

Comparative Analysis of Energy Management Strategies in Through-the-Road Hybrid Electric Vehicles for Improved Fuel Economy

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Abstract— Since the last few years, the earth is undergoing severe environmental changes which are producing adverse effects on the wellbeing of the humans as well as the planet. One of the main reasons behind these changes is the pollution caused by industrialization and the transportation facilities. The fossil fuels consumed by the internal combustion engines (ICE) in conventional vehicles are producing Greenhouse gas (GHG) emissions. Scientists across the globe have made a prediction that fossil fuels will only last for the 21st century. This made the governments worldwide to focus on the development of Renewable Energies and are thus offering various subsidies on battery electric vehicles (BEV). However, the primary concern is the use of fossil fuels for manufacturing batteries. A hybrid electric vehicle (HEV) is the combination of an internal combustion engine and electric motor with a battery. The through-the-road (TtR) is a concept used in parallel hybrid electric vehicles, in which the engine powers one axle and the electric motor powers the other axle. To increase the fuel-efficiency of the HEV and to produce less emissions, the HEV is integrated with an energy management system (EMS). In this paper two different EMS strategies such as Rule-based strategy and Optimization-based strategy used in TtR HEV are reviewed and compared. The aim of this paper is to find the most efficient EMS strategy for improving the fuel efficiency in TtR HEV. The results show that the solutions vary significantly in terms of fuel efficiency and real-time application, offering important information for future advancements in TTR HEV energy management.

Keywords—*hybrid electric vehicles, HEV architectures, through-the-road (TtR) parallel HEV, energy management strategies (EMS), deterministic rule-based strategy, dynamic programming optimization-based strategy*

I. INTRODUCTION

The development of Industrial Revolution in the 19th century has led to an increase in the Earth's average surface temperature by 1.5 °C till the year 2023. This is mainly caused by the release of harmful and toxic polluting substances into the Earth's atmosphere by burning fossil fuels [1]. Fossil fuels which played an important role in the foundation of human civilizations in the world are now decreasing at a much faster rate [1]. This has created a challenging environment for the conventional internal combustion engines (ICE). Thus, the researchers in automotive industries are focusing on developing alternative solutions which are environment-

friendly and more efficient [1]. Many countries around the globe have started working on the generation of energy using Renewable sources such as wind energy, solar energy and geothermal energy [2]. Taking these factors into consideration, the automotive industries are currently focusing on the development of battery electric vehicles (BEV) and hybrid electric vehicles (HEV) due to their capability of providing better fuel economy and producing less fuel emissions as compared to conventional vehicles [1]. A hybrid electric vehicle (HEV) consists of an internal combustion engine (ICE) along with electric motors (EM) which are used either together or independently to drive the vehicle [3]. The HEVs are found to provide better fuel mileage and are built with parts of various sizes as compared to the pure electric vehicles [4]. One of the main advantages of the HEVs is the regenerative braking in which the kinetic energy of the vehicle during braking is captured and stored in the battery which is further used to drive the electric motor [1]. Also, the ICE in HEV can be operated more efficiently using an energy management system (EMS) which switches the ICE ON or OFF as per the driving conditions [3].

There are three types of HEV namely Series HEV, Parallel HEV and Combined HEV. These types are discussed further in more detail. This paper focuses on the P4 architecture used in Parallel HEV. The P4 architecture works on the concept of through-the-road (TtR). In a TtR HEV the internal combustion engine connected to the front axle and the electric motor connected to the rear axle produces traction forces on the respective axles and are added together through the road while in conventional HEV the torque used in transmission is the combination of various systems [4]. According to source [5] the flow of energy between the fuel and the battery pack which is acting as an alternative energy storage system (ESS) is a challenging task and thus to improve the vehicle performance with better fuel economy and minimum fuel emissions an appropriate energy management system (EMS) is necessary. Many Scholars are working on this topic to make it more efficient. This paper addresses two such energy management methods namely Deterministic Rule-based (RB) method and Dynamic Programming (DP) method.

Since last 10 years many researchers have reviewed different energy management strategies used in HEVs but due to the latest development in automotives and the changing emission policies worldwide, more research must be done on this topic [5]. Source [4] has evaluated many different

architectures used in HEV which are discussed in the further section. However, there is only a limited investigation done on the TtR architecture [6]. The TtR concept was first introduced in the year 1989 with the concept Audi Duo car but it was first implemented in Peugeot 3008 car in the year 2011 which showed the potential of the TtR architecture [6]. In this paper the TtR architecture is implemented with a plug-in hybrid electric vehicle (PHEV). PHEV has an advantage over HEV as it can be charged using power supply from an external grid and can work in charge depletion (CD) mode as well as charge sustaining (CS) mode [7]. The goal of this paper is to review and compare the two EMS such as Deterministic Rule-based (RB) method with the Dynamic Programming (DP) method and thus find the most efficient method for enhancing the fuel economy of the TtR architecture.

This paper is arranged using the following sections. Section I provides an introduction to HEV and the TtR architecture. Section II gives a brief overview of the different architectures used in HEV such as series HEV, parallel HEV and the combined HEV. In Section III various energy management strategies are explained focusing on rule-based strategies and optimization-based strategies used in TtR architecture. Section IV compares the two EMS methods followed by results and discussions in Section V. The paper is concluded in Section VI.

II. HEV ARCHITECTURES

HEVs are further classified into series HEV, parallel HEV and combined HEV. Generally, HEV consists of an ICE and two or more EM with a battery pack, however different driving performance can be obtained by changing the connection between these power sources. These connections can be made either mechanically or electrically. This is achieved by using different architectures in the HEV which are discussed in this section with the help of figures.

A. Series hybrid electric vehicles

In series HEV the ICE is not directly connected to the drive wheels mechanically as in the case of conventional vehicles. Thus, the ICE is operated with high efficiency and the energy produced by it is passed in series through the Generator to the EM. The EM is connected mechanically to the drive wheels thus providing propulsion to the wheels. The kinetic energy produced during braking or stopping the vehicle is usually lost as heat. This energy can be captured and stored in the battery by using the EM as a generator. This concept is called regenerative braking. The battery which acts as ESS is connected to a Converter which is integrated with power electronics and acts as a medium for energy conversion between the EM on one side and the ICE and Generator on the other side [8]. This architecture is shown in Fig. 1 [8, Fig. 2].

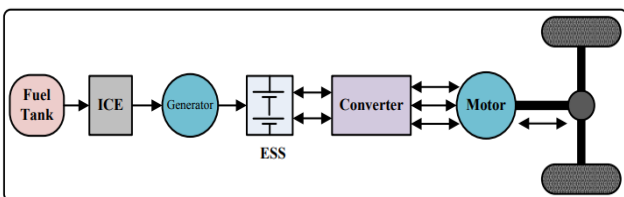


Fig. 1. Series HEV Architecture [8, Fig. 2]

B. Parallel hybrid electric vehicles

Parallel HEV consists of two driving operations. One is hybrid driving in which both the ICE and EM are used together and the second is the electric driving in which EM is used alone for propulsion. The ICE is connected to the wheels mechanically and thus cannot be operated with high efficiency. Like the series HEV the EM acts as a generator during regenerative braking. The ICE and EM are connected in parallel and the torques produced by them are coupled mechanically using a torque coupler [8]. Depending on the connection between the ICE, EM and the torque coupler, the parallel HEV is further classified into Pre-transmission parallel HEV, Post-transmission parallel HEV and Through-the-Road (TtR) parallel HEV.

1) Pre-transmission parallel HEV

In this architecture the torques produced by the ICE and EM are first added together and then supplied to the transmission [6]. Due to this the EM can charge the battery even when the vehicle is not moving [6]. The EM can run at a lower torque as it is driven faster than the vehicle wheels, which allows it to have a smaller size [6]. Also, the EM is connected to the output shaft of the ICE and the transmission's input shaft, which implies that the ICE and the EM must run at the same speed [6]. An example of this architecture is mild hybrid electric vehicles [6]. This configuration is illustrated in Fig. 2 [8, Fig. 3a].

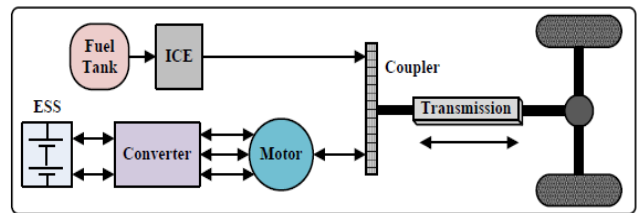


Fig. 2. Pre-transmission Parallel HEV Architecture [8, Fig. 3a]

2) Post-transmission parallel HEV

In this architecture the ICE is directly connected to the transmission before the coupler. The torque produced by the ICE is passed through the transmission and then combined with the torque produced by EM [6]. The EM is connected to the vehicle wheels with fixed gear ratio and thus operates at all speeds of the vehicle [6]. Thus, the motor used in this architecture is of large size as compared to pre-transmission parallel HEV. This configuration is generally used in small trucks [6]. This architecture is described in Fig. 3 [8, Fig. 3b].

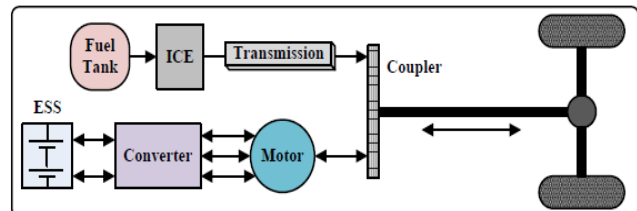


Fig. 3. Post-transmission Parallel HEV Architecture [8, Fig. 3b]

3) Through-the-road parallel HEV

In both the above parallel HEV architectures, a coupler is needed which combines the torques or speeds of ICE and EM and transmits it to only one single axle. But in the TtR architecture a coupler is not needed as the ICE and EM are connected to separate axles. Instead, the road is used as a coupler. An advantage of this architecture is it has two independent transmission systems which provide the comfort

and stability of four-wheel drive and thus better acceleration [4]. Another advantage is the architecture of this system is simple with one transmission system being similar to standard vehicles [6]. Thus, the TtR architecture can be implemented in traditional vehicles easily which has two differential axles [6]. Major automotive companies like Peugeot, Volvo and BMW have also adopted the TtR architecture. One of the best examples is the Peugeot 3008 Hybrid4 vehicle which is the facelift version of the Peugeot 3008 model manufactured in 2011. The TtR architecture is illustrated in Fig. 4 [8, Fig. 3c].

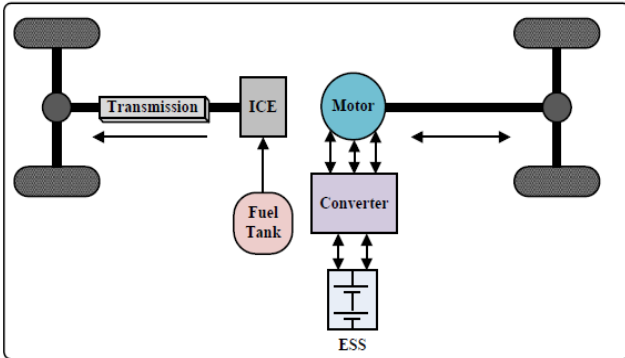


Fig. 4. Through-the-road Parallel HEV Architecture [8, Fig. 3c]

C. Combined hybrid electric vehicles

Combined HEV also called as Series-Parallel HEV is the combination of series HEV and parallel HEV. The coupler used in this architecture acts as a power split device (PSD) which has a planetary gearset with constant gear ratio. This PSD is mechanically connected to the ICE, the EM and an electric generator (EG) which is used separately in this architecture. The PSD connects the ICE to the vehicle wheels either mechanically or electrically thus allowing driving configurations from series HEV as well as parallel HEV. The power produced by ICE is partly transmitted to the vehicle wheels and partly to the EG. The EG acts as a generator and stores this power into the battery which is acting as an ESS. Also, the EM acts as a generator during regenerative braking and charges the battery. The power produced by EM in motor mode is added with the part power from ICE by the PSD and then is further transmitted to the transmission. The EG in motor mode is used for engine start/stop thus saving fuel consumption. However, designing and upgrading the Combined HEV with control theory is a difficult task [8]. The best example of this architecture is the Toyota Prius. This architecture is shown in Fig. 5 [8, Fig. 4].

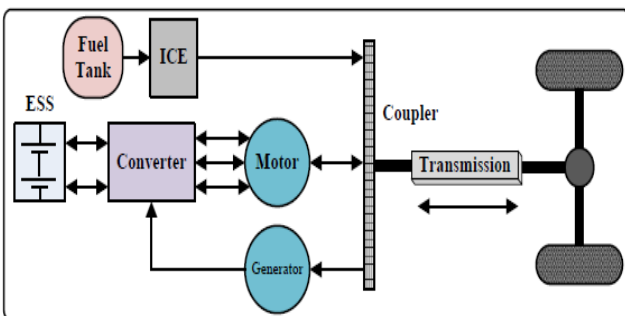


Fig. 5. Combined HEV Architecture [8, Fig. 4]

III. ENERGY MANAGEMENT STRATEGIES FOR HEV

This section gives an overview of the EMS strategies used in HEV. The main function of an EMS is to manage the flow of energy between the ICE and the EM [9]. It monitors the energy stored in the battery and thus supplies the energy to the EM for power generation as per the driver requirement [9]. The purpose of EMS is to provide better fuel efficiency to the HEV taking into consideration the emission standards [9]. As maintaining the minimum fuel consumption with minimum emissions simultaneously is a challenging task, the selection of an appropriate EMS strategy is essential [9]. The different EMS strategies used in HEV are illustrated using a flowchart in Fig. 6 [8, Fig. 7].

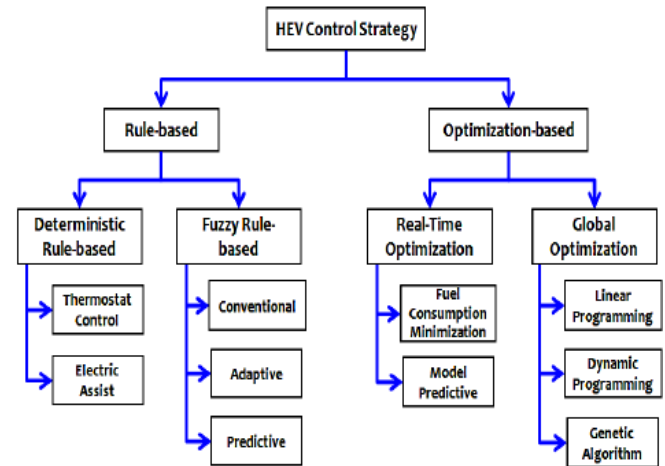


Fig. 6. Energy Management Strategies in HEV [8, Fig. 7]

A. Rule-based strategy

As the name suggests this strategy consists of a set of rules made by experienced and talented engineers taking into consideration the vehicle safety and the vehicle driving operations [10]. This strategy has a simple and less complex structure and using the defined rules, an efficient energy management between the ICE, EM and the state of charge (SOC) of the battery can be obtained [9]. This strategy does not require any prior information related to the future path of the vehicle [10]. But the system finds it difficult to adapt to the changing driving conditions [9]. This strategy is further divided into deterministic rule-based strategy and fuzzy rule-based strategy.

1) Deterministic Rule-based strategy

This paper focuses on this method. This strategy provides a set of guidelines to distribute power between the ICE and EM by considering both their respective performances as well as figuring out the threshold value for important vehicle attributes [9]. Due to its simplicity and lack of dependence on a mathematical model, this approach offers real-time control with minimal computational costs and reliability and is thus easy to put into practice [9]. This strategy includes two different control strategies such as thermostat control strategy and electric assist strategy.

2) Fuzzy Rule-based strategy

This strategy contains a fuzzy logic-based controller (FLC) which plays an important role in minimizing the challenges in non-linear time-varying systems [9]. To understand the working of FLC, Naser Azim Mohseni et al. [9] have described three stages in FLC such as fuzzification, intelligence and defuzzification. The fuzzification stage involves a change in the control input from numerical values

to state variables in FLC [9]. They chose factors such as speed of vehicle, battery SOC and vehicle demand torque as state variables and fed it to the FLC as inputs. Based on these state variables, the power-sharing ratio is calculated with the help of membership function thus considering factors such as engine torque and optimal engine torque for the given engine speed as output variables to the FLC [9]. The fuzzification process is further followed by the fuzzy interface and the defuzzification process [9]. This strategy is also easy to implement with real-time control and faster computational speed, but the selection of a suitable membership function is challenging [9]. Depending on the working and performance, the Fuzzy logic method is divided into three categories such as conventional, adaptive, and predictive.

B. Optimization-based strategy

These strategies have overall better performance as they provide optimum solutions to the problems using optimization techniques [9]. It helps in reducing the running costs over the estimated duration of time [9]. These strategies require the prior information of the vehicle motion and thus have a complex structure. These strategies are further classified into real-time optimization methods and global optimization methods.

1) Real-time Optimization strategy

These methods are dependent on the future predictions of the vehicle motion [9]. It focuses on maintaining a balance between the efficient computing techniques and the energy resource management. Depending on the vehicle motion and the changing vehicle operating modes, these methods must react quickly while working within the limitations of the on-board processing resources [9]. This method can be used to minimize the fuel consumption and predict the vehicle motion.

2) Global Optimization strategy

The Global Optimization method provides optimum solutions globally by using the real-time changes in the optimization problem's inputs [9]. These solutions are provided based on early information of the future driving and road conditions [9]. Because of this early information and high processing loads this method is not suitable for control strategies in real-time [9]. It consists of two approaches like static and dynamic [9]. Static optimisation looks for a constant, ideal value for each control parameter that yields balanced results under various operating conditions whereas in dynamic optimization the control parameters are precisely defined [9]. This method is categorised into linear programming, dynamic programming, and the genetic algorithm.

3) Dynamic Programming (DP) strategy

The second method used in this paper is the dynamic programming (DP). It is a decision-making process in which a complex problem is divided into many simple problems and is solved backwards using the Bellman's optimality concept [9]. In HEV it can be used to minimize the fuel consumption and reduce the emissions still providing the required performance [9]. DP has the ability of providing precise solutions and is thus used as an energy management strategy in HEV [9]. But it is not able to forecast the future driving situations and traffic conditions which makes it difficult to use with the EMS directly [9]. However, it can be used as a

reference to determine the operational factors that yield the most efficient fuel consumption across the globe [9].

IV. METHODS

In this paper two studies with two different EMS strategies such as deterministic rule-based strategy and dynamic programming optimization-based strategy are considered. This section focuses on the methods used in these two studies.

A. Deterministic Rule-based strategy

Chen et al. [11] developed an EMS strategy for Plug-in hybrid electric vehicle (PHEV) with TtR architecture. They used the deterministic rule-based strategy along with the Instantaneous Power Minimization (IPM) method because of its simplicity and easy implementation. The PHEV used in this study consists of an ICE, an electric traction motor (TM1) and an integrated starter/generator (ISG) connected to the front axle and an additional electric traction motor (TM2) connected to the rear wheels [11]. The power supplied to the front axle is either transmitted by the ICE or by the TM1 connected to a reduction gearbox with the help of two clutches [11]. Whereas the rear axle gets power from the TM2 which is connected to a two-speed gearbox and a reduction gearbox [11]. The ICE used in this PHEV has 1.5-liter capacity producing 132 kW power with the help of a turbocharger and is further connected to the ISG of 40 kW power [11]. The TM1 and TM2 produce 100 kW and 150 kW powers respectively [11]. Two Controller Area Network (CAN) bus systems are used in this architecture. CAN1 transmits the data such as vehicle speed and brake pedal to the Hybrid Control Unit (HCU) and the Engine Control Module (ECM) while the CAN2 is used for communicating between different controllers [11]. This architecture is illustrated in Fig. 7 [11, Fig. 2].

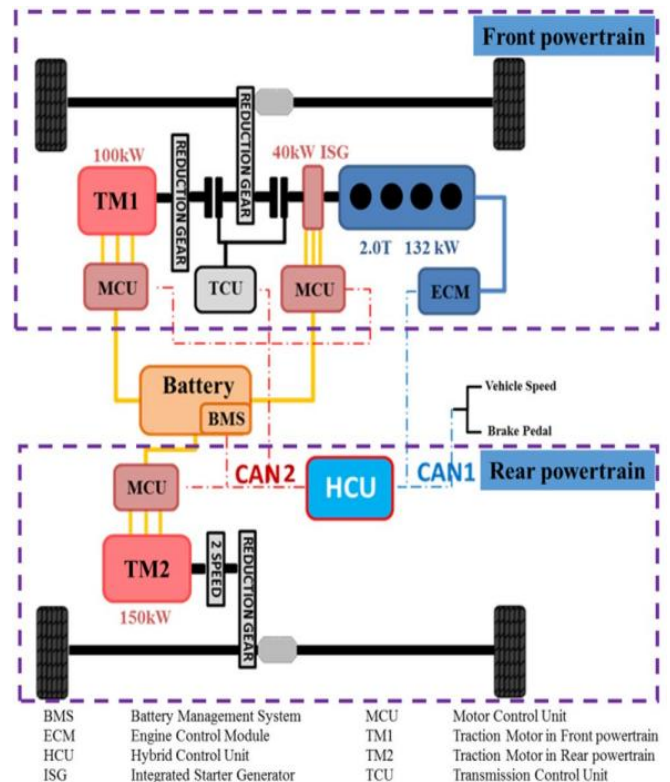


Fig. 7. Architecture of the proposed PHEV [11, Fig. 2]

To make the EMS strategy used in this PHEV more efficient, Chen et al. [11] used six different functional modules. These modules are discussed in further sections.

1) Component Capacity Calculation (CPC) module

To work efficiently, the EMS needs information of some factors affecting the vehicle. Factors such as speed of the vehicle and shaft, and the depth of pedal pressed is fed as inputs to the CPC module which acts as the first module in the EMS [11]. The main function of the CPC module is to monitor the constraints of torque and power required for the driving operation and send this data to the further modules [11].

2) Torque Demand Determination (TQD) module

This module focuses on the torque demanded by the driver as per the driving conditions. This is calculated using the effective accelerator pedal depth and the maximum torque available for the power mode on which the vehicle is currently running [11]. The effective accelerator pedal depth depends on the vehicle speed and the accelerator depth whereas the maximum available torque depends on the maximum torque provided by the ICE, ISG, TM1 and TM2 [11].

3) Determine Function State (FUN) module

This is the main module in the EMS as it focuses on the operation modes. It selects the necessary operation mode after receiving the required torque information from TQD and the inputs from the CPC [11]. There are four operation modes in this PHEV such as pure electric mode (EV), boost mode (BOOST), regenerative braking mode (RE) and pure engine mode (ICE) [11]. In EV mode only the electric motors are used to drive the vehicle [11]. In the BOOST mode the power produced by ICE and TM2 are combined to provide better acceleration and boost to the vehicle [11]. In the RE mode the regenerative braking is utilized where the TM1 and TM2 are used for vehicle propulsion and the battery is charged by the ICE [11]. Whereas during the ICE mode the power is produced only by the ICE [11]. These operation modes are also dependent on the SOC of battery. When it is below 40% the RE mode is selected and when it is above 70% the EV mode is selected [11]. The ICE mode is generally used at vehicle speeds above 80 kmph, but if more torque is required for acceleration, then the BOOST mode is activated [11].

4) Gearbox Control (GBC) module

The function of this module is to choose an appropriate gear ratio for the gearbox which is connected along with the TM2 to the rear axle. It controls the shifting of the gears by determining the speed and required torque for the vehicle and running the TM2 at maximum efficiency. [11]

5) Torque Split (TQS) module

The data generated by the CPC and TQD modules is send to the TQS module. The total torque produced by the vehicle can be splitted and provided to the power generating sources such as ICE, TM1 and TM2 as per requirement with the help of this module [11]. The TQS module is needed for charging the battery when the ICE is running during the regenerative braking mode [11].

6) Torque on Charging (TQC) module

The FUN module signals the TQC module to start charging the battery [11]. The main function of this module is to monitor the battery SOC thus providing maximum power to the electric motors and increasing the range of electric mode. This supports the TQS module while charging the battery during regenerative braking [11].

B. Dynamic Programming (DP) optimization-based strategy

C. Pisanti et al. [12] have proposed an EMS strategy for TtR HEV which uses the dynamic programming (DP) optimization method. Their study focuses on improving the fuel efficiency of the TtR HEV as the traditional vehicle can be easily hybridized by using the TtR architecture [12]. The analysis of fuel economy is obtained by comparing the traditional vehicle with the hybrid vehicle and by running the electric motors without any restrictions to obtain maximum electric power supported by the engine power [12]. For this study, C. Pisanti et al. [12] used a FIAT Punto vehicle with 1.3L diesel engine which is hybridized with a flexible solar panel fitted on its roof and by using two in-wheel motors which are directly coupled to the rear wheels. The DP strategy has the ability of working in reverse order that is beginning from the end time and finishing at the start time and thus requires the history of the vehicle motion [12]. As the algorithms in DP show an exponential increase in the computing complexity, it is used as an EMS strategy for the proposed vehicle [12].

In this study, four different vehicle architectures are used such as conventional vehicle (CV), ideal powertrain hybridization (IPH), TtR with drive by wire (DBW) and lastly the TtR itself [12]. In TtR the accelerator pedal is directly connected to the electronic control unit (ECU) of the vehicle [12]. Thus, the power of the engine depends on the depth of the pedal pressed by the driver as per the driving conditions [12]. Depending on the power split (PS) values between the ICE and the EM, the vehicle runs on five different modes [12]. When $PS=1$ the electric mode is activated [12]. When PS value lies between 0 and 1 and when the power of EM is more than 0 then the vehicle runs on hybrid mode utilizing both the ICE and the EM, but when the power of EM is less than 0 then the regenerative mode is activated for charging the battery [12]. When $PS=0$ the vehicle runs in thermal mode and when the PS value is less than 0 then the hybrid recharging mode is activated for faster charging of the vehicle battery [12]. As the PS value increases from 0 to 1, it is observed that the range of pedal decreases, but its sensitivity increases. In the DBW mode, the accelerator pedal is first attached to a Vehicle Management Unit (VMU) which is further connected to the ECU [12]. This configuration helps to reduce the power from ICE by increasing the power from the EM and thus producing the required power to the vehicle [12]. Due to this configuration the PS values in the DBW mode are not restricted whereas in the TtR mode it is limited till 0.5 and 0.7 [12]. The entire architecture is illustrated by plotting a graph of the pedal range and pedal sensitivity against the PS values in Fig. 8 [12, Fig. 4].

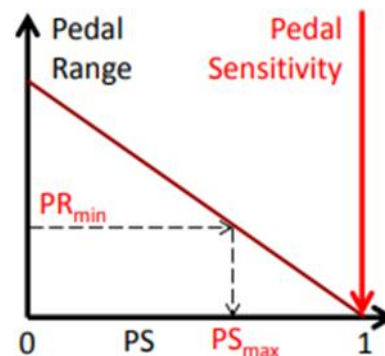


Fig.8 Pedal range and pedal sensitivity against PS values [12, Fig. 4]

V. RESULTS AND DISCUSSIONS

A. Deterministic Rule-based strategy

Chen et al. [11] used the Model-in-the-loop (MIL) simulation for testing the proposed EMS strategy. The simulation is done in the MATLAB-Simulink software by importing the vehicle models from dSPACE ASM application [11]. A PID controller is used as a driver model to calculate the depth of pedal during acceleration and braking which is further fed as inputs to the CPC module of EMS present in the vehicle model [11]. The EMS in vehicle model then selects the appropriate operation mode by using the six functional modules [11]. The simulation is carried out using three cases depending on the battery SOC [11]. In the first case the battery SOC is considered as 20% and the test is performed four times using the New European Driving Cycle (NEDC) [11]. Now as the battery SOC is below 40% the RE mode is selected to charge the battery by using the concept of regenerative braking [11]. When the vehicle speed increases and approaches 80 kmph then the ICE mode is activated [11]. Now if the vehicle reduces its speed below 80 kmph with the battery SOC still below 40% then again, the RE mode is selected [11]. The battery SOC is found to reach 70% supporting EV mode during the fourth test of the first case [11].

In the second case, Chen et al. [11] set the battery SOC to 45% with only one test of NEDC and therefore monitored that the battery SOC falls from 45% to 40% in 875 seconds changing the driving mode from EV to RE. During this phase, the ICE provides power to the ISG which charges the battery using regeneration process [11]. The third case is used to test the maximum acceleration for which the battery SOC is set as 100% [11]. When the speed of the vehicle increases above 80 kmph the EV mode is changed to BOOST mode in just 15 seconds thus providing maximum acceleration performance to the vehicle however it is shifted back to the EV mode when the driver decreases the speed below 100 kmph [11].

After testing the EMS strategy ten times using the NEDC, Chen et al. [11] examined that the proposed EMS strategy integrated with the proposed TtR HEV provided an average fuel economy of 32.88 kmpl for running 110.2 km distance consuming 3.352 Liters of fuel.

B. Dynamic Programming (DP) optimization-based strategy

C. Pisanti et al. [12] tested the proposed TtR HEV by using a Discrete-Time model with Quasi-Static Simulation in MATLAB. They used the DP algorithm developed by O. Sundstrom and L. Guzzella [13]. In this algorithm the battery SOC is used as a state variable and three different models for the ICE, the EM and the battery are considered [13]. The ICE model is derived using the approximation method by Willans, the EM model is derived from the electric power map and the battery model consists of a voltage source which is connected in series with the resistor [13]. The vehicle model used in this simulation is subjected to various driving resistance forces such as air resistance force, wheel resistance force and acceleration resistance force, and the efficiency of the gearbox is considered as 95% [13]. In this study the analysis has been done using three standard driving cycles such as New European Driving Cycle (NEDC), Federal Urban Driving Schedule (FUDS) and the Federal Highway Driving Schedule (FHDS) [12]. C. Pisanti et al. [12] tested the battery SOC with three different TtR architectures such as TtR with PS value less than 0.7, TtR with PS value less than 0.5 and lastly the

TtR combined with DBW configuration and thus they investigated that the battery SOC behaves similarly with all the three TtR architectures. This shows that the PS values with constraints has minimum impact on the battery SOC and thus the fuel consumption [12].

For the first TtR architecture with PS value less than 0.7, C. Pisanti et al. [12] compared the vehicle torque with the torque produced by the in-wheel motors connected to the rear wheels by plotting a graph using the FUDS driving cycle. This graph is illustrated in Fig. 9 [12, Fig. 6]. The points which are present on the X-axis with zero in-wheel motors torque are produced by the regenerative braking mode as the maximum value of PS in this architecture is 0.7 [12]. It is observed that the in-wheel motors torque tends to reach its highest values in both its negative and positive sides as the vehicle torque increases from its negative side to its positive side [12]. During the traction, the thermal mode is selected most of the times [12]. It is noticed that for this architecture even if any PS value between 0 and 0.7 is chosen, the PS value always tends to the maximum value of 0.7 thus making it difficult for the recharge mode for which the PS value should be less than 0 [12]. Thus, a basic control strategy can be achieved by using the PS value in regenerative braking mode and the real values of battery SOC, to utilize the maximum value of PS available in this architecture which is 0.7 [12].

The results obtained by C. Pisanti et al. [12] in terms of fuel consumption in kmpl for the three driving cycles such as NEDC, FUDS and FHDS are provided in Table I [12, Tab. 6]. This shows that the fuel consumption has almost same values for all the three TtR architectures. After comparing with the corresponding conventional vehicle (CV) it was found that the proposed TtR HEV provides an average fuel economy of 9% in absence of DBW and by using the urban driving cycle (FUDS) [12]. However, C. Pisanti et al. [12] further investigated that by increasing the efficiency of the in-wheel electric motors the average fuel economy can be increased to 18%.

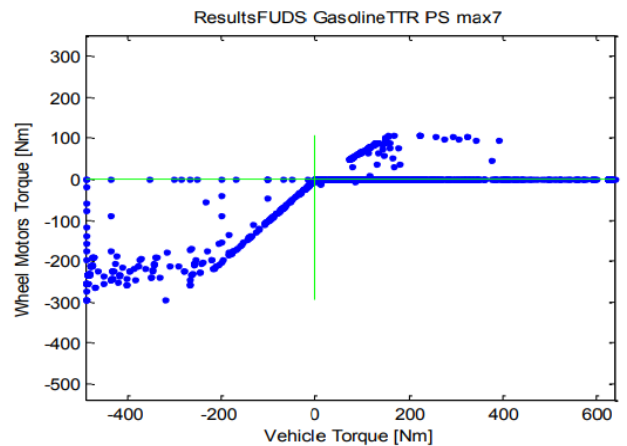


Fig.9 Vehicle Torque vs In-wheels Motors Torque [12, Fig. 6]

TABLE I. Fuel economy (km/l) for different driving cycles [12, Tab. 6]

Scenario	NEDC	%	FUDS	%	FHDS	%
1.CV	15.09	0	14.67	0	16.82	0
2.IPH	16.75	11	17.68	20.52	17.30	2.85
3.TTR DBW	16.13	6.89	16.61	13.22	16.93	0.65
4a.TTR PS≤0.7	15.52	2.85	16.24	10.70	16.78	-0.24
4b.TTR PS≤0.5	15.32	1.52	16.16	10.16	16.76	-0.36

VI. CONCLUSION

The comparison done in this paper illustrates the advantages and disadvantages between real-time application and optimisation precision. The results produced by the DP method shows better fuel economy. The tests are carried out using three standard driving cycles such as NEDC, FUDS and the FHDS. The TtR HEV with DP method provided an average fuel economy of 9% for urban driving cycle (FUDS) but it was not suitable for the highway driving cycle (FHDS). However, because of its high computing complexity, it is limited in real time applications.

On the other hand, the deterministic rule-based approach, improved by the IPM technique, provides a balance between real-time practicality and fuel economy. The power split between the ICE and the EM is efficiently managed by the IPM method which is capable of taking immediate actions for the changing driving conditions thus providing better fuel economy. For the deterministic rule-based strategy, the TtR architecture was tested using the NEDC cycle only. After testing ten times, the proposed TtR HEV provided an average fuel economy of 32.88 kmpl. The vehicle used for DP method is Fiat Punto with 1.3L diesel engine. Comparing it with the traditional Fiat Punto III 1.3 Multijet (85 Hp) which offers fuel economy of 22.73 kmpl for urban driving, the proposed TtR HEV accounts to 24.77 kmpl of fuel economy. This shows that the TtR HEV with deterministic rule-based strategy is a better choice for the real-world applications.

The research done on the TtR architecture shows its increasing popularity and capability of integrating it with the traditional vehicles. Further research should concentrate on increasing the computational efficiency of optimization-based strategies such as DP method and further develop it with rule-based strategies.

REFERENCES

- [1] M.F. M. Sabri, K.A. Danapalasingam n, M.F. Rahmat, "A review on hybrid electric vehicles architecture and energy management strategies", *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 1433-1442, Jan. 2016, doi: <https://doi.org/10.1016/j.rser.2015.09.036>
- [2] Stigka EK, Paravantis J a, Mihalakakou GK, "Social acceptance of renewable energy sources: A review of contingent valuation applications", *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 100-106, April. 2014, doi: <http://dx.doi.org/10.1016/j.rser.2013.12.026>
- [3] Wei Liu, "Introduction to hybrid vehicle system modeling and control", pp. 25-61, March 2013, doi: <http://dx.doi.org/10.1002/9781118407400>
- [4] Iqbal Husain, "Electric and Hybrid Vehicles: Design Fundamentals (3rd ed.)", CRC Press, Feb. 2021, doi: <https://doi.org/10.1201/9780429490927>
- [5] F. R. Salmasi, "Control Strategies for Hybrid Electric Vehicles: Evolution, Classification, Comparison, and Future Trends," in *IEEE Transactions on Vehicular Technology*, vol. 56, no. 5, pp. 2393-2404, Sept. 2007, doi: <https://doi.org/10.1109/TVT.2007.899933>
- [6] J. Meisel, W. Shabbir and S. A. Evangelou, "Evaluation of the Through-the-Road Architecture for Plug-In Hybrid Electric Vehicle Powertrains," 2013 IEEE International Electric Vehicle Conference (IEVC), Santa Clara, CA, USA, 2013, pp. 1-5, doi: <https://doi.org/10.1109/IEVC.2013.6681143>
- [7] Y. Gao and M. Ehsani, "Design and Control Methodology of Plug-in Hybrid Electric Vehicles," in *IEEE Transactions on Industrial Electronics*, vol. 57, no. 2, pp. 633-640, Feb. 2010, doi: <https://doi.org/10.1109/TIE.2009.2027918>
- [8] C. Desai, "Design and optimization of hybrid electric vehicle drivetrain and control strategy parameters using evolutionary algorithms", Doctoral dissertation, Concordia University, Dec. 2010, doi: <https://spectrum.library.concordia.ca/id/eprint/7496/>
- [9] Naser Azim Mohseni, Navid Bayati, Thomas Ebel, "Energy management strategies of hybrid electric vehicles: A comparative review", *IET Smart Grid*, Sep. 2023, doi: <http://dx.doi.org/10.1049/stg2.12133>
- [10] Zhu, Di & Pritchard, Ewan & Dadam, Sumanth & Kumar, Vivek & Xu, Yang, "Optimization of rule-based energy management strategies for hybrid vehicles using dynamic programming", *Polish Scientific society of Combustion Engines*, vol. 184, pp. 3-10, March 2021, doi: <https://doi.org/10.19206/CE-131967>
- [11] Ming-Yen Chen, Kang Yang, Yun-Zhong Sun, Jung-Ho Cheng, "An Energy Management Strategy for Through-the-Road Type Plug-in Hybrid Electric Vehicles", *SAE International Journal*, vol. 8, pp. 61-74, Sep. 2019, doi: <https://doi.org/10.4271/08-08-01-0004>
- [12] C. Pisanti, G. Rizzo, V. Marano, "Energy Management of Through-The-Road Parallel Hybrid Vehicles", *IFAC Proceedings Volumes*, vol. 47, pp. 2118-2124, Aug. 2014, doi: <https://doi.org/10.3182/20140824-6-ZA-1003.02494>
- [13] O. Sundstrom and L. Guzzella, "A generic dynamic programming Matlab function," 2009 IEEE Control Applications, (CCA) & Intelligent Control, (ISIC), St. Petersburg, Russia, 2009, pp. 1625-1630, doi: <https://doi.org/10.1109/CCA.2009.5281131>