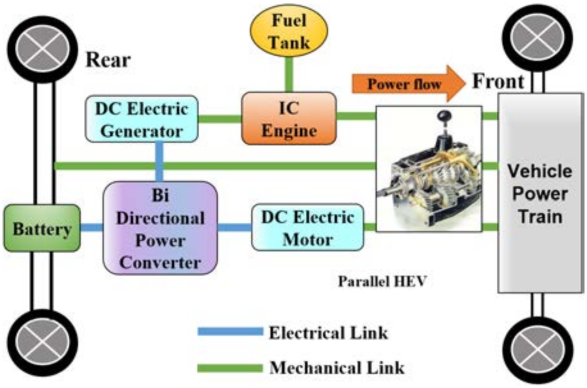
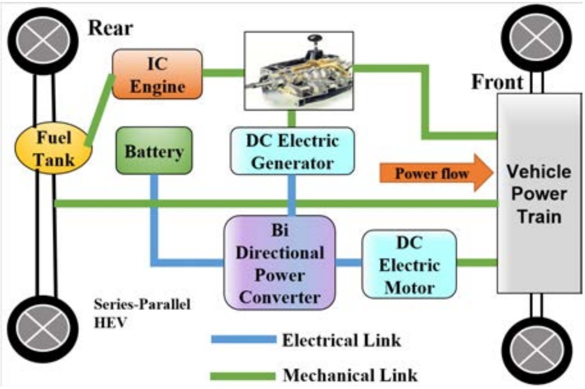


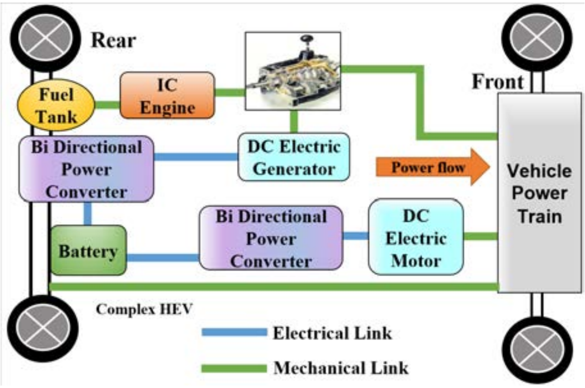
Figure 3 Series-parallel HEV architecture model (see online version for colours)



2.1 *Introduction to power train in vehicles*

A powertrain is a platform that comprise of power generating and distributing components in any vehicle. In a HEV, it comprises of motor, ICE, differentials, transmission and many other components which help in vehicle propulsion. The powertrain is also called as the power plant because it is the source which provide force to drive the vehicle forward as it contains the power generation components. The powertrain can be viewed as energy storage mechanism and the way it is coupled to driveline determine the forward or backward movement of a vehicle.

Figure 4 Complex HEV architecture model (see online version for colours)



2.2 *Introduction to drive train in vehicles*

The drivetrain in a vehicle is very important in determining how the power generated by motors/ICE is delivered to the wheels for motion. The motors and ICEs convert electrical and chemical energy into mechanical energy. The drivetrain is important in converting rotational motion into translational motion and also helps in energy distribution to the wheels through components such as driveshaft, differential, axle shafts and different types of joints. The connection is established by physically linking the components. A proper gear-ratio must be maintained to match different operating speeds of engine and wheels. During the operation, if there is any change in vehicle speed, the engine speed must remain to be idle for efficient drive. In practice, drives like front-wheel drive (FWD), four-wheel drive, all-wheel drive, six-wheel drive, 6 × 4 (drivetrain), eight-wheel drive, continuous track, and H-drive systems are developed by using various components. Basically all these drives are classified into manual transmission or automatic transmission. The manual transmission (MT) comprise of flywheel, clutch, dual mass flywheel, gearbox, propeller shaft, overdrive, rear axle, differentials, and final drive. For the automatic type, the components present are transmission, torque converter, tear axle, propeller shaft, differential, and spool. The main difference is that MT uses various gear sets attached to the drive shaft and a clutch pad whereas AT has a planetary gear system which produces different gear ratios and a torque converter.

In development of powertrains for HEVT and EVT, development of traction motors is a thrust area. Recent developments in the powertrain is focussed on the electrification of many components like providing faster charging for larger batteries by integration of torque generated by EM and ICE using powertrain and coupling to the wheels. Optimisation techniques used on parameters such as battery charge, power train management, helps in achieving good acceleration and reduced emissions (Li et al., 2015; Wu et al., 2015; Dagci et al., 2018). The powertrains with gear systems are being brought for improving fuel efficiency (Karaoglan et al., 2019; Kabriaei et al., 2015). According to Jochem et al. (2018), the best in hybrid powertrains architecture is the power-split type which provide good efficiency.

ICE or EVT driven vehicles have only one source of power driving the vehicle. But in hybrid vehicles, the drive trains are designed to transmit power to the wheels in multiple formats. In general, a hybrid vehicle may receive its energy from ICE, but capable of switching between EM and a ICE depending on power availability and requirement. Hybrid vehicles combine a battery or supercapacitor in addition to the ICE, which can be used to recharge the batteries or provide the power for vehicle movement. In parallel hybrids simultaneously the power is provided from both ICE and EM (Gaygani et al., 2016). In series hybrids, ICE is used to charge the battery whereas the power through he battery is used to propel the vehicle. So, power electronics plays an important role in HEV's performance and when clubbed with optimum gearshifts control strategy would lead to further performance enhancement (Sarlioglu et al., 2016; Jochem et al., 2018).

2.3 Two-wheel drive systems with the FWD and RWD

In four-wheel vehicles, two-wheel drive (2WD) vehicles utilise drivetrain which allows two wheels to receive power from the engine simultaneously. Similarly for all four-wheeled vehicles (and also vehicles with six, eight, or more wheels) if two wheels are powered, it is referred to as either front or rear-wheel drive. Most of the vehicles used today are two-wheel drives because to its light weight, simplicity and also the less cost when compared to other types. The two-wheel drive vehicles are basically classified as FWD and rear-wheel drive (RWD). Each one of these configurations have their own advantages and disadvantages and are used in EVs and HEVs (Kim, 2016). FWD cars are preferred by the users because of lower cost and easy installation. Some of the advantages for the FWD are simple drivetrain design, lower implementation costs, fuel economy, good traction in adverse weather conditions like rain, snow, etc. On the other hand, RWD which powers the rear wheel of the vehicle and pushes the vehicle in the direction of movement of the vehicle whereas FWD pulls the vehicle. The only advantage with RWD powered system is that it provides better handling of the vehicle in bad conditions.

2.4 System modelling and computations

A power train for any architecture in general consists of a power source (ICE or EM), clutch (to do manual transmissions) or torque converter (to do automatic transmissions), transmission box (gears) differentials, driveshaft, and wheels. The power delivered from the power source to drive shaft is transmitted directly to wheels through the user by applying torque converter or clutch, driveshaft, differentials, and gearbox. The clutch used in the manual transmissions will couple/decouple through the gearbox to the engine while the torque converter in the automatic transmissions changes the gear ratios in continuously variable format. The gears form the gear ratios from the input to the output shaft, for the engine speed-torque to match as per the load. The final drive has a pair of gears, which provides an additional speed and does the torque distribution to each wheel over the differentials. Various equations used to model the system are given below.

2.4.1 Torque and speed calculations

The torque delivered (T_{wheel}) to the wheels is calculated as per equations (1) and (2). The rotating speed of the wheels (S_{wheel}) in (rpm) is given by equation (3), total vehicle speed (S_v) in (m/s) is given by equation (4), and the traction force of the vehicle is defined by equation (5).

$$T_{wheel} = i_g i_o \eta_t T_{op} \tag{1}$$

$$T_{op} = k_1 T_{in1} + k_2 T_{in2} \tag{2}$$

$$S_{wheel} = \frac{S_{out}}{i_g i_o} \tag{3}$$

$$S_v = \frac{\pi \times S_{wheel} \times r}{30} \tag{4}$$

$$F_{traction} = \frac{T_{wheel}}{r} \tag{5}$$

where $i_g = (S_{in}/S_{out})$ is transmission gear ratio, S_{in} is input rotating speed and S_{out} is output rotating speed, i_o is final drive's gear ratio, η_t is driveline efficiency of the engine to wheels, T_{op} is output torque delivered, k_1 and k_2 are constants derived by torque coupling parameters, r is the radius of wheels.

2.4.2 Fuel calculations

Fuel calculation of the vehicle is done as the consumption of fuel per 100 km of distance travelled (litres/100 km). The fuel consumption is based on factors such as engine type, number of gears, weight, vehicle resistance, and operating settings. The ICE fuel economy is estimated as a ratio of used fuel per energy output (kWh). This is denoted as the specific fuel consumption (g_{sf}) in g/kWh. So as to calculate the fuel economy of the vehicle, specific fuel consumption and engine load power must be known. The engine load power is equal to the vehicle's resistance power as given in equation (6). With the calculation of engine power, the engine speed is calculated by equation (7). Further, a graph depicting S_{engine} versus P_{engine} is plotted to calculate the gsf to determine the time rate of fuel consumption in (l/h) as per equation (8).

$$P_{engine}\,(kW) = \frac{S_v}{\eta_t}\left(F_f + F_w + F_g + M_{vehicle}\delta\frac{dS_v}{dt}\right) \tag{6}$$

$$S_{engine} = \frac{30 \times S_v \times i_g i_o}{\pi r} \tag{7}$$

$$Q = \frac{P_{engine} \times g_{sf}}{1{,}000 \times \gamma_f} \tag{8}$$

where F_f is the frictional force (rolling friction), F_w is the force due to wind (aerodynamic drag), F_g is grading force, $M_{vehicle}$ is the vehicle mass, S_v is vehicle speed, γ_f represents the fuel's mass density in kg/l. The maximum possible power that can be delivered by the battery to the load is given by equation (9)

$$P_{max}\,(kW) = \frac{V_{op}^2}{4\left(R_c + R_{int}\right)} \tag{9}$$

where V_{op} is the operating voltage of the battery, R_{int} is the internal resistance.

2.4.3 Power calculations

The maximum possible power that can be delivered by the battery to the load is given by equation (9). The power delivered by the engine in P_1 architecture is given by equation (10) and P_2 architecture is given by equation (11). Further, the power delivered by the motors in P_3 and P_4 architectures is given by equation (12).

$$P_{engine}^{P_1} = \frac{S_v}{1{,}000\eta_{t,e}} \left(M_{vehicle} g f_r + \frac{\rho_a C_D A_f S_v^2}{2} \right) \tag{10}$$

$$P_{engine}^{P_2} = \frac{S_v}{1{,}000\eta_{t,e}} \left(M_{vehicle} g \left(f_r + 1 \right) + \frac{\rho_a C_D A_f S_v^2}{2} \right) \tag{11}$$

$$P_{motor} = P_{transmission} - P_{engine} = T_c \omega_c - P_{engine} \tag{12}$$

where V_{op} is the operating voltage of the battery, R_{int} is the internal resistance, R_c is the conductor resistance, f_r is tire rolling resistance coefficient (= 0.01), g is the gravity acceleration in 9.80 m/s^2, ρ_a is the air density (= 1.202 kg/m^3), A_f is the vehicle's front area (= 2 m^2), C_D is coefficient of the aerodynamic drag (= 0.3), η_t is the transmission efficiency, η_m is the traction motor efficiency, $\eta_{t,e}$ is the efficiency of transmission to wheels.

3 Problem statement and system implementation

The study of the performance parameters of any vehicle under dynamic acceleration (m/s^2) conditions is very essential to understand vehicle's behaviour and helps to estimate future actions for the driver to be performed. The Simulink models of all the four HEV architectures mentioned above are developed and simulated under three acceleration conditions that are commonly experienced in real-time. The Simulink models of series, parallel, series-parallel and complex HEV architecture models are given in Figures 5 to 8, respectively. Then eight different performance metrics are extracted from the simulation, which would help us to draw conclusions regarding the use of different types of HEVs under various dynamical operational conditions.

The acceleration inputs used in this study are – continuous acceleration (input 1), pulse type acceleration (input 2). And the parameters studied are vehicle speed (km/hr), shaft speeds of motor and engine (RPM), engine and battery power (kW), battery electric losses (kW), battery charge status (Ah), fuel consumed by the vehicle (lit).

The speed of the vehicle is an indication to show how effectively the given input is affecting the vehicle. The shaft speeds of motor and engine are measured to see how the speed is varied in tune with the input. The power of the ICE and battery are measured to see how effectively the vehicle handles the power balance between ICE and EM. The Battery charge is another parameter of interest as it gives information regarding the energy that is utilised and can be utilised by the vehicle on the run. Variation of charging and discharging patterns of battery corresponding to the applied inputs give an indication of how the battery is able to cope up with the sudden power requirements demanded by the driver, while the battery-electric losses show how much of power is converted for actual propulsion and how much charge is lost. Finally, fuel consumption is also monitored to see how efficiently the fuel is being consumed and what amount of fuel is being saved.

Figure 5 Simulink model of series HEV architecture (see online version for colours)

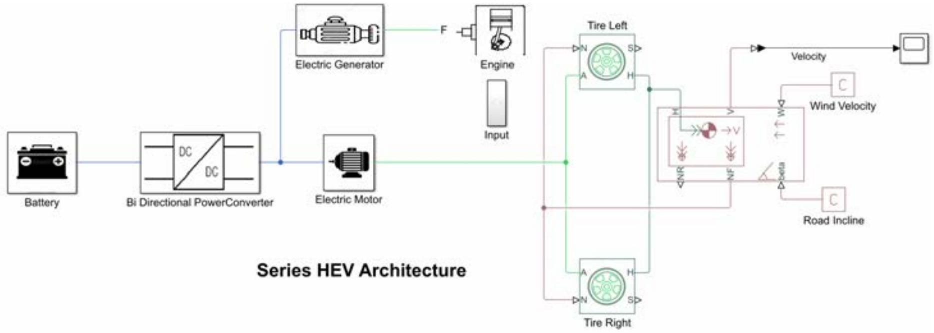


Figure 6 Simulink model of parallel HEV architecture (see online version for colours)

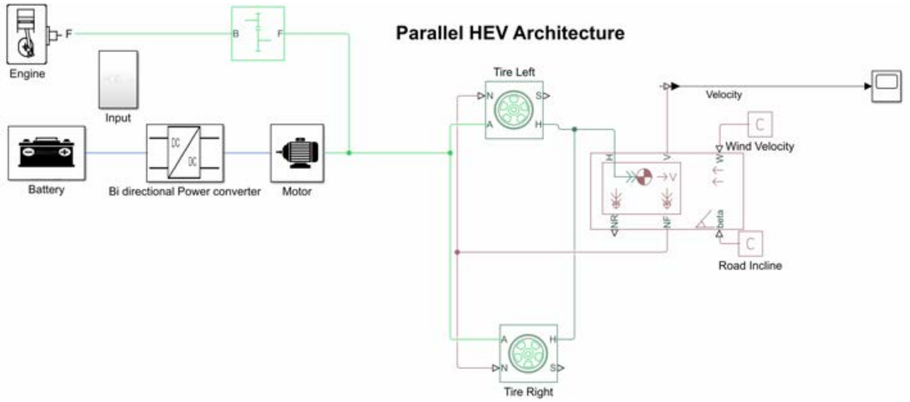
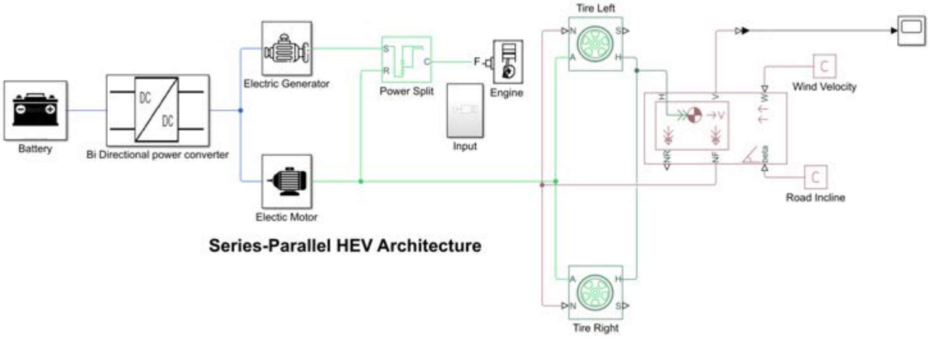


Figure 7 Simulink model of series-parallel HEV architecture (see online version for colours)



4 Results and discussion

The results are organised into three subsections. In the first subsection, the performance metrics listed in Table 1 are given for input 1. Similarly, in second and third sections, the performance metrics for input 2 and input 3 are presented. All the results are plotted with per unit (pu) metrics on the y-axis, as different parameters with different units are given in the same plot for the purpose of comparison. An extensive comparison of the performance parameters for three inputs applied to different HEV architectures is made at the conclusion of the results. The engine capacity, the battery rating, power converter rating of all the architectures is assumed to be the same. The duration for which the input is applied is for 45 s.

Figure 8 Simulink model of complex HEV architecture (see online version for colours)

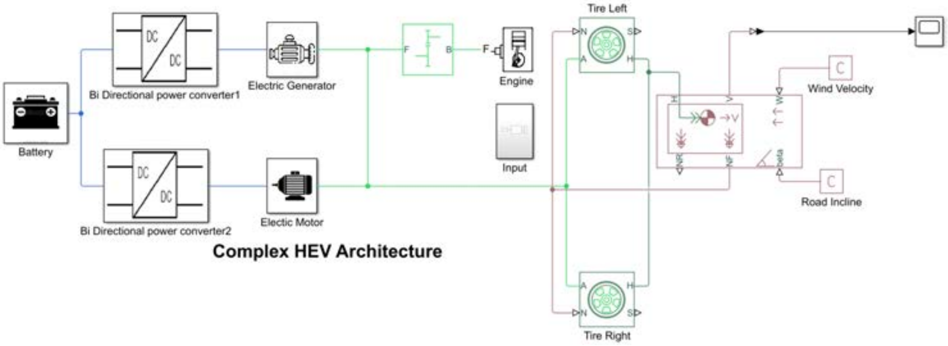


Table 1 Conditions and parameters used in this study

Test conditions or inputs		*Observed parameters*	
1	Continuous acceleration	1	Vehicle speeds
2	Pulse-type acceleration	2	Engine speeds
3	Step-up type acceleration	3	Motor speeds
		4	Engine power
		5	Battery power
		6	Battery electrical loss
		7	Battery charge
		8	Fuel consumption

4.1 Performance analysis of HEV architectures for input 1

The speed plots of different HEV architectures for input 1 are given in Figure 9. From the plots, it is observed that the parallel architecture responds instantaneously to the change in input. The engine speed profiles of HEV architectures for input 1 given in Figure 10. From this response, it can be noted that the parallel architecture performed extremely well, closely followed by complex HEV. The Motor speeds profiles of HEV architectures for input 1 is given in Figure 11, and from this response, parallel HEV scores ahead compared to all other HEV architectures under consideration. The engine power profiles of HEV architectures for input 1 given in Figure 12. From this the response, it can be noted that the parallel HEV performance is superior due to low usage of the engine and series HEV is the next to have the best engine power values. The battery power profiles of HEVs for input 1 are given in Figure 13. From this figure, it is observed that for architectures parallel and complex, series and series-parallel have nearly the same performance with a minute difference.

Figure 9 Vehicle speed response of all the HEV architectures for input 1 (see online version for colours)

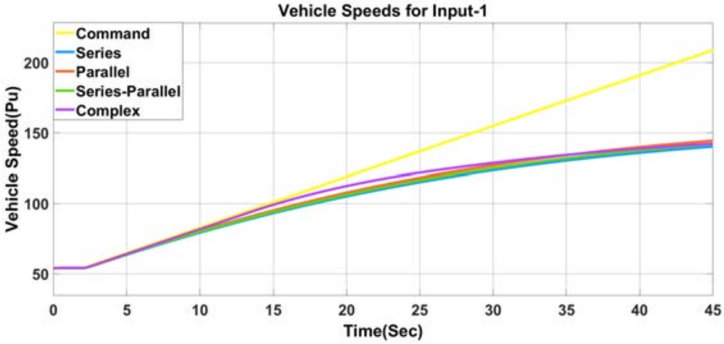


Figure 10 Engine speed response of all the HEV architectures for input 1 (see online version for colours)

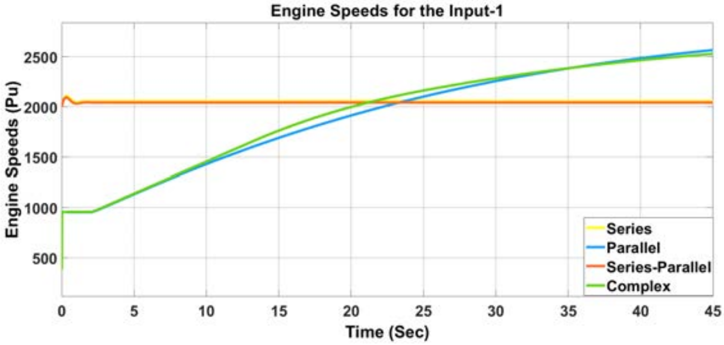


Figure 11 Motor speed response of all the HEV architectures for input 1 (see online version for colours)

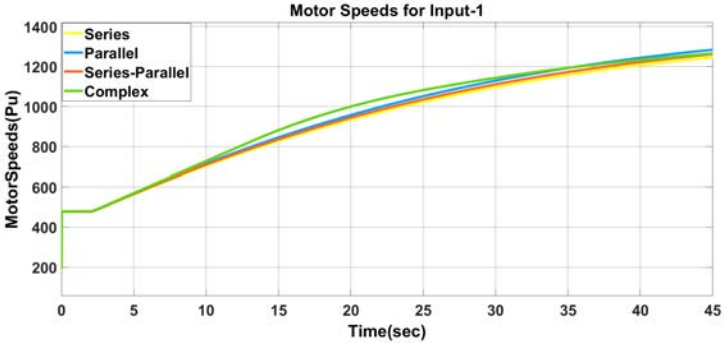


Figure 12 Engine power profiles of all the HEV architectures for input 1 (see online version for colours)

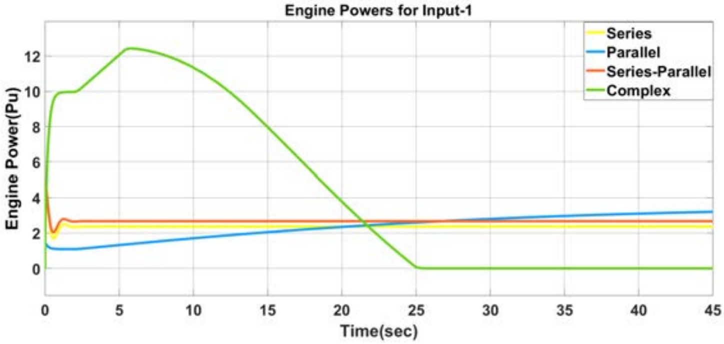


Figure 13 Battery power profiles of all the HEV architectures for input 1 (see online version for colours)

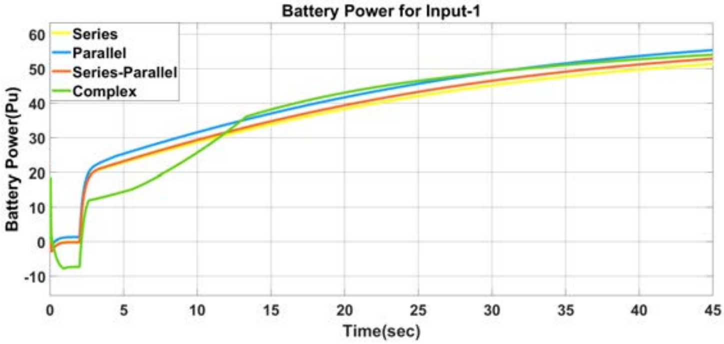


Figure 14 Battery electric loss profiles of all the HEV architectures for input 1 (see online version for colours)

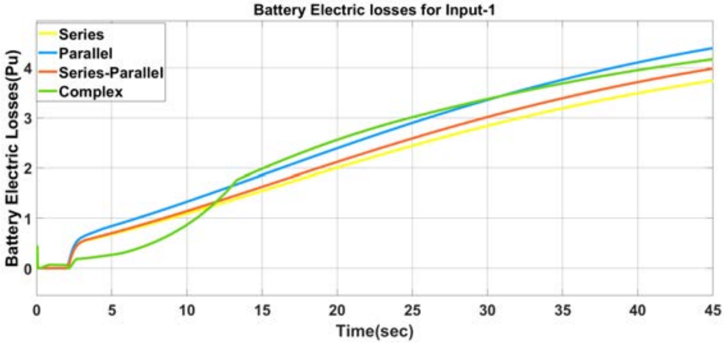


Figure 15 Battery charge profiles of all the HEV architectures for input 1 (see online version for colours)

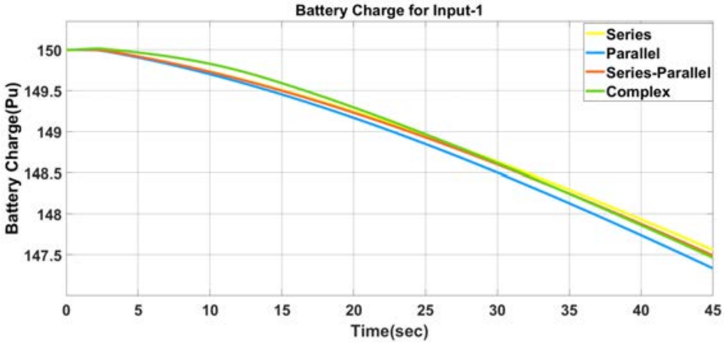
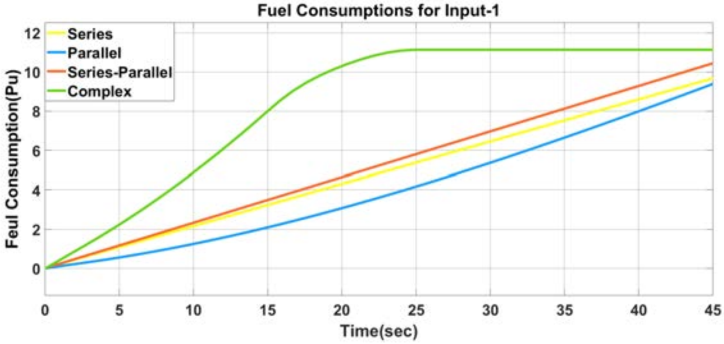


Figure 16 Fuel consumption profiles of all the HEV architectures for input 1 (see online version for colours)



Battery electric loss profiles of different HEV architectures for input 1 are given in Figure 14. The series-parallel architecture is shown to have least loss, whereas parallel architecture poses higher loss. The state of battery charge for different HEV architectures for input 1 is given in Figure 15. From these profiles, it is noted that in all architectures have shown a decrement of approximately 2.5 pu. The fuel consumption profiles of different HEV architectures are plotted, in Figure 16, which shows that parallel architecture consumes the least fuel whereas complex architecture consumes the highest.

4.2 Performance analysis of HEV architectures for input 2

Pulse-type acceleration can be seen applied in low to moderate traffic regions. So, the analysis of the effects of such input on HEV efficacy is of interest. A pulse with a fall time, rise time, and pulse width of 5 seconds each are applied to the HEV architectures in two continuous cycles in a period of 40 seconds, and the performance is analysed.

The plots of speed variation with respect to input 2 for different HEV architectures are given in Figure 17. From this, it is noticed that the response of all architectures almost similar and near to 71 units. The response of complex type HEV seems to lag the input during deceleration. The engine speed profiles of HEV architectures for input 2 are given in Figure 18, which shows that series architecture shows superior characteristics and series-parallel was the next to have higher engine speeds. The motor speeds profiles of HEV architectures for input 2 given in Figure 19. From this, the responses, all of the architectures have around generated 632 to 637 rpm with slight changes. The engine power profiles of HEV architectures for input 2 are given in Figure 20. From these responses, parallel architecture shows superior performance and utilises less engine power than other architectures. The battery power profiles of HEVs for input 2 are given in Figure 21. From these plots, it is observed that parallel architecture shows superior characteristics; and series and series-parallel architectures show similar characteristics while complex architecture utilises very less battery power.

Figure 17 Vehicle speed response of all the HEV architectures for input 2 (see online version for colours)

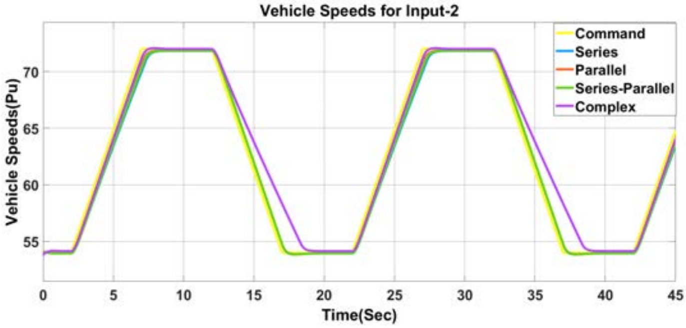
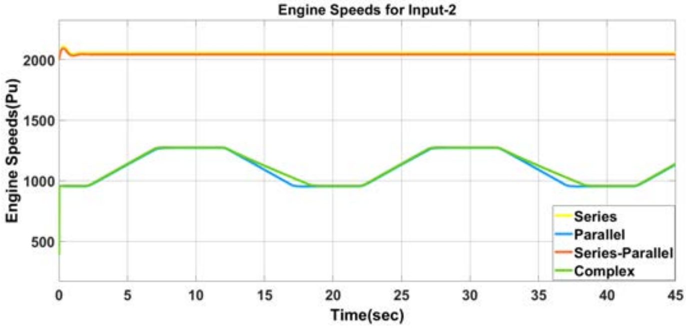


Figure 18 Engine speed response of all the HEV architectures for input 2 (see online version for colours)



Battery electric loss profiles of different HEV architectures for input 2 are given in Figure 22. The series architecture shows least loss and parallel architecture incurs a higher loss. Battery charge profiles of different HEV architectures for a pulsated acceleration are provided, as given in Figure 23. For complex architecture, it is observed that the charge decreases as time progresses. In contrast, the charge profile of the battery charge in complex architecture is improved with this type of pulsed input. So, as the battery discharge is least in complex, it is suggested as the best architecture with respect to the battery charge. The fuel consumption profiles of various HEV architectures for input 2 are given in Figure 24. From these responses, it is noted that complex architectures has highest fuel consumption profile and consume a higher amount of fuel when compared to other architectures. Further, it is observed that parallel architecture consumes the least fuel among all the other architectures.

Figure 19 Motor speed response of all the HEV architectures for input 2 (see online version for colours)

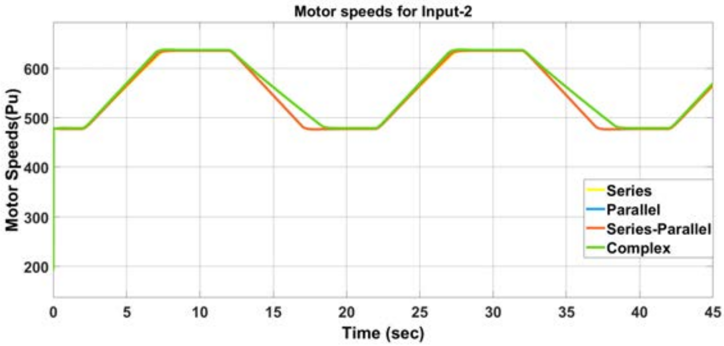


Figure 20 Engine power profiles of all the HEV architectures for input 2 (see online version for colours)

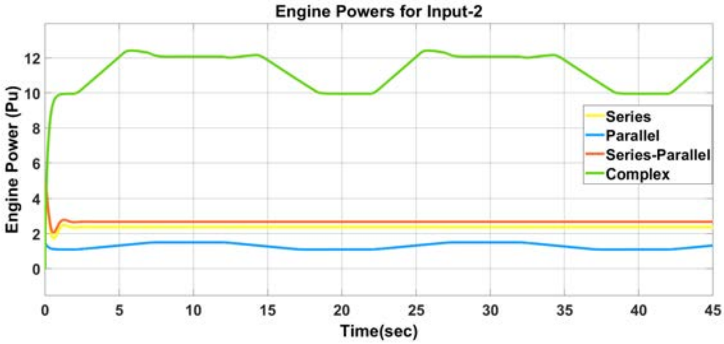


Figure 21 Battery power profiles of all the HEV architectures for input 2 (see online version for colours)

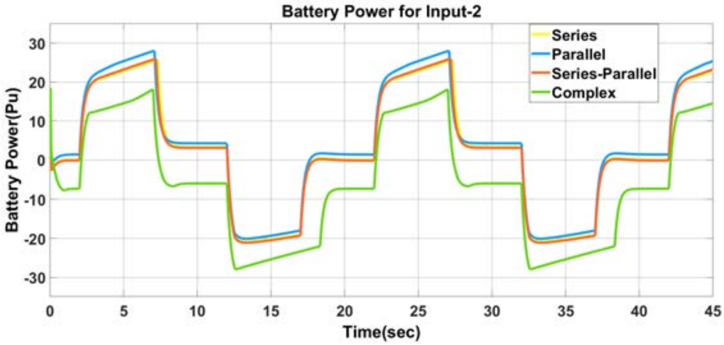


Figure 22 Battery electric loss profiles of all the HEV architectures for input 2 (see online version for colours)

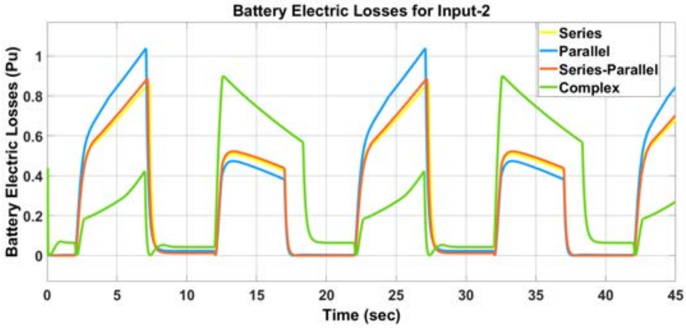


Figure 23 Battery charge profiles of all the HEV architectures for input 2 (see online version for colours)

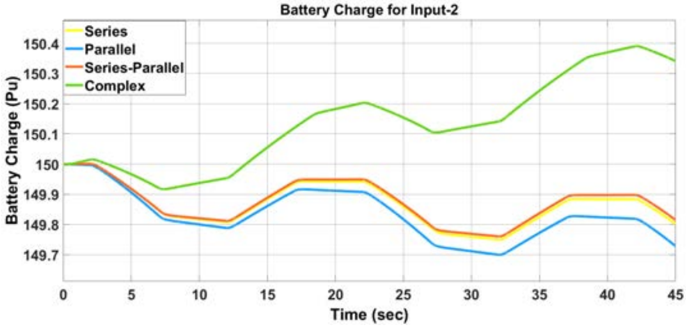
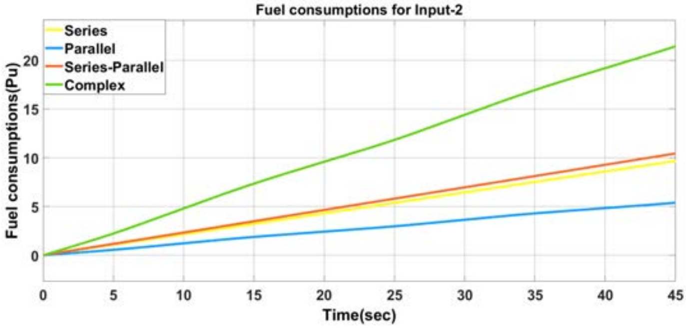


Figure 24 Fuel consumption profiles of all the HEV architectures for input 2 (see online version for colours)



4.3 Performance analysis of HEV architectures for input 3

Step acceleration is a special acceleration case usually seen in racing and road rage situations. The acceleration increases linearly for 10 seconds and then decelerates briefly for 5 seconds, and this cycle is continued for 45 seconds. The response of the speed of different HEV architectures for input 3 is given in Figure 25. In comparison, the speed response of HEVs almost came to 120 units at the end with a unit difference among them, complex architecture reached 119.7 units. The engine speed profiles of HEV architectures for input 3 are given in Figure 26. From the responses, complex architecture showed superior engine speed whereas parallel architecture was the next. The motor speed profiles of HEV architectures for input 3 are given in Figure 27. From the responses, it can be seen that complex architecture showed superior performance. The engine power profiles of HEV architectures for input 3 are given in Figure 28. From these responses, it can be noticed that series architecture showed superior engine power characteristics and parallel architecture was the next. The battery power profiles of HEVs for input 3 are given in Figure 29. From these plots, it is observed that for architectures series-parallel and parallel have similar profiles while series architecture showed very less battery power utilisation. Battery electric loss profiles of different HEV architectures for input 3 are given in Figure 30. The series is having least loss and complex has a higher loss. The state of battery charge for different HEV architectures for input 3 is given in Figure 31. From these profiles, it is noted that complex architecture discharges less compared to the other HEV architectures. The fuel consumption profiles of different HEV architectures are plotted in Figure 32. From these plots, it is observed that complex architecture consumed the most whereas parallel architecture consumed least among all the HEV architectures. Series and series-parallel architectures consumed almost same fuel with less than a unit difference.

Figure 25 Vehicle speed response of all the HEV architectures for input 3 (see online version for colours)

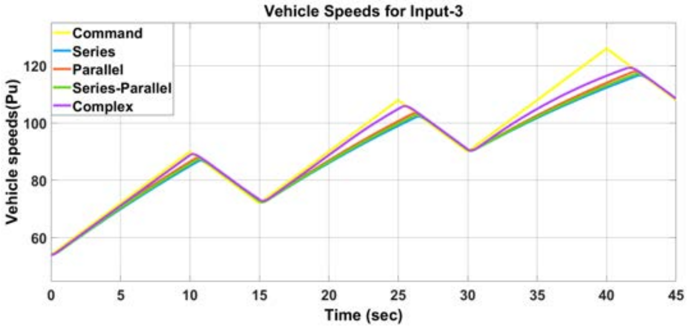


Figure 26 Engine speed response of all the HEV architectures for input 3 (see online version for colours)

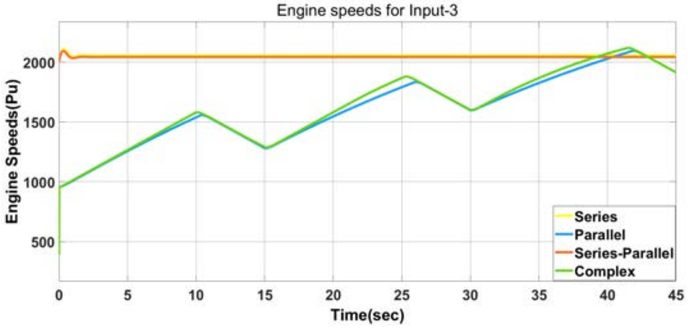


Figure 27 Motor speed response of all the HEV architectures for input 3 (see online version for colours)

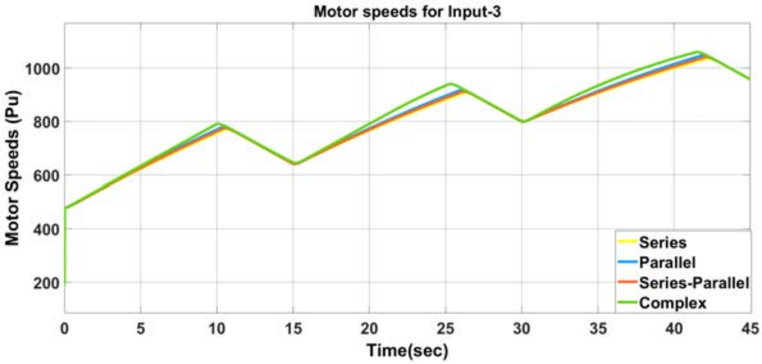


Figure 28 Engine power profiles of all the HEV architectures for input 3 (see online version for colours)

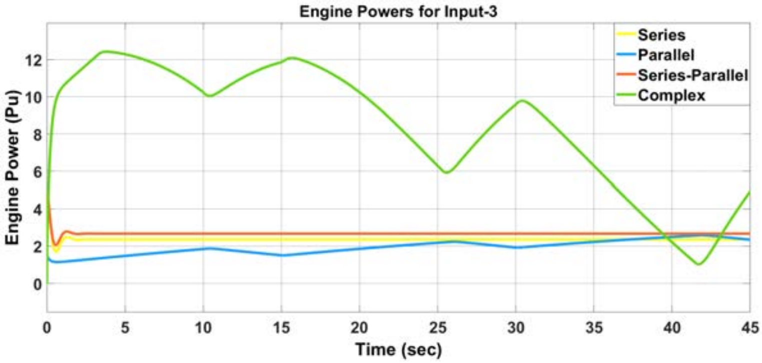


Figure 29 Battery power profiles of all the HEV architectures for input 3 (see online version for colours)

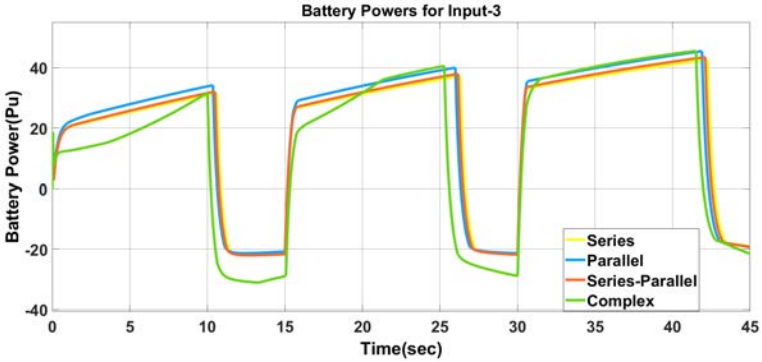


Figure 30 Battery electric loss profiles of all the HEV architectures for input 3 (see online version for colours)

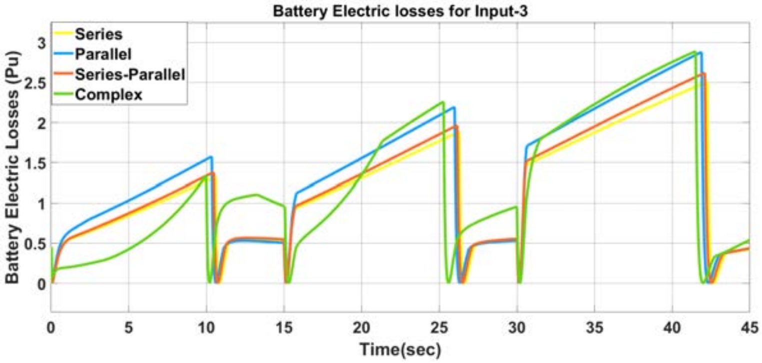


Figure 31 Battery charge profiles of all the HEV architectures for input 3 (see online version for colours)

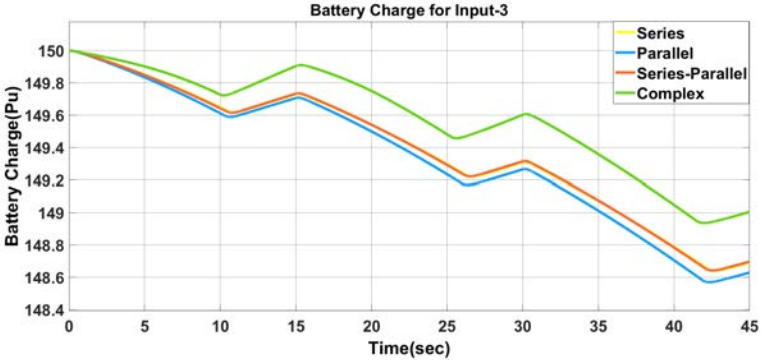
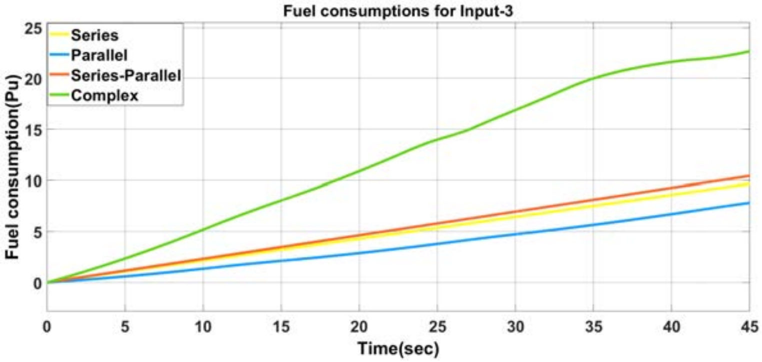


Figure 32 Fuel consumption profiles of all the HEV architectures for input 3 (see online version for colours)



5 Conclusions

This paper presents a comprehensive investigation of the performance of HEV architectures under various dynamic operating conditions that match real-time scenarios. For the comparative analysis, all the performance parameters were computed under the influence of the dynamic inputs such as continuous acceleration, pulse acceleration, and step-up acceleration. All these computed values are given in Tables 2 to 5 for the inputs 1, 2 and 3.

Table 2 Comparison of vehicle speed and motor speed for all HEV architectures for different input conditions

HEV type	*Vehicle speed*			*Motor speed*		
Input	1	2	3	1	2	3
Series	140	71.76	116.6	1,247	633.7	1,035
Parallel	144.2	71.65	118	1,284	636.6	1,049
Series-parallel	141.7	71.84	117.2	1,261	634.3	1,039
Complex	142.2	72.06	119.7	1,265	637.3	1,060
Superior	Parallel	Complex	Complex	Parallel	Complex	Complex

Table 3 Comparison of engine speed and engine power for all HEV architectures for different input conditions

HEV type	*Engine speed*			*Engine power*		
Input	1	2	3	1	2	3
Series	2,057	2,057	2,057	2.8	3.2	2.37
Parallel	2,567	1,272	2,097	2.2	1.35	2.45
Series-parallel	2,043	2,043	2,043	3.4	3.46	2.67
Complex	2,529	1,275	2,120	3.5	10.04	6.51
Superior	Parallel	Series	Complex	Parallel	Parallel	Series

Table 4 Comparison of battery power and battery electric loss for all HEV architectures for different input conditions

HEV type	*Battery power*			*Battery electric loss*		
Input	1	2	3	1	2	3
Series	51.41	25.65	27.86	3.74	0.84	1.01
Parallel	55.36	28.03	29.8	4.40	1.03	1.15
Series-parallel	52.92	25.99	29.02	3.39	0.88	1.06
Complex	54.04	18.13	34.01	4.10	0.90	1.34
Superior	Parallel	Parallel	Complex	Series	Series	Series

On comparing the results, the following conclusions are made:

- if the fuel economy is of utmost importance, then parallel HEV architecture is recommended

- if the user is interested in power performance and speed and the fuel consumption is not of importance, then complex HEV architecture is recommended
- for a balanced performance with respect to fuel consumption, power and speed are given importance then series-parallel HEV architecture is recommended, followed by series HEV architecture
- if only fuel consumption is of importance, then undoubtedly, the parallel HEV architecture is the best choice, which can be understood from Table 5.

The presented analysis has given an insight into what type of HEV architectures are to be considered when a FWD HEV is subjected to different dynamic driving conditions.

Table 5 Comparison of battery charge and fuel consumption for all HEV architectures for different input conditions

HEV type	*Battery charge*			*Fuel consumption*		
Input	1	2	3	1	2	3
Series	147.6	149.8	147.8	9.67	9.69	9.67
Parallel	147.3	149.7	148.6	9.39	5.39	7.86
Series-parallel	147.5	149.8	147.8	10.44	10.44	10.44
Complex	147.5	150.3	149	11.14	21.4	22.69
Superior	Series	Complex	Complex	Parallel	Parallel	Parallel

References

Assadian, F. (2010) 'Mechatronics and its role in the automotive domain', *UKACC International Conference on Control 2010*, Coventry, pp.1–5.

Bernard, J., Delprat, S., Guerra, T.M. and Büchi, F.N. (2010) 'Fuel efficient power management strategy for fuel cell hybrid power trains', *Control Engineering Practice*, Vol. 18, No. 4, pp.408–417.

Boschert, S. (2006) *Plug-in Hybrids: The Cars That Will Recharge America*, 1st ed., New Society Publishers, Gabriola Island, BC, Canada.

Bucherl, D., Nuscheler, R., Meyer, W. and Herzog, H.G. (2008) 'Comparison of electrical machine types in hybrid drive trains: induction machine vs. permanent magnet synchronous machine', *2008 18th International Conference on Electrical Machines*, September, IEEE, pp.1–6.

Chan, C.C., Bouscayrol, A., Chen, K. (2009) 'Electric, hybrid, and fuel-cell vehicles: architectures and modeling', *IEEE Transactions on Vehicular Technology* Vol. 59, No. 2, pp.589–598.

Chowdhury, M.S.A., Al Mamun, K.A. and Rahman, A.M. (2016) 'Modelling and simulation of power system of battery, solar and fuel cell powered hybrid electric vehicle', *2016 3rd International Conference on Electrical Engineering and Information Communication Technology (ICEEICT)*, IEEE, pp.1–6.

Chen, L., Xi, G. and Sun, J. (2012) 'Torque coordination control during mode transition for a series-parallel hybrid electric vehicle', *IEEE Transactions on Vehicular Technology*, Vol. 61, No. 7, pp.2936–2949.

Cordiner, S., Galeani, S., Mecocci, F., Mulone, V. and Zaccarian, L. (2014) 'Torque setpoint tracking for parallel hybrid electric vehicles using dynamic input allocation', *IEEE Transactions on Control Systems Technology*, Vol. 22, No. 5, pp.2007–2015.

Dagci, O.H., Peng, H. and Grizzle, J.W. (2018) 'Hybrid electric powertrain design methodology with planetary gear sets for performance and fuel economy', *IEEE Access*, Vol. 6, pp.9585–9602.

De Jager, B., Steinbuch, M. and van Keulen, T. (2008) 'An adaptive sub-optimal energy management strategy for hybrid drive-trains', *IFAC Proceedings Volumes*, Vol. 41, No. 2, pp.102–107.

Eshani, M., Gao, Y., Gay, S.E. and Emadi, A. (2005) 'Modern electric, hybrid electric and fuel cell vehicles', *Fundamentals, Theory, and Design*, CRC, Boca Raton, FL.

Ehsani, M., Gao, Y. and Miller, J.M. (2007) 'Hybrid electric vehicles: architecture and motor drives', *Proceedings of the IEEE*, Vol. 95, No. 4, pp.719–728.

Emadi, A., Rajashekara, K., Williamson, S.S. and Lukic, S.M. (2005) 'Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations', *IEEE Transactions on Vehicular Technology*, Vol. 54, No. 3, pp.763–770.

Frieske, B., Kloetzke, M. and Mauser, F. (2013) 'Trends in vehicle concept and key technology development for hybrid and battery electric vehicles', *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, IEEE, pp.1–12.

Gong, X., Dong, F., Mohamed, M.A., Abdalla, O.M. and Ali, Z.M. (2020) 'A secured energy management architecture for smart hybrid microgrids considering PEM-fuel cell and electric vehicles', *IEEE Access*, Vol. 8, pp.47807–47823.

Ghasemi, M. and Song, X. (2018) 'Powertrain energy management for autonomous hybrid electric vehicles with flexible driveline power demand', *IEEE Transactions on Control Systems Technology*, Vol. 27, No. 5, pp.2229–2236.

Guzzella, L. and Amstutz, A. (1999) 'CAE tools for quasi-static modeling and optimization of hybrid powertrains', *IEEE Transactions on Vehicular Technology*, Vol. 48, No. 6, pp.1762–1769.

Gavgani, A.M., Sorniotti, A., Doherty, J. and Cavallino, C. (2016) 'Optimal gearshift control for a novel hybrid electric drivetrain', *Mechanism and Machine Theory*, Vol. 105, pp.352–368.

Johannesson, L. and Egardt, B. (2008) 'Approximate dynamic programming applied to parallel hybrid powertrains', *IFAC Proceedings Volumes*, Vol. 41, No. 2, pp.3374–3379.

Jochem, P., Vilchez, J.J.G., Ensslen, A., Schäuble, J. and Fichtner, W. (2018) 'Methods for forecasting the market penetration of electric drivetrains in the passenger car market', *Transport Reviews*, Vol. 38, No. 3, pp.322–348.

Kebriaei, M., Niasar, A.H. and Asaei, B. (2015) 'Hybrid electric vehicles: an overview', *2015 International Conference on Connected Vehicles and Expo (ICCVE)*, October, pp.299–305, IEEE.

Karaoglan, M.U., Kuralay, N.S. and Colpan, C.O. (2019) 'The effect of gear ratıos on the exhaust emıssıons and fuel consumptıon of a parallel hybrid vehicle powertrain', *Journal of Cleaner Production*, Vol. 210, pp.1033–1041.

Katrasnik, T., Trenc, F. and Opresnik, S.R. (2007) 'Analysis of energy conversion efficiency in parallel and series hybrid powertrains', *IEEE Transactions on Vehicular Technology*, Vol. 56, No. 6, pp.3649–3659.

Kim, J. (2016) 'Optimal power distribution of front and rear motors for minimizing energy consumption of 4-wheel-drive electric vehicles', *International Journal of Automotive Technology*, Vol. 17, No. 2, pp.319–326.

Kumar, Y.P. and Bhimasingu, R. (2015) 'Renewable energy based microgrid system sizing and energy management for green buildings', *Journal of Modern Power Systems and Clean Energy*, Vol. 3, No. 1, pp.1–13.

Kumar, Y.P. and Ravikumar, B. (2016) 'A simple modular multilevel inverter topology for the power quality improvement in renewable energy based green building microgrids', *Electric Power Systems Research*, Vol. 140, pp.147–161.

Lajunen, A., Yang, Y. and Emadi, A. (2018) 'Recent developments in thermal management of electrified powertrains', *IEEE Transactions on Vehicular Technology*, Vol. 67, No. 12, pp.11486–11499.

Lenzo, B., Bucchi, F., Sorniotti, A. and Frendo, F. (2018) 'On the handling performance of a vehicle with different front-to-rear wheel torque distributions', *International Journal of Vehicle Mechanics and Mobility*, Vol. 57, No. 11, pp.1685–1704.

Li, L., Zhang, Y., Yang, C., Jiao, X., Zhang, L. and Song, J. (2015) 'Hybrid genetic algorithm-based optimization of powertrain and control parameters of plug-in hybrid electric bus', *Journal of the Franklin Institute*, Vol. 352, No. 3, pp.776–801.

Magnussen (2004) *On Design and Analysis of Synchronous Permanent Magnet Machines for Field-Weakening Operation in Hybrid Electric Vehicles*, PhD thesis.

Mocera, F., Vergori, E. and Somà, A. (2019) 'Battery performance analysis for working vehicle applications', *IEEE Transactions on Industry Applications*, Vol. 56, No. 1, pp.644–653.

Paganelli, G., Delprat, S., Guerra, T.M., Rimaux, J. and Santin, J.J. (2002) 'Equivalent consumption minimization strategy for parallel hybrid powertrains', *IEEE 55th Vehicular Technology Conference, VTC Spring 2002 (Cat. No. 02CH37367)*, May, IEEE, Vol. 4, pp.2076–2081.

Siddharth, R.R., Chandu, V.S., Babu, D.M., Pradeep, D.J. and Kumar, Y.V.P. (2020) 'Performance analysis of hybrid electric vehicle architectures under dynamic operating conditions', *International Journal of Advanced Science and Technology*, Vol. 29, No. 10S, pp.4370–4390.

Reddy, Y.J., Kumar, Y.P., Kumar, V.S. and Raju, K.P. (2012) 'Distributed ANNs in a layered architecture for energy management and maintenance scheduling of renewable energy HPS microgrids', *2012 International Conference on Advances in Power Conversion and Energy Technologies (APCET)*, August, IEEE, pp.1–6.

Rivera, S., Kouro, S. and Wu, B. (2017) 'Charging architectures for electric and plug-in hybrid electric vehicles', *Technologies and Applications for Smart Charging of Electric and Plug-in Hybrid Vehicles*, pp.111–149, Springer, Cham.

Rizzoni, G., Guzzella, L. and Baumann, B.M. (1999) 'Unified modeling of hybrid electric vehicle drivetrains', *IEEE/ASME Transactions on Mechatronics*, Vol. 4, No. 3, pp.246–257.

Singh, K.V., Bansal, H.O. and Singh, D. (2019) 'A comprehensive review on hybrid electric vehicles: architectures and components', *Journal of Modern Transportation*, Vol. 27, No. 2, pp.77–107.

Sarlioglu, B., Morris, C.T., Han, D. and Li, S. (2016) 'Driving toward accessibility: a review of technological improvements for electric machines, power electronics, and batteries for electric and hybrid vehicles', *IEEE Industry Applications Magazine*, Vol. 23, No. 1, pp.14–25.

Tran, D.D., Vafaeipour, M., El Baghdadi, M., Barrero, R., van Mierlo, J. and Hegazy, O. (2020) 'Thorough state-of-the-art analysis of electric and hybrid vehicle powertrains: topologies and integrated energy management strategies', *Renewable and Sustainable Energy Reviews*, Vol. 119, p.109596.

Trovao, J.P.F., Santos, V.D., Antunes, C.H., Pereirinha, P.G. and Jorge, H.M. (2014) 'A real-time energy management architecture for multisource electric vehicles', *IEEE Transactions on Industrial Electronics*, Vol. 62, No. 5, pp.3223–3233.

Wu, G., Zhang, X. and Dong, Z. (2015) 'Powertrain architectures of electrified vehicles: review, classification and comparison', *Journal of the Franklin Institute*, Vol. 352, No. 2, pp.425–448.

Yamin, M., Mahandari, C.P. and Sudono, R.H. (2016) 'Dynamic simulation of wheel drive and suspension system in a through-the-road parallel hybrid electric vehicle', *Proceedings of Second International Conference on Electrical Systems, Technology and Information 2015 (ICESTI 2015)*, Springer, Singapore, pp.263–270.

Zhao, J. and Sciarretta, A. (2016) 'Design and control co-optimization for hybrid powertrains: Development of dedicated optimal energy management strategy', *IFAC-Papers Online*, Vol. 49, No. 11, pp.277–284.

Zheng, T. (2011) *Advanced Model Predictive Control*, InTech Publisher, Croatia.

Zhou, W., Zhang, C. and Li, J. (2014) 'Analysis of optimal power management strategy for series plug-in hybrid electric vehicles via dynamic programming', *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, August, IEEE, pp.1–5.

Zhou, X., Qin, D., Rotella, D. and Cammalleri, M. (2018) 'Hybrid electric vehicle powertrain design: construction of topologies and initial design schemes', *The International Conference of IFToMM ITALY*, November, Springer, Cham, pp.49–60.

Zhou, X., Qin, D., Yao, M. and Xie, Z. (2020) 'Representation, generation, and optimization methodology of hybrid electric vehicle powertrain architectures', *Journal of Cleaner Production*, Vol. 256, p.120711.

Zhu, H., Song, Z., Hou, J., Hofmann, H.F. and Sun, J. (2020) 'Simultaneous identification and control using active signal injection for series hybrid electric vehicles based on dynamic programming', *IEEE Transactions on Transportation Electrification*, Vol. 6, No. 1, pp.298–307.

Zhuang, W., Zhang, X., Ding, Y., Wang, L. and Hu, X. (2016) 'Comparison of multi-mode hybrid powertrains with multiple planetary gears', *Applied Energy*, Vol. 178, pp.624–632.

Zia, A. (2016) 'A comprehensive overview on the architecture of hybrid electric vehicles (HEV)', *2016 19th International Multi-Topic Conference (INMIC)*, December, IEEE, pp.1–7.