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ADAPTIVE ENERGY MANAGEMENT STRATEGY FOR SUSTAINABLE OPERATION OF HYBRID ELECTRIC VEHICLE

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Abstract: Hybrid electric vehicles (HEVs) in the transportation sector is spearheading the industry towards embracing green technology to ensure the sustainability of the environment. HEVs offer significant reduction of exhaust emissions while retaining vehicle performance achieved via a revolutionary energy management strategy (EMS) which reforms the management of power flow from the dual energy sources of a HEV. However, researchers are faced with challenges to extract the maximum performance out of HEVs due to the contradicting nature between its main objectives, namely vehicle performance, fuel consumption and cost. In this study, an investigation focusing on the fuel-saving potential of a power-split type HEV using a fuzzy logic-based EMS is conducted. The purpose of this research is to explore methods to improve fuel efficiency of a HEV through a smart and adaptive EMS. The power flow in the proposed model is decided based on its current vehicle speed and the global discharge rate value derived from the real-time battery state-of-charge and remaining trip distance. From simulations over standard drive cycles, the proposed controller is able to outperform a rule-based EMS by an improvement of up to 65.4% in terms of fuel consumption which subsequently reduces the volume of pollutants released to the atmosphere.

Keywords: HEV, energy management strategy, fuzzy logic, fuel efficiency, global discharge rate.

Introduction

Fossil fuel is a finite substance that has been driving the world's industrial revolution since its inception. However, dependency on its combustion properties has negatively affected the atmospheric quality as hazardous tailpipe fumes are emanated to the air from all sorts of human activities. The COVID-19 pandemic, which halted economic growth worldwide in 2020 has caused the annual demand for oil to drop by 9% from 2019 (International Energy Agency [IEA], 2021). The transportation sector was the biggest contributor of CO_2 emission behind power generation at around 25% in 2018 (IEA, 2020). Strict emission standards are imposed to force manufacturers to produce more energy-efficient vehicles (EEVs). These standards imposed by governments and related agencies aim to aggressively reduce fuel consumption and exhaust emissions. To abide to these stringent regulations and as fuel prices are fickle to the unstable conditions of the market, the transportation sector has seen innovations towards greener vehicles with the ultimate objective of achieving zero emission as car manufacturers and researchers are finding ways to push the industry forward while dealing with these challenges in the best way possible.

Hybrid electric vehicles (HEVs) with the combination of internal combustion engine (ICE) and electric motor (EM) at their core of propulsion are currently the most popular selection in the EEV segment. In their operation, HEVs still produce exhaust emissions due to the inclusion of the ICE but with the presence of the electrical drivetrain and proper power flow management strategies, HEVs operate with lower fuel consumption and produce lesser emissions as a result (Enang & Bannister, 2017; Singh *et al.,* 2019; Sabri *et al.,* 2021). With

HEVs, there is no fear of having no recharging stations in the vicinity as they are capable of operating similarly as conventional vehicles at any given time and the on-board battery pack is constantly being recharged when possible and discharged when necessary to allow a hybrid mode operation, which yields high fuel efficiency that is unattainable by conventional vehicles in the same segment (M. Sabri *et al.,* 2016; Enang & Bannister, 2017).

The main objectives of HEVs revolve around the idea of sustainability, which are to cut back the reliance on fossil fuel (sustainable resources), to reduce hazardous exhaust emissions (sustainable environment) and to ensure the sustenance of the battery pack (sustainable design and material). The genuine challenge in achieving these objectives is the contradictory nature between the power demand, fuel consumption and cost. For example, more fuel is required to extract more power from the ICE to satisfy the driver's demand, but it will result in unfavourable fuel consumption and consequently exhaust emissions. However, if fuel consumption is aggressively restricted, less power could be extracted from the ICE and in turn, excessive strain will be put on the EM, which might not be sufficient if the electrical drivetrain is not proportionately sized and it could lead to battery failure. Furthermore, going for the absolute best performance from the dual drivetrain will incur a high system cost (M. Sabri *et al.*, 2016; Huang *et al.,* 2018). The problem is further convoluted by the desire to avoid a performance penalty compared with conventional vehicles. Therefore, finding the right optimum balance of HEV efficiency is the key to a successful HEV development. From the literature and observations on the recent developments in HEV research, researchers are applying various methods from drivetrain optimisation (Tran *et al.,* 2020) and energy storage optimisation (Bai *et al.,* 2020) to an energy management system (EMS) design based on deep learning algorithms, such as online data-driven EMS using model-based Q-learning (Lee *et al.,* 2020) and parametric study on reinforced learning (Xu *et al.,* 2020) to extract every bit of performance from modern HEV; thus, proving that the robustness of the HEV system allows researchers to approach the EMS problem from many different perspectives.

The difficulty in addressing the power flow control in HEV arises given the limited energy supply from the battery pack and the requirements to minimise fuel consumption and exhaust emissions whenever possible. A carefully formulated EMS is crucial. EMS is a control algorithm that decides on a vehicle's operating points, which is at the heart of every HEV control system (Enang & Bannister, 2017; Martinez *et al.*, 2017; Huang *et al.*, 2018). There are many types of EMS and they vary in their complexity and execution, but they are designed to achieve the same goal. They are largely divided into online and offline types and have been the topic of interest for many researchers over the years. For any chosen HEV architecture, the EMS is responsible in managing the dual energy sources and the power flow within the constrained system of the HEV to satisfy the driver's demand and other objectives. It is important to have an accurate representation of the vehicle model of the HEV as a platform to perform the simulations needed to verify the performance of the chosen HEV architecture.

The most common type of EMS being deployed in commercial HEVs currently is the deterministic rule-based EMS. This type of EMS uses simple rules to determine the mode of operation that the HEV should execute in real time (M. Sabri *et al.,* 2016; Enang & Bannister, 2017). Most rule-based EMS are designed to prioritise driver's demands that is determined by vehicle speed and followed by state-of-charge (SOC) preservations whenever possible through regenerative braking or when cruising at a high speed. However, they are not designed to push the boundaries of peak efficiency due to the rigidness of the rules, which do not allow for the adaptation to everchanging vehicle and driving conditions. As a result, the design approach that relies heavily on exact mathematical models and fixated rules such as rule-based EMS, almost always yield non-optimal solutions. This impreciseness affects the overall efficiency of the vehicle.

On the other hand, fuzzy logic has been used in a variety of applications thanks to its robustness and relatively high efficiency. In fuzzy logic control, fuzzy sets have elements with degrees of membership between 0 and 1, called the membership function, in a series of fuzzification and defuzzification process to map two or more interrelated sets of parameters. In other words, the available sets of data are non-linearly mapped to each other by the membership function which allows for a wider array of output options (Enang & Bannister, 2017; Mohd Sabri *et al.,* 2018).

In recent years, researchers have applied fuzzy logic to EMS problems with different levels of success (Mahyiddin *et al*., 2016; Dawei *et al.,* 2017; Gujarathi *et al*., 2017; Tian *et al*., 2018; Wang *et al*., 2019; Singh *et al*., 2020). Their contributions are summarised in Table 1.

From the literature, the selection of fuzzy logic is focused on as the method of choice for the research as it often offers the perfect balance of complexity and performance.

Table 1: Recent proposals on fuzzy logic-based EMS

Publication	**HEV Configuration**	**Contribution**
Dawei *et al.* (2017)	Parallel HEV	• Intelligent fuzzy logic control strategy optimised using genetic algorithm (GA) • Ratio between target and demand EM torque and battery SOC as inputs for fuzzy controller • Torque distribution ratio between EM and ICE as output • Reduction in fuel consumption and emission via avoidance of peak torque by ICE and better-balanced battery management
Gujarathi *et al.* (2017)	Parallel plug-in HEV	• Fuzzy logic-based EMS decides on preferred operating points to minimise fuel consumption • Battery SOC-required torque and SOC-required speed are inputs for fuzzy logic controller • Resulted in significant reduction in fuel consumption and emission for a modified HEV
Mahyiddin *et al.* (2016)	Series HEV	• Fuzzy logic applied for battery management • Different membership functions are observed to affect the power flow dynamics between ICE, generator and battery • Triangular membership shape chosen for its better power flow performance and lower fuel consumption
Singh *et al.* (2020)	Power-split HEV	• Fuzzy logic-enabled EMS based on torque demand, battery SOC and regenerative braking • EMS follows driver's demand while allowing ICE and EM to operate efficiently • Performance validation through hardware-in-the-loop setup using FPGA-based controller • Reduction in fuel consumption and emission with exceptional drivability

Tian *et al.* (2018)	Hybrid bus	• Optimal power flow solutions for different drive cycles are obtained offline using Pontryagin's minimum principle • A neural network module is trained to learn the optimal battery SOC curves and generate SOC reference curves using partial trip data • An adaptive fuzzy logic controller is applied to trace the reference SOC curve • The output highlights the benefits of SOC usage planning with up to 13.49% of the fuel saved on trained and untrained drive cycles
Wang *et al.* (2019)	Parallel HEV	• Fuzzy adaptive-equivalent consumption minimisation strategy (Fuzzy A-ECMS) is proposed • Created by combining ECMS obtained from PMP with fuzzy logic controller to adjust the equivalent factor (EF) based on the differences between reference and actual battery SOC • Simulations produced up to 5.91% improvement in fuel economy and more stable SOC sustenance

Materials and Methods

A model-based design is deployed in this research that consists of several steps.

Modelling of the Power-split HEV

An original series-parallel HEV with rule-based EMS model Simulink is downloaded and its parameters are modified (Miller, 2021). A highly customisable model is preferred to allow for flexible drivetrain design more suited for the objectives of the research. The Simulink model will consist of the vehicle body, ICE, EM/generator, battery dynamics and other related blocks. The driver model is included in the form of a proportional-integral (PI) controller which will generate the speed demand signal based on standard drive cycles. This stage is important to help deepen the understanding of the HEV architecture and the functions and behaviour of the components underneath. The aim is to develop a simulation platform that will be used as the foundation in the EMS controller design and simulation that follow. MATLAB® has been chosen as the tool to develop the desired simulation platform. The original Simulink model is shown in Figure 1.

The original model is a power-split type HEV with rule-based EMS at the EMS control. The mathematical modelling backbone of the model follows exactly as the one in Mohd Sabri *et al.* (2018) and will not be elaborated further. The focus of the research will be directed to the EMS control block, where the original rule-based EMS will be replaced by a fuzzy logic-based EMS. The results from the rule-based EMS will be used as a benchmark for comparison.

Analysing and Synthesising the EMS Controller

In the second phase of the research, an optimal power flow strategy is formulated to determine when and how the hybrid powertrain should be used to drive the vehicle. Fuzzy logic has been chosen as the method of choice due to its robustness and flexibility, which allows for the online implementation of the EMS controller, which is aligned with the research objective. An EMS controller is then designed to achieve the optimal power flow solution in the power-split HEV model. The EMS controller should be able to decide the amount of power or torque to be produced by the ICE and the EM, respectively, based on the desired driver request and drive cycle requirement. The SOC and other relevant constraints related to vehicle performance are also included to ensure the resulting performance from the model is theoretically attainable in real life. For the time being, drivability and

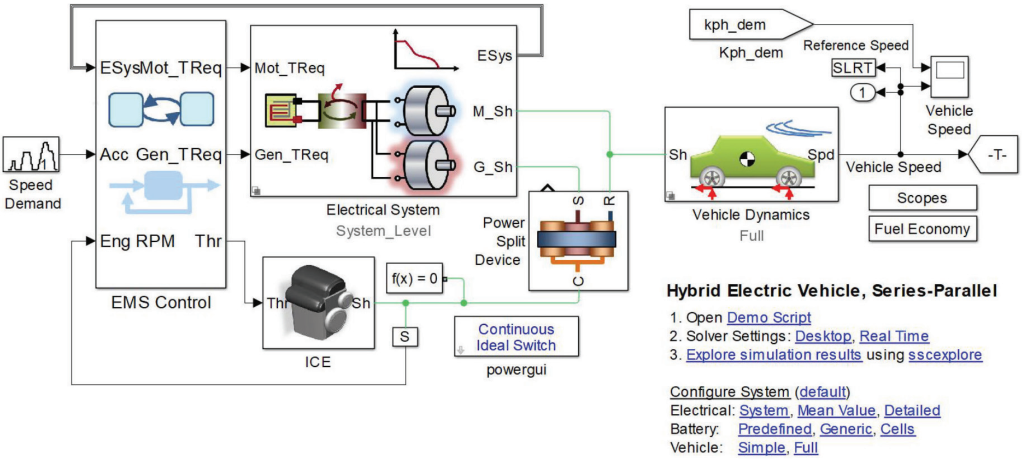
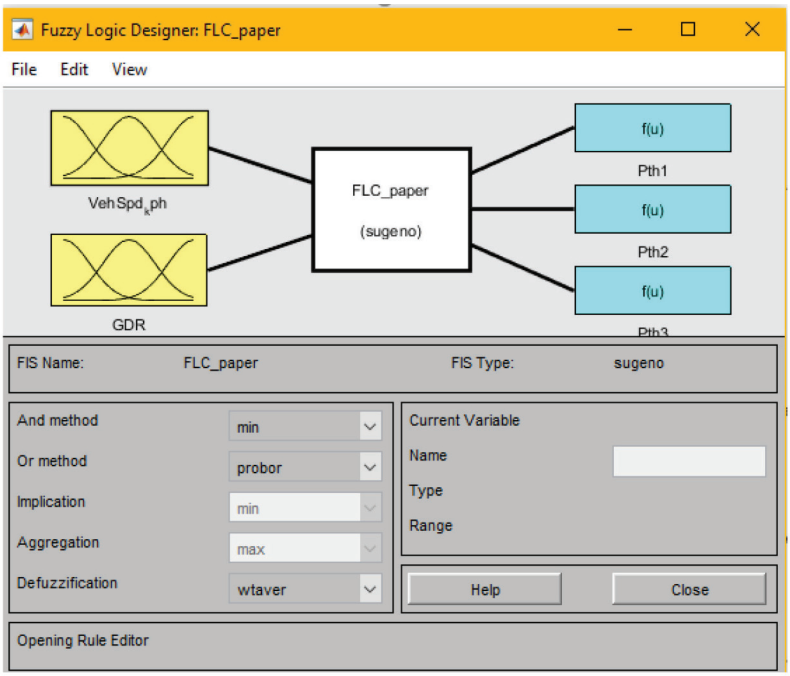


Figure 1: HEV Model in Simulink from Mathworks

fuel consumption have been chosen as the performance indicator for the EMS controller.

The Fuzzy Logic Toolbox in MATLAB is used in the design process of the controller using the Fuzzy Logic Designer, visualised in Figure 2.

Here, a Sugeno type solver, which relies on the "singleton" theory to produce either a constant or a linear mathematical equation, is used as it relies on the weighted average of the outcomes of the fuzzy rules. On the input side, are the speed demand and a dynamic input, called



FIS Name: FLC_paper
FIS Type: sugeno
And method: min
Or method: probor
Implication: min
Aggregation: max
Defuzzification: wtaver
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Figure 2: Fuzzy logic designer in MATLAB

the global discharge rate, which is obtained from Equation 1 (Mohd Sabri *et al.,* 2018).

$$GDR = \frac{SOC_{init} - SOC_{tar}}{l_{tot}} \tag{1}$$

SOC_{init} is the real-time SOC value and SOC_{tar} is the lower threshold for SOC, which is set at 30%. This threshold is a determined value for the lithium-ion (Li-ion) battery pack and the SOC should not fall below it or the battery pack will be damaged. l_{tot} stands for the remaining trip distance, which is obtained from GPS data. From this equation, the GDR value will slowly increase as the HEV approaches its pre-determined destination but will decrease rapidly if the HEV uses the EM too frequently, causing the SOC to drop. From simulations, it is found that the GDR value can be set between 0 and 8%/km. GDR at 0% represents the situation where the SOC threshold has been reached and the HEV will operate in a charge sustaining (CS) mode where the ICE will be used to drive the vehicle and 20% of its output torque is diverted to charge the battery pack and is the worst-case scenario for the HEV. GDR at 8% (or higher) is the best-case scenario where the SOC is at the peak and the remaining trip distance is close, allowing the HEV to take full advantage of the electrical drivetrain to exclusively provide power to the wheels in a charge depleting (CD) mode while operating at a maximum fuel saving mode.

On the output side, the controller will determine the power output by the EM, labelled as P_{th}, depending on the GDR and speed demand. This value is divided into three classes of speed, which are slow ($P_{th}1$), medium ($P_{th}2$) and fast ($P_{th}3$), to ensure high precision results. The fuzzy set for P_{th} is obtained through offline simulations using dynamic programming. The full controller design is shown in Figure 3.

P_{th} is the value of power deliverable by the EM at any given time which is set to allow the vehicle to operate in hybrid mode for the entirety of the trip. This means that if the remaining distance is still further away, the HEV system only uses the battery power sparingly with the ICE, which is set to operate efficiently to drive the vehicle to avoid the GDR approaching 0%. The MODE_SELECT represents the selection of power flow ratio to be executed by the ICE and EM in every cycle depending on the value of P_{th}. If the P_{th} value is higher than the power demand, the HEV will operate in CD and fuel saving modes, but if the power demand exceeds the P_{th} value, the HEV will operate in hybrid mode. The modified controller block is shown in Figure 4, where the final output of the EMS controller are the three signals – Mot Enable, ICE Enable and Gen Enable, acting as the "switches" for the PI-speed controllers to send out their respective signals.

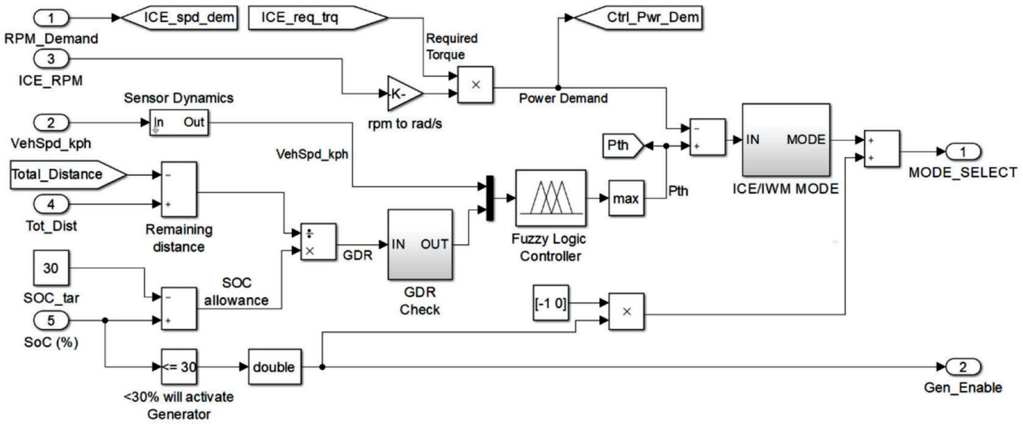

Figure 3: Fuzzy logic-based EMS design

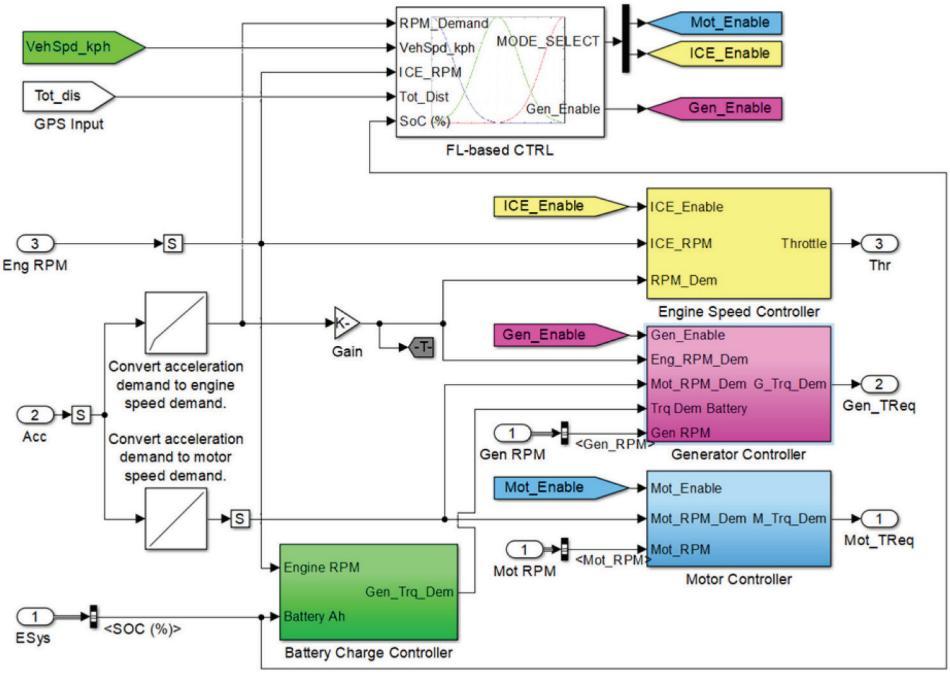

Figure 4: Main EMS controller block

Simulating the TtR HEV Control System

The third phase involves simulations and analyses of the HEV model with the fuzzy logic-based EMS controller to test its feasibility in minimising fuel consumption and to ensure drivability. This stage is important to test the effectiveness and capability of the proposed optimal power flow strategy before it can be implemented in an actual HEV system. Standard drive cycles such as the ECE R15, EUDC, NEDC and HWFET (Sabri *et al.,* 2021) which are commonly used by other publications are used in the simulations to ensure the integrity of the developed model. The Simulink platform in MATLAB is a powerful tool that allows easy and detailed analysis of a simulation. The following data acquisition setups displayed in Figure 5 is deployed for this research to ensure all the relevant parameters from speed demand down to the final fuel consumption are observed and analysed.

Results and Discussion

Standard drive cycles are used in this simulation to ensure the integrity and validity of the HEV model. The parameters for the HEV platform are stated in Table 2. For all the simulations, the initial SOC is set at 75% capacity. For the results, two drive cycles will be selected to better highlight the performance gain by the fuzzy logic-based EMS compared with the original rule-based EMS. First is the ECE R15 cycle which represents a low-speed, short distance urban driving condition and the second is the Highway Fuel Economy Test (HWFET) cycle which represents a high-speed, long distance highway driving situation.

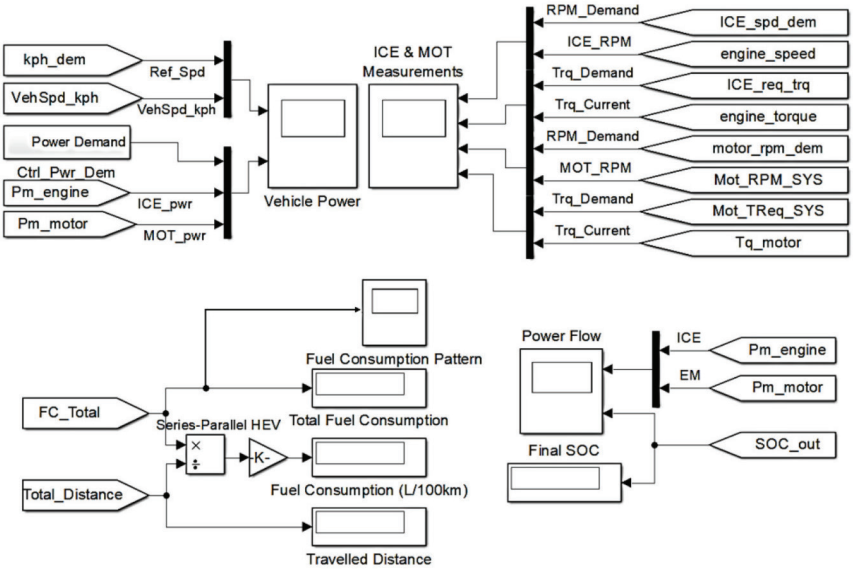

Figure 5: Data acquisition setup

Table 2: Vehicle parameter

Vehicle Body	
Mass	1,200 kg
Frontal area	2.16 m^2
ICE	
Maximum power	114 kW
Speed at maximum power	5,000 rpm
Maximum speed	6,000 rpm
Fuel consumption	By speed and torque
EM	
Maximum power	30 kW
Maximum torque	400 Nm
Battery Pack	
Type	Li-ion
Nominal voltage	200 V
Rated capacity	15 Ah

Urban Drive Cycle (ECE R15)

This drive cycle is a low-speed urban driving with frequent stop-go operation, a distance of 995 m and an average speed of just 18.4 km/h. The results for the simulation using the fuzzy logic-based controller are exhibited in Figure 6. For drivability, the EMS controller is able to fulfil the driver's demand while the P_{th} value calculated by the fuzzy logic-based EMS consistently exceeds the power demand for this cycle. The power flow pattern for this cycle can be observed in Figure 7 where the clear discrepancy in power flow management is exhibited by both methods.

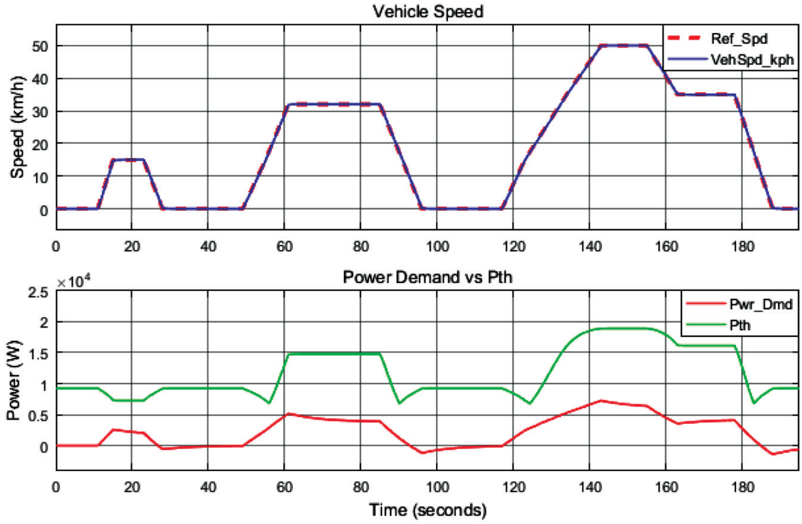

Figure 6: Speed vs power on the ECE R15 drive cycle

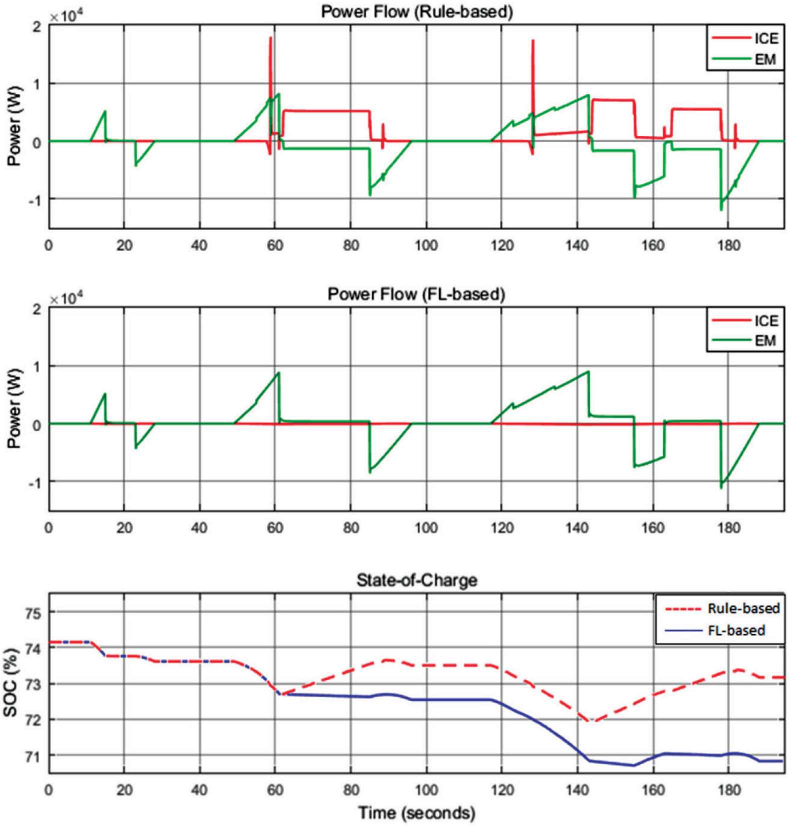

Figure 7: Power flow comparison between rule-based and FL-based EMS on ECE R15

The rule-based EMS uses the ICE whenever the car accelerates or cruises and subsequently charges the battery. On the other hand, the fuzzy logic-based EMS fulfil the power demand by only using the EM while the ICE remains idle all the time, thus achieving the better fuel economy as shown is Figure 8. The rule-based EMS achieved a fuel consumption of 0.1664 L with a final SOC of 73.16% whereas the fuzzy logic-based EMS achieves a 21.86% better fuel economy at 0.13 L with a final SOC figure of 70.83%. These results show that the HEV can be driven by only the EM for the whole trip while still retaining respectable SOC balance at the end of the cycle. The fuzzy logic-based EMS achieves better fuel economy by not unnecessarily extracting the power from the ICE.

Highway Fuel Economy Test Cycle (HWFET)

This is a high-speed highway driving condition with high average speed of 77.7 km/h over a distance of about 16.5 km. This cycle features high-speed cruising with high power demand with no stop-go instance. The result of the simulation shows that the fuzzy logic-based EMS is still able to provide acceptable drivability performance in Figure 9 and Figure 10 shows the difference in power flow management between both methods.

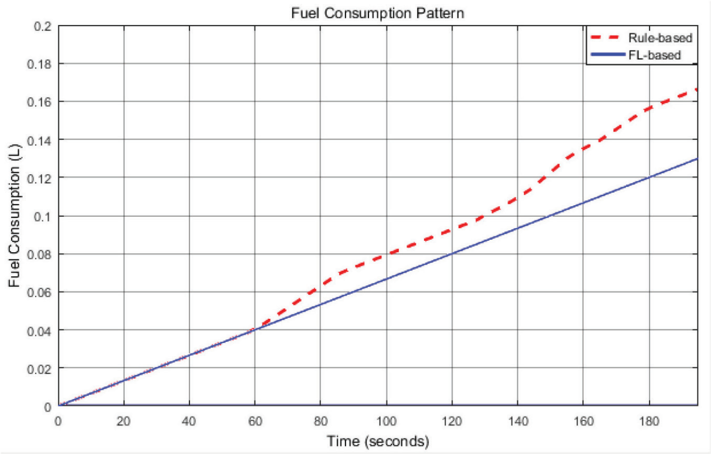

Figure 8: Fuel consumption comparison on ECE R15

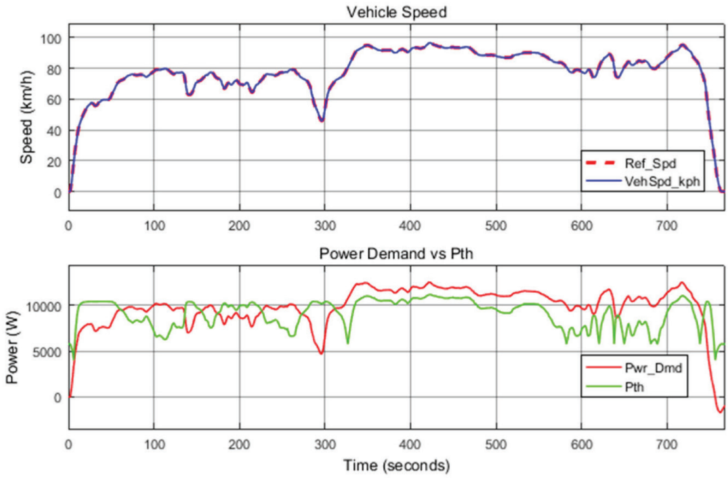

Figure 9: Speed vs power on the HWFET drive cycle

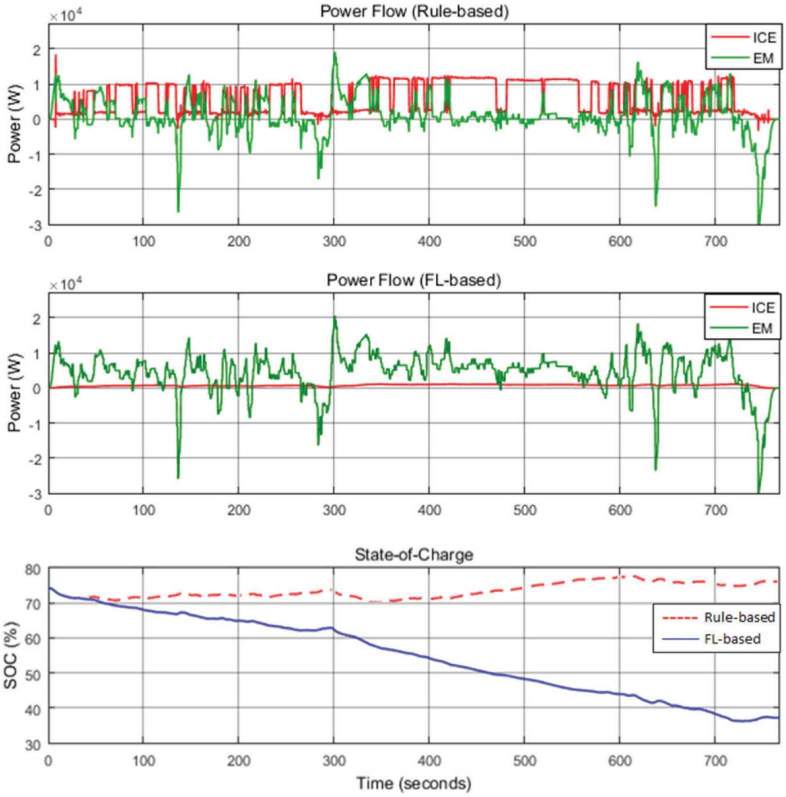

Figure 10: Power flow comparison between rule-based and FL-based EMS on HWFET

The rule-based EMS once again lavishly used the ICE to fulfil the power demand while the EM which is more energy efficient is left under-utilised. This subsequently caused aggressive SOC sustenance which saw the final SOC value standing at 76.12%, exceeding the initial SOC. High SOC is not necessarily a bad thing but only if it is achieved through efficient recharging and regenerative braking, which neither occurred here as the vehicle was cruising at a high speed most of the time. On the fuzzy logic side, the P_{th} is calculated to match the power demand, with the later part of the simulation showing that the demand exceeds the P_{th} due to a constantly high demand for power. However, the EMS still prioritised the power delivery from the EM and only extracted the remaining power requirement from the ICE. This results in a very low fuel consumption despite the higher power demand as depicted in Figure 11 and the low final SOC of 37.22%, which is still above the lower threshold of 30% at the end of the cycle.

Due to the restricted usage of ICE by the fuzzy logic-based EMS, the new controller is able to achieve a fuel economy of just 0.512 L compared with 1.422 L by using the rule-based EMS to mark a 65.4% improvement. This outcome is the result of the aggressive push for fuel efficiency by the fuzzy-logic controller, which sees the opportunity to fulfil the power demand using mostly the EM through its fuzzy logic algorithm.

Conclusion

From the simulations, it can be observed that the proposed control method is able to achieve sustainable HEV operation to suppress fuel consumption to the minimum while retaining drivability by careful formulation of power

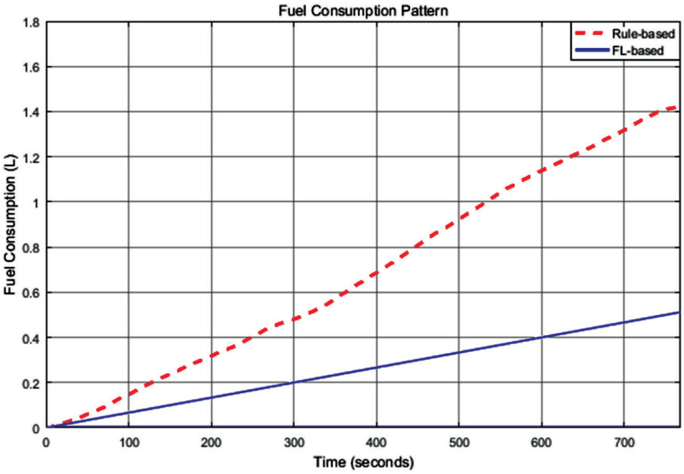

Figure 11: Fuel consumption comparison on HWFET

flow from the dual energy sources. Several conclusions can be construed from the simulation results. Firstly, the modelling of the HEV and the design of a new fuzzy logic-based controller on the same platform can be considered as a success as this model provides a good platform for simulation and further developments thanks to its exploits of commonly used equations in vehicle dynamics simulations. The traits of MATLAB® as a powerful simulation tool has provided a robust platform for an efficient HEV development and the EMS controller has performed exceptionally on standard drive cycles to boost the performance of HEVs compared with using a simple rule-based EMS. The simulations have provided invaluable data for future improvements of the research.

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