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Investigation on Energy performance of Fuel Cell Hybrid Electric Vehicle (FC-HEV)

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Abstract

The Environmental problems faced in a conventional vehicle with Internal Combustion Engine (ICE) is widespread as harmful gases are being released into the atmosphere. Another problem is related to fossil fuel availability which is reducing drastically due to high power demands all over the world. Looking for an Environmentally friendly solution is best alternative to cater to these problems and thus Electric Vehicle is the way forward for the future of transportation (Jiageng et al., 2021, p. 1). There are different types of electric vehicle technologies currently available like Battery electric vehicle, Fuel Cell based vehicle technologies. The FC-HEV is used in this research work which considers battery as well as FC as sources. In the present chain of vehicles in this segment, multiple problems persist with respect to energy consumption and uncertainty in meeting the required power demands. A lot of researchers have worked in this area by developing a control strategy to work on this Energy Management aspect. The use of traditional Energy Management Strategy (EMS) techniques is not solving all problems like optimal energy usage, and optimal use of FC and batteries to meet maximum range in vehicles. Still work needs to be done in this area as in most of the papers referred, they have not considered developing an optimum control strategy which aims at effective utilization of multiple energy sources (battery, fuel-cell) without over-compensating on the constraint limits specified for individual sources. Therefore, in this project, a novel energy management strategy using Fuzzy Logic Controller is developed to mitigate the need for excess energy and to reduce the over-usage of an individual source. The advantages of using this EMS are improvement of fuel cell economy, reducing the Fuel Cell degradation and improving the Efficiency of the system (Di Shen et al., 2020, p. 1). Finally, a detailed Simulation study using MATLAB/ Simulink is done to showcase the effectiveness of the proposed energy management strategy over conventional one.

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Abbreviations	**Description**
ICE	Internal Combustion Engine
FC-HEV	Fuel Cell Hybrid Electric Vehicle
EMS	Energy Management Strategy
EM	Electric Motor
DC	Direct Current
SOC	State of Charge
PEM-FC	Proton Exchange Membrane Fuel Cell
PID	Proportion Integral Derivative
FTP-75	EPA Federal Test Procedure
UDDS	Urban Dynamometer Driving Schedule
NYCC	New York City Cycle
FLC	Fuzzy Logic Controller

Acknowledgements

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1 Introduction

In the following section multiple aspects related to the need for FC-HEV, advantages of using FC-HEV, objectives to be achieved from the current work and overview of the process to be followed will be discussed.

1.1 Background to the Project

The excessive usage of ICE engine vehicles has led to the drastic increase in air pollution due to harmful gases being released into the atmosphere which in turn leads to global warming, Also, there is reduction in the amount of fossil fuels available to meet consumer requirements due to exponential rise in population of human beings (Di Shen et al., 2020, p.1). Thus, Fuel Cell Vehicles or Battery Electric Vehicles becomes the new alternative to cater to these problems. But fuel cell vehicles generally have slow response time and are unable to meet peak power demands of the vehicle. Furthermore, it can easily degrade and reduce the efficiency of the system. So, by hybridizing the Fuel Cell with a battery it is possible to achieve higher power needs, reduce degradation of the system and an added benefit of recharging the battery using regenerative braking.

1.2 Project Objectives

In the currently existing Fuel Cell Vehicles, it is difficult to meet peak power requirements generally during hill climbing scenarios, high acceleration conditions. So, the traditionally available fuel cell mechanism is replaced by adding an additional power storage device (Battery) to help address the above issues (Silvia C et al., 2020, p. 1). Also, the range travelled by the normal fuel cell vehicle is less which can be improved comparatively by using this concept. It can also reduce the cost incurred on hydrogen gas re-fuelling by applying proper energy management principles thus benefitting the End User.

To perform this functionality, Energy Management strategy needs to be applied which caters to the required amount of energy as per the user demand and supplies it from multiple energy sources. So, a controller will be required to monitor the energy demand/need and thus supply the required energy from multiple sources in the plant model. Multiple controllers can be used here to perform this Energy Management Control strategy and each controller will have its advantages and disadvantages which will learn about more in the upcoming section.

To develop an Effective Energy Management strategy, there are multiple challenges which is to be monitored in the system-

1) Increasing the Operating Efficiency of Fuel Cell component and in turn decreasing the fuel cell degradation.
2) Maintaining the Battery State of Charge in the admissible ranges to improve battery usage lifetime. (Note-This can be checked by operating it under different drive cycle scenarios)

In this project, a Simulation Model using MATLAB Simulink software is developed for the following Fuel Cell Hybrid Vehicle architecture using the Powertrain Blockset. It also consists of a controller model for devising an optimal energy management strategy to increase the range of travel, minimize the cost incurred for the Fuel Cell recharging/replacement and increasing the battery lifetime (Jiageng et al., 2021, p. 1). Multiple controllers were considered -PID Controller (Conventional) and Fuzzy Logic Controller to understand the usage of the multiple power sources in each controller model. Also, comparative analysis was done to understand which is better. To verify the effectiveness of the developed controller model, multiple drive cycles such as FTP75, UDDS etc. were considered as an Input to measure/analyse the total energy, power data consumed/absorbed by the vehicle model at the output side by using a dashboard.

An optimum control mechanism will be proposed in this thesis to allocate required energy/power to the FC-HEV system (Derick et al., 2020, p. 3). The following objectives were achieved at the end of this work.

a) Reduction in the consumption of Hydrogen in Fuel Cell -This will also reduce the degradation of the system and optimize the use of FC.
b) Increase in the Fuel Economy- By using proper control mechanism the fuel consumption is reduced and the Range/Distance travelled by the vehicle is increased.
c) To prevent Excessive Discharge of Battery- By using the current controlled mechanism of the Fuel Cell the SOC of the Battery can be maintained to not go below a certain percentage.
d) Excessive charging prevention-As the battery is recharged with the help of Fuel Cell it needs to be monitored whether the battery does not get charged beyond a certain level (Silvia C et al., 2020, p. 1).

1.3 Overview of This Report

The following report consists of firstly the literature review section where the findings from the different research papers have been identified. The Methodology section consists of the methods for research design and the process followed in the current work. The Analysis section consists of multiple factors considered to measure the performance of FCHEV. The Requirement section mentions the functional and non-functional requirements of the project. Moving further in the design section, implementation and testing sections explanation of the current work is provided with observed behaviours and findings. Then in the project management section the timelines and other management aspects considered in the current project are mentioned. Further in the critical appraisal section the detailed understanding of the project with respect to advantages and disadvantages of the system developed has been noted. Finally, in the conclusion part the final understanding of the findings from the project have been tabulated. Lastly, in the student reflection section the process which was followed along with the lessons learnt and further changes which could have been done in the project work have been mentioned.

2 Literature Review

Hybrid Electric Vehicles are a promising solution to the environmental problems and emissions caused by the Internal Combustion Engine (ICE). Also, there is shortage of petroleum/fossil fuels which leads us to looking for an alternative energy supplement. Fuel Cell Electric vehicle is one of the best solution available as there is no emission of pollutant gases and on top of it, they also have a greater energy density (Jiageng et al., 2021, p. 1). Hybridization of FC-EV is done so that vehicle can meet peak power demand when needed in drive cycle. Furthermore, it helps in improving the efficiency of the system and reducing the size of fuel cell components. In an FC-HEV, the driving range is longer and re-fuelling time is quite short.

In a FC-HEV, there are multiple ways in which this hybrid structure can be made like series hybrid, parallel hybrid, or series-parallel hybrid. Generally, the FC acts as the main component/energy source battery acts as secondary/auxiliary source. The battery can also be recharged by the FC component in the vehicle as it works in alignment with the State of Charge (SOC). The mechanism of charge sustaining is applied here as emphasis is on maintaining the battery SOC in the appropriate range (Silvia C et al., 2020, p. 1).

Proton Exchange Membrane (PEM-FC) will be considered for this research work. It is one of the mostly used application since they are compact, have high power density, low operation temperature and low operating pressure in comparison with other FC technologies (Alvaro Macias et al., 2019). The disadvantage which they possess is the high cost with respect to structure. In addition, the cost incurred in purchase of hydrogen gas is also higher than the normal Hybrid Electric Vehicle (HEV). Thus, to solve the relevant issues mentioned above a control strategy needs to be developed for optimized energy management of FC-HEV to make the system more efficient and economically advantageous (Derick F et al., 2020, p. 1-2).

There are Different drive cycles to measure the vehicle performance in the Automotive Industry such as UDDS, FTP-75, NYCC. The Urban Dynamometer Driving Schedule is a mandated dynamometer test on tailpipe emissions of a car that represents city driving conditions. The cycle simulates an urban route of 7.5 mi (12.07 km) with frequent stops. The maximum speed is 56.7 mph (91.2 km/h) and the average speed is 19.6 mph (31.5 km/h). The cycle has two phases: a "cold start" phase of 505 seconds over a projected distance of 3.59 mi at 25.6 mph average speed, and a "transient phase" of 864 seconds, for a total duration of 1369 seconds. In the case of FTP-75 i.e., EPA Federal Test Procedure is identical to UDDS with additional UDDS cycle added to it. The procedure is updated by adding the "hot start" cycle that repeats the "cold start" cycle of the beginning of the UDDS cycle. The average speed is thus different, but the maximum speed remains the same as in the UDDS. The New York City Cycle (NYCC) features low speed stop-and-go traffic conditions (FTP-75. Wikipedia). The Truck segment vehicles are generally used to transport parcels/goods from one place to another and hence was being used in test.

There are generally two different types of controllers available -one is an Offline Controller and other one is Online. While using offline optimization techniques it considers a fixed path/track (Drive Cycle path) which is the basis for Public Transport and Racing Cars. In those scenarios where the driving path is uncertain as to what will happen in the future, Online Controllers are used (Fazhan Tao et al., 2020).

Different papers have presented different control strategies to undergo energy management scenarios. Two different control methods mentioned are Heuristic method and optimal control theory method. Heuristic method uses Rule based strategies to control parameters. There are multiple ways in which this approach can be used like hysteresis band control (HBC), fuzzy logic controllers, maximum efficiency point tracking (MEPT), maximum power point tracking (MPPT), neural network modelling and extremum seeking method (Jamila Snoussi et al., 2018). The Problems faced in this type of methods are when the complexity of the model increases it will be very difficult to perform prioritization of multiple rules. Thus, it will not be able to exploit maximum performance of the vehicle. Many Researchers have worked on multiple optimization techniques like Particle Swarm Optimization (PSO), Genetic Algorithm (GA) to find out the optimum values of control parameters and thus helping increase the fuel economy of the system.

Whereas optimal controllers are considered advantageous as they have the capability to handle multiple system constraints simultaneously. One of the most used methods here is Model Predictive Control (MPC) (Di Shen et al., 2020, p. 1-2). The following controller can also control multiple variables together and thus have an added advantage. Some practical implementation challenges are still faced in these types of controllers like if the predictive control mechanism implemented is inaccurate then it will be difficult to control future power request for the system which in turn will lead to reduced efficiency of the system.

Proportional-integral-derived controllers (PIDs) are widely used in many industrial processes due to their simplicity and efficient control mechanism. This type of control is generally used in fluid, flow, heat, and electrical systems as well as in motor vehicles. In addition, the PID controller design is considered easy to use because only three parameters need to be set and tuning can be done. Some of the most used PID tuning methods in the control engineering literature are Ziegler and Nichols, Cohen and Conn, Relay method, and Relatus Apparatus. These methods are very useful and get good results when controlling unconstrained systems, but some of them can be applied to many systems (Daming Zhou et al., 2018). However, this method still does not consider limitations when setting up the controller, so this method is not suitable always as they do not lead to an optimal control signal mechanism.

Fuzzy logic control (FLC) is the most researched area in fuzzy set theory, fuzzy inference, and applications of fuzzy logic. The application spectrum of FLC ranges from industrial process control to biomedical devices and safety. Compared to traditional control methods, FLC is ideal for solving complex, problem-free problems that can be managed by skilled workers unknowingly by their nature.

So, developing an optimal control system for EMS without the need for predicting future driving scenarios and operating under various driving scenarios efficiently is the motive behind this study. Through these control mechanisms, it was clear that multiple challenges exist in each of the control mechanism, but we just need to devise a strategy which is more economical and effective for Driving.

3 Methodology

Research Design-

1) Collecting secondary Data -
- Principle method- (Published papers) relevant to topic were found out and understood the process undertaken and benefits to be achieved from it.

- Benefits of FC-HEV- In the currently existing Fuel Cell Passenger Vehicles it is difficult to meet peak power requirements generally during hill climbing scenarios, high acceleration conditions. So here we replaced the traditionally available fuel cell mechanism by adding an addition power storage device (Battery) to help address the above issues. Also, the Range travelled by the normal fuel cell vehicle is less which can be improved comparatively by using this concept. Adding on top of it can also reduce the cost incurred on Hydrogen Gas re-fuelling by applying proper energy management principles thus benefitting the End User.

2) Identifying the Model or Block Diagram -
- Primary Method- Validated the Inputs and Output and different parameters to be considered for the Topic and it is the end goal which was achieved.

- Approach- In the FC-HEV combination of Fuel Cell and Battery was used as it is a hybrid configuration. Here battery is charged by FC whenever required through converter and it can work as a supplement to FC whenever excess power is requested by EM.

  The current of the Fuel cell Module is controlled by regulating DC/DC converter and the Power required by battery is calculated as difference between Power required by Electric motor and Power of the Fuel Cell vehicle.

  Control mechanism is developed to measure the reference value of FC current by applying proper optimization technique.

3) Developed a Simulation Model to validate the Topic and verified the objectives mentioned previously.

The methodology considered the following sequence of sections mentioned below:

1. Requirement Analysis:
   a) A comprehensive analysis of the needs of the FCHEV project was made by going through various performance targets, energy efficiency, economic advantages, and mitigation techniques.
   b) Identified key topics which have already been researched by individuals, such as engineers, researchers, as per literature available in database (like journals and conference papers), to gather their input and understand their needs and expectations. Based on the initial literature review, the research gaps were identified.
   c) Information on operation and malfunction of the FCHEV system, considering various parameters such as output torque, speed, SOC, range, fuel consumption/economy and control techniques used.

2. System Design:
   a) Development of detailed system architecture and design for FCHEV, including fuel cell technology, battery, electric propulsion (electric motors), powertrain and control system (i.e., plant models and controllers) integration.
   b) Described the interface and interaction of various components such as fuel cell components, battery components, electric motor, and inverter/converter (power management) basically inside a Plant model.
   c) Used modelling and simulation tools to validate designs and optimize system performance.

3. Parameter Selection and Updating:
   a) Researched and analysed about various commercially available fuel cell technologies, battery topologies, engine types and control systems.
   b) Checked information on currently used vehicles related to FCHEV to ensure compliance with current standards in terms of performance, cost, durability, and compatibility.
   c) Based on the data collected, the most appropriate measures in the design are determined and used for further research.
   d) Selected the most suitable ratings for FCHEV systems and used those parameters in the models.

4. Simulation/Software Development:
   a) Created simulation prototypes of FCHEV systems based on design specifications and component/parameter selection. It also includes the development of software components such as controllers and control systems for power management.
   b) Used the programming language in MATLAB according to the specific requirements of each software module.
   c) Integrated multiple components together to ensure compatibility. This is done in various ways such as unit testing, integration and system testing to evaluate the reliability and functionality of the software.
   d) Iteratively refined the model blocks and its parameters based on testing results by re-verifying the simulation.

An iterative strategy was applied to the existing model to ensure the effectiveness of the system. Thus, the model is regularly refined by changing the parameters and repeating the simulation.

6. Testing and Evaluation:
   a) Several tests were performed on the above FCHEV simulation model to evaluate the performance, effectiveness, and reliability of the data.
   b) Performed functional and non-functional tests to ensure that the system meets the requirements.
   c) Performance tests to measure performance in different driving cycles and different vehicle classes/segments.
   d) Check the performance of the FCHEV system by comparing multiple controllers to determine the quality of each system.

7. Documentation and Reporting:
   a) Documented the entire development process, including design, software architecture, and test results. In addition, data analysis was recorded to identify inconsistencies between the multiple controllers used and the main outcomes found out from it.

8. Iterative Improvement:
   a) Analysed test results to identify areas of improvement and applied appropriate adjustments to the model.
   b) Followed the redesign process to modify the FCHEV system based on results, multiple iterations of the model, and user needs.
   c) Continued to evaluate the performance and functionality of the FCHEV system to make minor improvements and innovations to the system.

Ethical Considerations:
Ethical considerations included evaluating the environmental impact of the FCHEV system and ensuring its alignment with sustainability goals. Thus, by considering the following factors it was found out be following the required guidelines as mentioned above.

4 Requirements

Functional Requirements:

1. Information and Measurement:
    a. The system should be able to record and measure major functionalities such as power output, voltage, current, fuel economy, energy consumption, and exhaust emissions.
    b. Must provide data capable of capturing and recording data during investigation of the topic.

2. Driving Cycle Simulation:
    a. The system must be able to simulate various types of driving, including city, highway, and mixed traffic, to mimic real-world driving.
    b. It should allow parameters such as speed and acceleration to be adjusted to accurately simulate different driving situations and handle it properly.

3. Performance Analysis:
    a. The system should facilitate the analysis of energy performance indicators, including energy consumption, energy output, range, fuel consumption and emissions.
    b. It should be possible to calculate and compare these parameters under different driving conditions and test conditions.

4. Comparative Analysis:
    a. The system should support comparison of the energy efficiency of FCHEVs with current energy management strategies of ICEs or HEVs and additionally it should be able to compare performance between different controllers.
    b. Should provide functionality to evaluate and measure the improvement in energy efficiency achieved by FCHEV compared to baseline.

Non-Functional Requirements:

1. Accuracy and Precision:

   a) The system must ensure that measuring instruments (MATLAB Simulink) are accurate and provide reliable information.
   b) It should reduce measurement errors and deviations during data collection and analysis.

2. Scalability:
   a) The system should be scalable to accommodate different experimental configurations and changes in FCHEV system design.
   b) Should allow the integration of additional input or measurement parameters into the modelling environment to gather more detailed information as needed.

3. Usability and User Interface:
   a) The system should have a user interface that allows easy configuration of parameters and understandability.
   b) It should provide a clear and visual view of the collected data and analysis results.

4. Reliability and Repeatability:
   a) The system should be reliable, able to provide consistent and repeatable results across multiple observations and test runs.
   b) Procedures, experimental setups, and data analysis procedures should be documented to ensure reproducibility by other investigators.

5. Performance:
   a) The system must have sufficient computing power and processing power to process simulated data, analysis, and simulations.
   b) Must be efficient and effective to provide timely results during the investigation.

The following mentioned requirements will help in developing an effective energy management strategy to measure vehicle performance and help us give a better clarity of the data.

5 Analysis

In this section, we will conduct a detailed analysis of a Fuel Cell hybrid electric vehicle (FCHEV) data collected during energy performance analysis. The analysis is based on the following performance indicators such as power consumption, power output, range, and fuel economy.

1. Energy Efficiency Analysis:

   a) Calculation of energy consumption: The energy consumption of FCHEV is calculated by dividing the total distance travelled by the total energy consumption. The average energy efficiency for electric plant in the drive cycle test is found to be around 60-70 percent in a passenger car segment.

   b) Comparison with measurement results: The data is compared with measurement results to evaluate the power performance of the FCHEV. The base value for conventional internal combustion engine vehicles is usually between 20 to 30 percent only. FCHEV's energy efficiency is way higher as per the data captured above, a significant improvement over baseline.

2. Power output measurement:

   a) Power output measurement: Measure the power output of the FCHEV electric motor during acceleration and steady driving. The results showed a maximum power of 80-100 kW for a passenger car segment thus providing adequate performance for driving needs.

   b) Comparison with test results: To evaluate the electrical power of FCHEVs, we compare it with the results of similar components of HEVs. The power rating is within the range of 60 to 100 kW. The FCHEV's maximum power is 80kW, which falls within the range, and its performance is satisfactory.

3. Range Analysis:

   a) Range measurement: FCHEV range is measured by determining the distance the vehicle can travel at a given speed. The study found that the average distance travelled was around 250-300 miles.

   b) Comparison with the base: To evaluate the range of the FCHEV, we compared it to the base models of the hybrid electric vehicle. The range considered there is usually between 250 and 400 miles.

4. Fuel Economy Analysis:

a) Fuel Economy Measurement: The fuel economy of FCHEV is measured by tracking amount of energy consumed per kWh (converted to gallons) equivalent required to travel a certain distance (miles). The study found the average fuel economy was around 130-140 MPGe in the passenger segment vehicle and around 14-16 MPGe for Truck segment.

b) Comparison with convention vehicles: To measure fuel economy of FCHEV, it is compared with normal gasoline engine. The average fuel consumption of the gasoline passenger car engine is between 50-60 MPG only which Is far lesser.

In conclusion, FCHEV's energy efficiency analysis shows that it is good for many performance indicators. FCHEV achieves a high operating efficiency as discussed above, which is a significant improvement over conventional combustion engine vehicle. The mentioned findings highlight the potential of FCHEVs as an efficient and cost-effective mode of transport that helps reduce environmental impact and increase energy efficiency.

Further Breakdown can be down based on Use Case of Driving Conditions. For evaluating the energy performance of the FCHEV three use cases have been considered- Urban Commuting, Highway Commuting and Mixed Urban and Highway Commuting. The three systems can also be individually evaluated for multiple parameters like Energy Efficiency, Power Output, Range and Fuel Consumption which you see in the below Figure1.

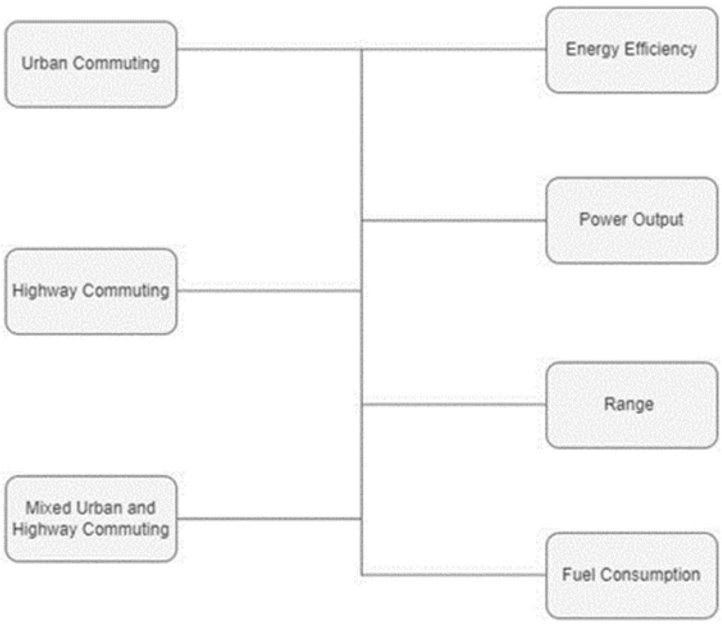

Figure 1 Use Cases (Energy Performance Measurement)

6 Design

Powertrain Model-

The developed FCHEV can be seen as per block diagram mentioned below where you can see a combination of Fuel Cell and Battery as it is a hybrid configuration. Here battery is charged by FC whenever required through converter and it can work as a supplement to FC whenever excess power is requested by EM. The architecture considered can be seen in below Figure2. (Note- The Inverter considered here has been replaced by DC/DC converter as motor used is a DC Motor itself)

The current of the Fuel cell Module is controlled by regulating DC/DC converter and the Power required by battery is calculated as difference between Power required by Electric motor and Power of the Fuel Cell vehicle.

Control mechanism is developed to measure the reference value of FC current by applying proper optimization technique.

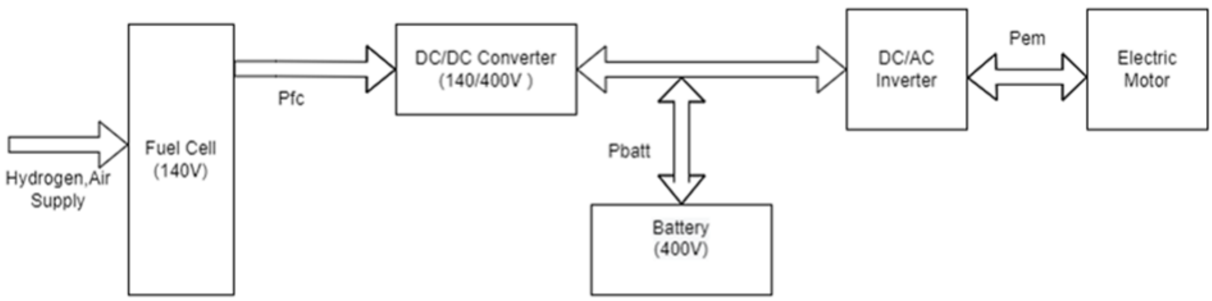

Figure 2 FCHEV Architecture

Plant Model-

In the following system, the Battery can be charged with Fuel Cell using the DC/DC Boost Converter. The Fuel Cell current value is controlled by regulating the converter based on the power demand requirements (Derick F et al., 2020, p. 2-3). The power required by Electric Machine is met by using the Fuel Cell and Battery power excluding power consumed by auxiliary loads.

Motor-

The following part is used to propel the vehicle based on the driver's needs or driving cycle conditions. The Amount of Power Required i.e., Traction Power is calculated by measuring the maximum power required calculation (Jiageng et al., 2021, p. 1). Also, the size of the motor is determined by the following calculations mentioned in the below equation (1).

$$P_m = \frac{V}{1000\eta_T}\left(Mgf\cos\alpha + \frac{1}{2}\rho_a C_d A_f V^2 + Mg\sin\alpha + M\delta\frac{dv}{dt}\right) \tag{1}$$

where P_m is the required power, Vmax is the maximum speed, M is the total vehicle mass, g is the acceleration due to gravitational force, f is the coefficient of rolling resistance, C_d is the aerodynamic drag coefficient, A_f is the vehicle cross sectional area, η_T is the efficiency of the Energy Transfer (motor to wheels), α is slope angle of road or gradeability, δ is the inertia Factor for rotating mass and $Þ_a$ is air density.

$$P_e = \frac{V_{max}}{3600\ \eta_T}\left(Mgf + \frac{C_d A_f V_{max^2}}{21.15}\right) \quad (2)$$

$$P_a = \frac{V_i}{3600\ \eta_T}\left(Mgf cos\alpha_{max} + Mgf sin\alpha_{max} + \frac{C_d A_f V_{i^2}}{21.15}\right) \quad (3)$$

$$P_c = \frac{V_a}{3600 t_a\ \eta_T}\left(\delta M \frac{V_a}{2\sqrt{t_a}} + Mgf \frac{1}{1.5} t_a + \frac{C_d A_f V_{ia^2}}{21.15 \times 2.5} t_a\right) \quad (4)$$

Additionally, calculation can be done in three different scenarios-

1) Power at maximum speed (P_e) – This can be calculated from the above equation (2) itself by considering maximum speed of vehicle.
2) Power at maximum slope (P_a) – This can be calculated from the equation (3) where, P_a is the power at maximum gradeability, V_i is the vehicle speed at maximum gradeability, 30km/h, α_{max} is the angle of maximum gradeability.
3) Power measurement for 0 to 100km/hr change (P_c)- This can be calculated from equation (4) where, P_c is the power at 0-100 km/h of acceleration, δ is correction coefficient of rotating mass, V_a is the final vehicle speed i.e., 100km/h, ta is the acceleration time. The motor peak power P_m, $peak \geq max$ [P_e, P_a, P_c].

Fuel Cell –

The Fuel Cell is the Primary Source of the FCHEV system which provides most of the necessary Power required by the Motor (Jiageng et al., 2021, p. 1). Multiple types of Fuel Cell are available to be used in the market but here PEM Fuel Cell has been used as the primary source.

The power ratio between the fuel cell system and the Total Power of the vehicle is referred to as the degree of hybridization (DOH). The Degree of Hybridization (DOH) required can be found using the following formulas mentioned below in equation (5).

$$DOH = \frac{P_{FCMax}}{P_{sTotal}} \quad (5)$$

The cost of the Fuel Cell System used in the vehicles and its system efficiency can be calculated as per the needs. The Hydrogen consumption can also be calculated based on the efficiency parameters. Overall, by calculating these parameters the degradation of the Fuel Cell part can also be monitored based on these values.

Battery-

There are multiple types of Battery available in the market but if we consider the performance characteristics Li-Ion Battery has excellent energy and power density. So, it is widely used in most of the electric vehicles around the globe.

Typically, battery is used as a supplement to PEMFC whenever required by the system. It works as an additional source which helps in increasing the performance of the FC System. Additionally, it also stores Braking Energy i.e., it helps to recover the lost energy by Regenerative Braking. Overall, the Efficiency of the system is increased.

The Battery state of charge and current can be measured by calculating the open circuit voltage, current and internal resistance of the Battery. This is for the basic calculations part initially.

Multiple battery configurations can be considered while developing a FCHEV system. In first scenario, Fuel Cell acts as the major energy source whereas battery acts as the supplement to the main component. In second scenario, the battery acts as the major source of energy and FC contributes significantly less (Fazhan T et al., 2020, p. 2-3). This scenario can be mapped to the existing configuration through Degree of Hybridization (DOH) concept. Based on the energy requirements from the battery either higher power or higher energy density battery can be used. Here, in our case a higher power density battery will be used which will have a higher power rating and will only be used to supply excess power as per the driver needs when capacity of Fuel Cell exceeded the required power.

Battery degradation is also considered while using this system and SOC of the battery must be maintained and prevents excessive charge and discharge of the battery system (Current change). It is also affected by multiple factors like aging and temperature.

So, these factors must be considered while developing a proper EMS for fulfilling driver demand without over-compensating on individual sources usage.

Controller-

The controller is developed to achieve an optimum set-point value of Fuel Cell current to meet the objectives specified in the below section. Based on the Power demand and SOC of the Battery the controller tries to maintain the amount of Energy drawn from the battery. The system also considers Fuel Cell voltage as an input for measuring the setpoint (Derick F et al., 2020, p. 2-3).

Control Parameters-
Input- 1) Power Required by Electric Motor, 2) SOC of the battery, 3) Voltage of Fuel Cell
Output- 1) Power Supplied by the Fuel Cell, 2) Required Fuel Cell Current.
Process- 1) PID Controller or 2) Fuzzy Logic Controller

PID Controller-

The following controller is used as default controller in the following model. This method of control is best suited for controlling uncertain dynamic systems. It is typically a less complex system as only tuning of K_p, K_i and K_d values is required where K_p is proportional control gain, K_i is Integrator control gain and K_d is derivative control gain.

PID Tuning is done to meet the required Energy management requirements criteria (Xiang Meng et al., 2019). There are multiple standards by which tuning can be done and one of the famous tuning methods is Ziegler-Nichols method. The benefit of using this method is that there is a starting point from where tuning can be done.

The Fuel Cell Power requirement is measured by monitoring the Battery SOC. It calculates the requested power by the driver (Torque, Speed) and then compares it with the SOC of the Battery to decide on what amount must been transferred from the Fuel Cell.

Fuzzy Logic Controller-

The following controller is mostly used in many vehicle applications for Energy Management. It has multiple advantages due to its simplicity and flexibility as it uses If-Then Rules to control the system. The following controller can counter invalid/inaccurate data and improve the efficiency of the system. Also, it is a cost-effective controller hence for vehicles it can act as an added advantage.

Functionality/Working mechanism-
The fuzzy rules generation process plays an important role when designing fuzzy logic controllers. There are four types of fuzzy production methods:

1. A set of Rules that represents certain policies set by the implementer.
2. A set of input data evaluated just before the actual decision.
3. A method for evaluating whether a request complies with specified rules, where data is available.
4. A way to get good results and decide not to look for better.

All required parameters used in fuzzy logic controllers are defined by membership function. Evaluation of policies is done using techniques such as forecasting or discussion. These four fuzzy rules help to obtain control-related points for the measured parameters or outputs. Then, the control centre can be sampled for the number of points and a control table can be created based on this information. The monitoring table contains information about the control centre that can be loaded into read-only memory.

In the following model the Rule Based strategy is followed where the Required Power at the Output and SOC of the Battery is monitored against a specific set of rules to control the Fuel cell power. This method thus helps in proper control of EMS as per the constraints set.

7 Implementation

In the following project, EMS strategy of a FCHEV was implemented in a simulation environment to understand the benefits/advantages of multiple controllers to investigate the Energy Performance of the system.

Numerical Analysis/Calculation-
The data related to different vehicles currently available in the industry were collected and interpreted. The vehicle parameters were tabulated to measure multiple parameters such as Power of individual components (Battery Output, Fuel Cell Output, Inverter Input, Motor Input), System losses and Overall Efficiency of the system. This was done by considering different vehicle speeds and acceleration constants. The default data was taken from either a Commercial Truck or a Passenger Car (Hyundai XCIENT Fuel Cell).

By Applying the following strategy, it was easier to understand the mechanism of Power/Energy Transfer and mathematical formulas applied for measurement. Hence, considering the following calculations it was easier to develop a model.

The Vehicle parameters considered in the process have been mentioned as per Table1 and 2.

S.No.	Parameter	Rating
1.	Fuel Cell Stack	190 kW (95 kW x 2 EA)
2.	Battery	661 V / 73.2 kWh
3.	Motor/Inverter	350 kW / 3,400 Nm
4.	Hydrogen Tank Capacity	32.09 kg H2 (available hydrogen amount at SOF 100%)

Table 1 Plant Model Parameters

S.No.	Parameter	Value
1.	Aerodynamic drag coefficient	0.6
2.	Coefficient of rolling resistance	0.01
3.	Cross-Section area of the vehicle	1
4.	Mass of the vehicle	9795 kg
5.	Gear ratio	4.269

Table 2 Drivetrain Parameters

Simulation Modelling-

The FCHEV Model mentioned in above section was developed in a MATLAB Simulink Environment to investigate the EMS functionality (MATLAB Simulink Library).
The following model consists of a Plant Model and Controller as well as Input and Output parameters. The system developed is a closed loop system where you can see that output parameters are fed back to input side to trace the delta change in parameters (Actuating Error) and thus help control the Input parameter to obtain desired output response. It also consists of an Environmental Parameter Blockset where all the Aerodynamics relevant parameters like Wind, Gradeability, Temperature, Pressure etc are mapped which you can see in Figure 4. These parameters are important to measure the Force applied to the vehicle and hence an important part of the system. The longitudinal driver block which you can see in the Figure 3 mentioned is used to switch between Open Loop and Closed Loop system. Currently, in the implementation the open loop system is not considered.

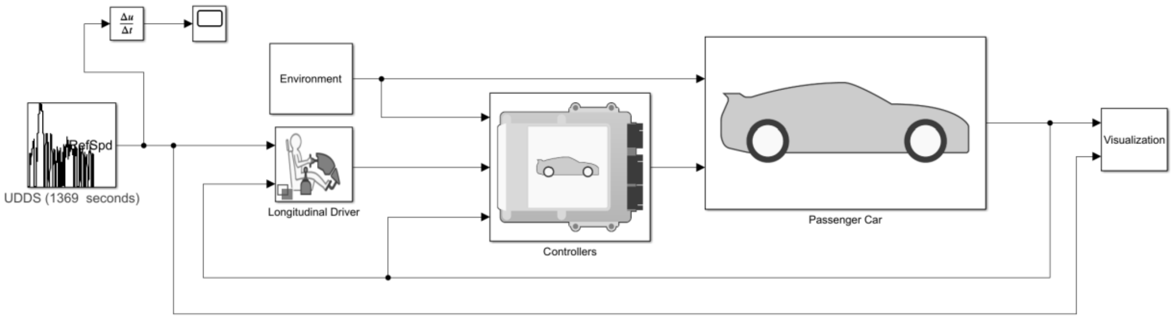

Figure 3 Simulink Vehicle Model

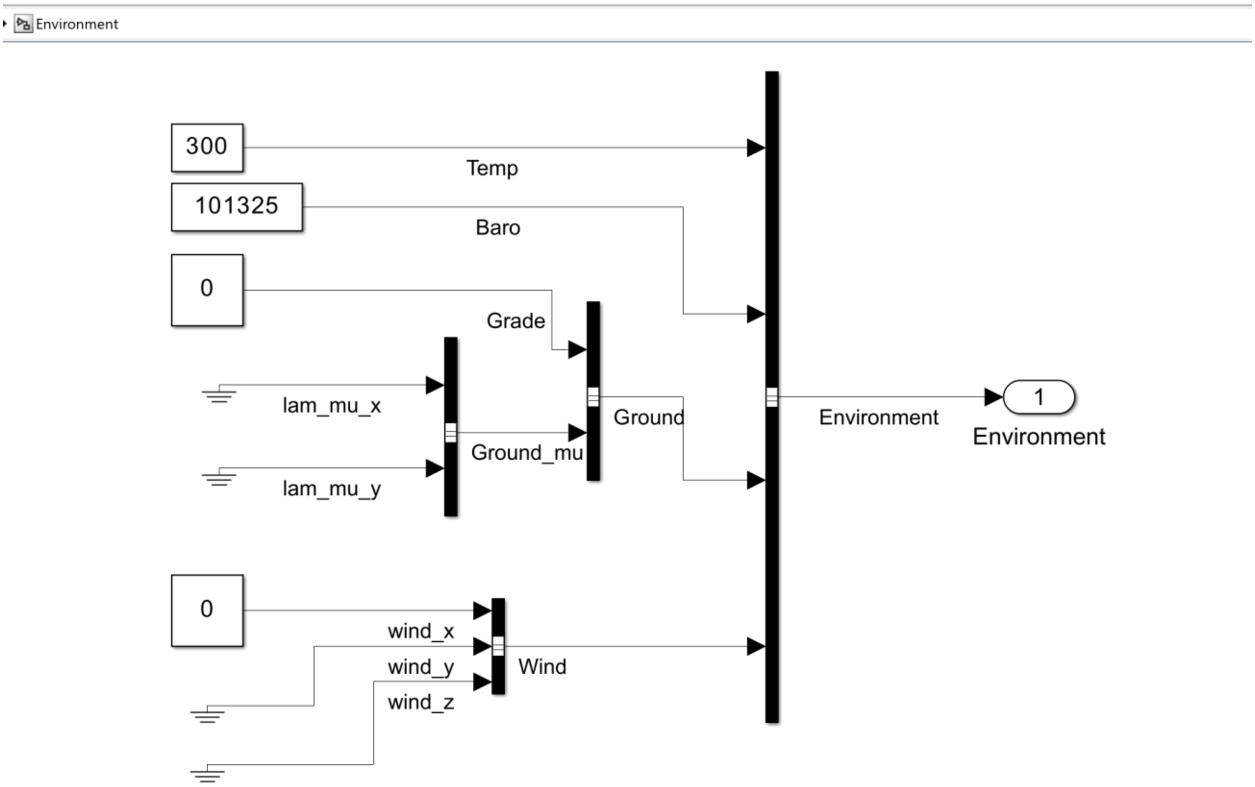

Figure 4 Environmental Parameters

Input Parameters-

The Input considered in the system is different Drive Cycles used in the Automotive Industry such as FTP75, UDDS, NYCC, FTP72, WLTP. Here, FTP75, UDDS and NYCC were considered in the following model to understand vehicle characteristics and energy performance.

The Drive Cycle plots (Speed vs Time) for both can be seen in the below figures. The FTP75 Drive cycle is tested over a period of 2474 seconds where maximum speed which is considered is around 25m/s whereas in the case of UDDS drive cycle it is considered for 1369 seconds with max speed considered to be similar which you see in Figure 5 and Figure 6.

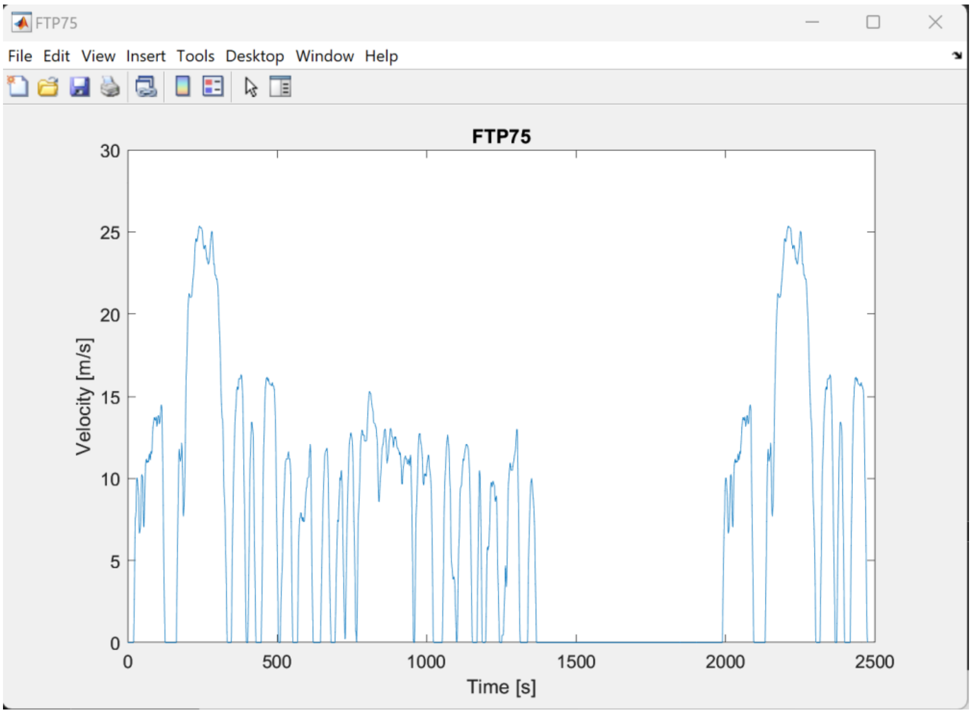

Figure 5 FTP75 Drive Cycle

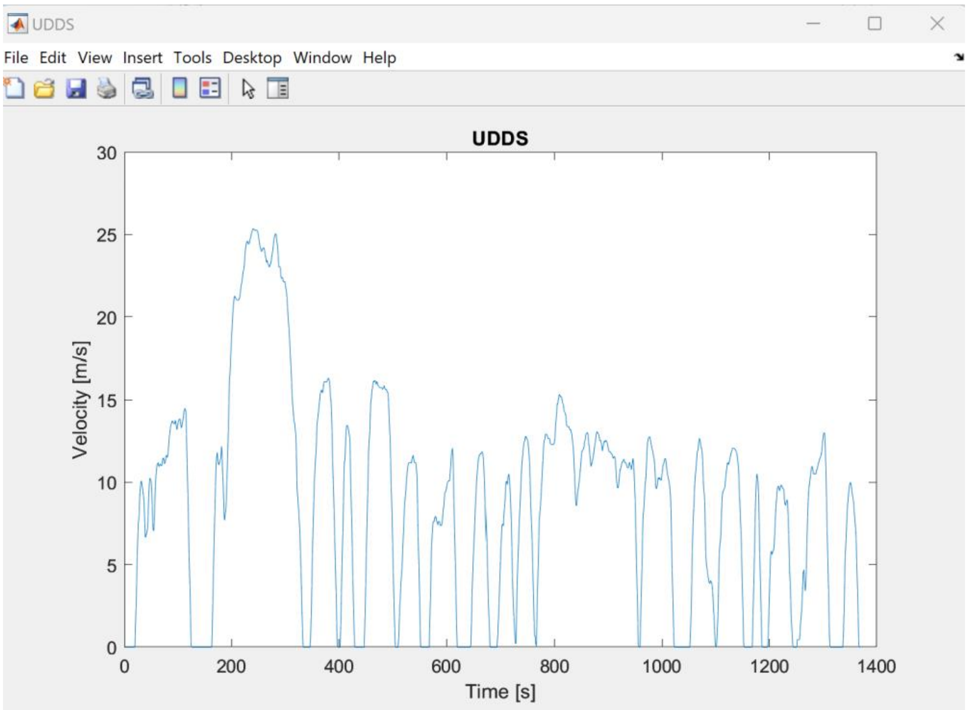

Figure 6 UDDS Drive Cycle

Output Parameters-

The Data from the Plant Model which consists of Plant Model and Drivetrain is collected and represented in a Dashboard Plot i.e., multiple parameters are measured like vehicle actual speed, target speed to compare the estimate difference between requested speed and actual speed processed. The other information measured are motor torque, motor speed, Battery Current and SOC of the Battery, Fuel Cell voltage and Current to monitor the power drawn from individual components based on the needs. The Fuel Economy of the vehicle is also measured in Miles per gallon equivalent (MPGe) to find out the Range the vehicle can travel with a specific amount of Energy. So, by doing this the objectives of the Project are monitored like checking Fuel cell voltage is maintained and not depleting, SOC of the battery is maintained or not, and lastly whether excessive charging/discharging of the battery over the continuous drive cycle.

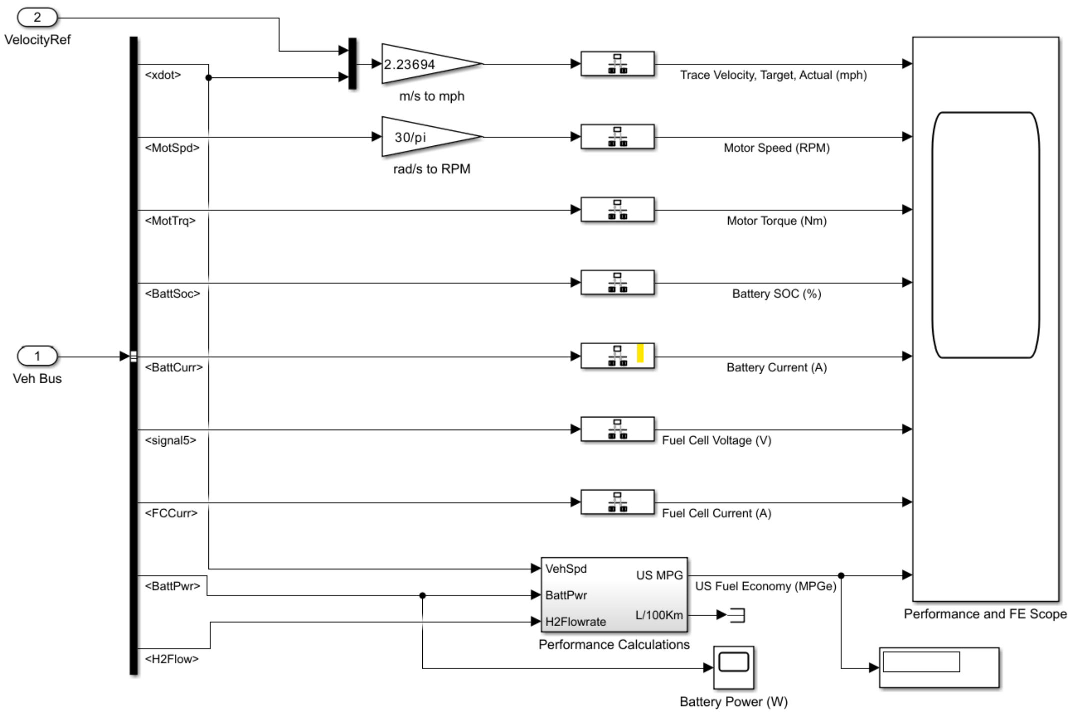

Figure 7 Output Dashboard Parameters

Plant Model-

The Plant model considered here is a Vehicle with parameters values or data taken from current data available for FCHEV. Initial model parameters are taken from the Passenger Car Segment. In the figure given below you can see the two major components of the vehicle that is Electric Plant and Drivetrain. The Electric Plant consists of the main components Fuel Cell, Battery System, and Motor which you can observe in Figure 8. Additional components for Thermal Management of the system also exist for each of the Individual Energy Sources and Motor which is named as Electrical Cooling System. The Fuel Cell model consists of a Boost Converter to boost up the generated Power and the Battery consists of bi-directional DC-DC Converter because it has both energy supply and re-generation mechanism. The battery is recharged from the motor through regenerative braking concept. The SOC of the battery is thus maintained through the recharging mechanism. The data from the Electric Plant is collected and stored in ports to be tabulated in Dashboard Plots.

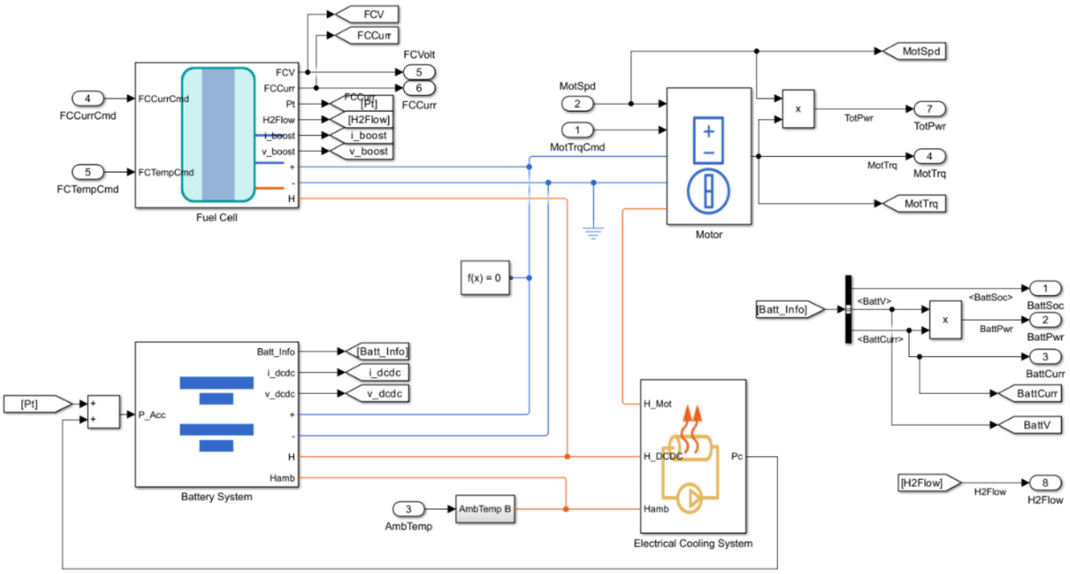

Figure 8 Plant Model

The Drivetrain Model consists of configuration of selecting multiple configurations either Front-Wheel Drive or Rear-Wheel Drive whichever is required so that the following wheels (Front or Rear) will be transferred with the required Power. The Torque and Speed required is supplied to wheels/brakes via the differential component which can be used to drive or stop the vehicle. The data collected from the Plant model system is also sent to the output side. Additionally, the vehicle information is also fed back to the input side as it is mentioned as closed loop system.

The Energy Consumption is also calculated for all the individual components considered here and by calculating that the individual efficiencies of each component considered in the Electric plant and thus overall efficiency of the FCHEV system is determined.

Controller

The control mechanism Is employed in order the perform the Energy Management Strategy and determine the vehicle performance. The main components of the control system are Fuel Cell control, Battery Management system, Torque/Power Management control and Regenerative Braking control. The BMS system is used to monitor the battery charge/discharge amount so that the battery SOC is properly maintained without degrading the battery. The Power Management system is used to monitor the required torque demand and check the amount of power to be transferred from the individual components based on the needs or instead transfer energy back to the Battery through the regeneration mechanism of brakes. The regenerative mechanism is monitored using the regenerative braking control system which will monitor the constrain conditions. Finally, the Fuel Cell control is used to control the amount delivered from the Fuel Cell source based on the user demand and the battery SOC. For the fuel cell current control mechanism is applied to vary the Fuel Cell current based on higher or lower power demands.

We have considered multiple control strategies for Fuel Cell control- one is using PID controller and the other is using Fuzzy Logic controller.

PID Controller-
The SOC of the Battery is monitored by comparing it with the reference FC SOC Target value which is then passed through the PID Controller. The processed value will be used to check the accurate requirement of Fuel Cell Power by subtracting the value obtained from the controller after tuning from the required amount determined from the calculated power (as per the Torque demand and Vehicle speed) which you can see in Figure 9. Here the functionality of PID Controller mainly was to provide a specific gain value which is called Proportional Constant (K_P). The Integrator and Derivative blocks are of minimal use in the current model.

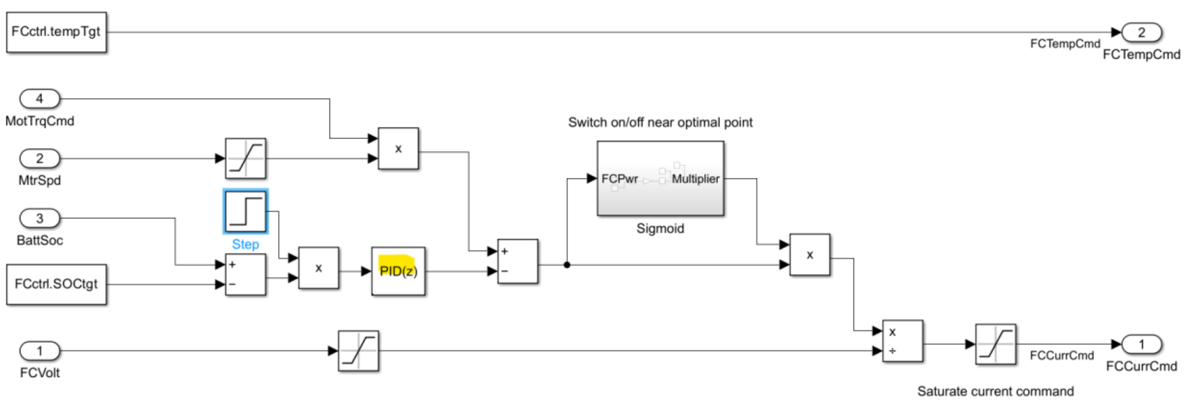

Figure 9 PID Controller Model

So, by doing the following tuning process via PID Controller, the value of FC Power was adjusted as per different speed demands. Hence, the current control was possible by using this mechanism and thus it was able to maintain the Energy Requirements without overutilizing the individual sources.

Fuzzy Logic Controller-

Here the control mechanism is developed to monitor the requested power and SOC of the battery in order to control the Fuel Cell Power requirements and corresponding setting the required Fuel Cell current value.

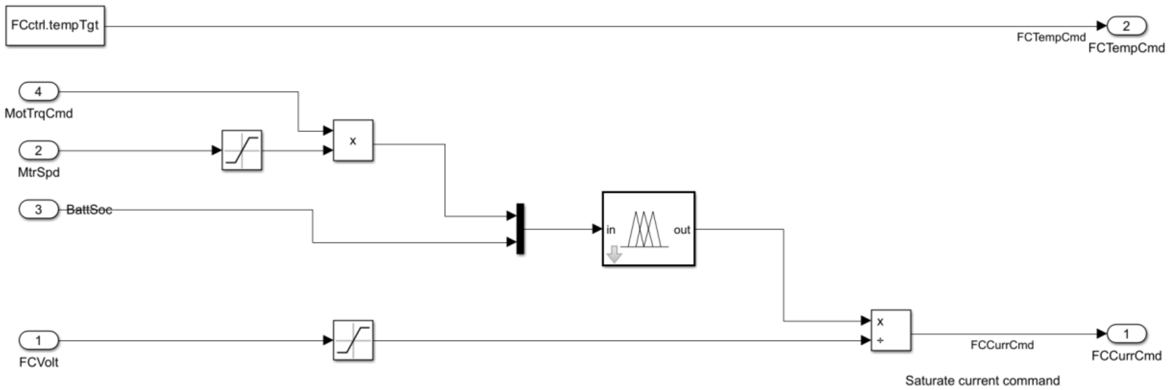

Figure 10 Fuzzy Logic Model

There are multiple methods in which this controller can be designed either by using Mamdani Function or Sugeno Function. Here, we have used Sugeno methodology based upon 1st Order. The controller will consider two Input Functions I.e., Power Requested by the Passenger (P_{rqd}) and SOC of the Battery (SOC_B) and one Output Function i.e., Fuel Cell Power (P_{FC}).

The Membership Functions considered for the following model consists of-

(a) 5 subsets [TL L M H TH] for the P_{rqd}, where these MFs are denoted as Too Low (TL), Low(L), Medium (M), High (H) and Too High (TH). The Range of the following Input is considered between a set upper limit and lower limit of power requested [P_{rqdmin}, P_{rqdmax}].

(b) 3 subsets (L, M, H) are there MFs considered for Battery SOC (SOC_B) which are denoted as Low SOC(L), Medium SOC(M) and High SOC(H). The Range of the SOC considered is between 0 to 1.

The Output of the following controller i.e., Fuel Cell Power (P_{FC}) consists of 5MFs [TL L M H TH] which are having same denotation as that for P_{rqd}. The Range of the following parameter is between 0 to P_{rqdmax} (Robert L et al., 2022, p. 3).

At the Input side the Type of MF considered is Trapezoidal Function. Hence the Fuzzy Logic Rule/Strategy applied consists of 15 Rules which are formulated as mentioned below in Table 3. Also, you can see the rule logic added in fuzzy logic designer in Figure 12 which is implemented as per above rules.

P_{FC}		**P_{rqd}**				
		TL	**L**	**M**	**H**	**TH**
SOC	**L**	L	M	H	H	TH
	M	TL	L	M	H	TH
	H	TL	L	M	H	TH

Table 3 Fuzzy Logic Rule Strategy

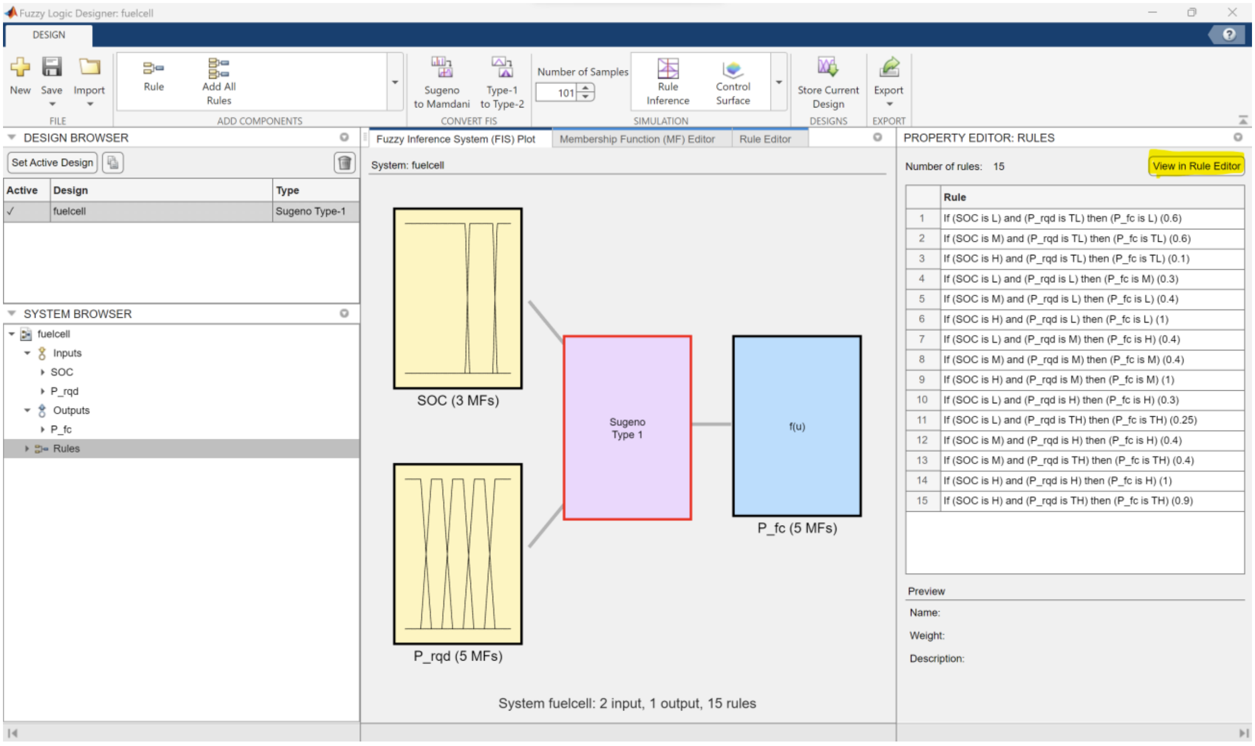

Figure 11 Fuzzy Logic Designer Rules Update

For both of the following controllers the parameter values were modified multiple times in Iterative manner after testing it in each scenario to find out for which values, we had obtained the best Energy Performance. So, finally the label values specified for the controllers are the optimized values obtained after multiple iterations of the model. Further things will be understood in the upcoming module.

8 Testing

The Testing Strategy applied was based on Iterative Technique and the multiple functionalities of the Vehicle Model in Simulink were modified and made accurate by this re-run procedure.

The functionalities which were verified by this approach or pattern are-

1) Parameter Definition-The Plant Model which was considered initially was of a Passenger Car segment. The Parameter values/data was taken from the different vehicle specifications after validating the values with real world FCHEV vehicles. The Parameter values which were best suited to drive the system could be found out by this approach.

2) Controller Design- The Controller part was developed for Fuel Cell Controller part to manage the power split-up between Fuel Cell and Battery. In the case of PID Controller the tuning of values was done by this re-iteration mechanism and in case of Fuzzy Logic Controller the MFs values were optimized to find out the most effective values.

3) Vehicle Parameters Measurement- In the output dashboard of the Model we verify multiple parameters with respect to Power, Voltage, Current and SOC Parameters. This was done by considering multiple drive cycles to check the characteristics. Additionally, the dashboard was also used to find out the approximate fuel economy which could be achieved from the system i.e., measuring the miles per gallon equivalent (MPGe) value.

4) Energy and Efficiency Measurement- Multiple Drive Cycles were considered to verify the Effectiveness of the system such as FTP75, UDDS etc to verify the Energy Consumption and efficiency of Individual Components. So, finding out the better controller model in terms of this parameter was easily possible by checking the data populated.

5) Model Adaptability Check- Based on the above-mentioned functionalities verification the best suited parameters were found out as well as controller to be used in this new model. As per the above findings the data was modified to be used for a Truck Segment and verified whether the same mechanism was working properly for a higher mass vehicle with higher ratings of Energy Sources. By multiple iterations we were able to simulate the new model and verify the 3rd and 4th functionalities as mentioned above.

Parameter definition-

A) The Ratings of multiple components such as Fuel Cell Control, Fuel Cell Converter, Battery, Battery DC-DC Converter, Vehicle Drivetrain components values were fixed for parameters like Max Power, Operating Limit, SOC reference, Capacity of Battery, Vehicle Weight, Axle ratio (Front/Rear) etc. based on Passenger Car Segment actual vehicle parameters reference.

B) The Parameters were then also re-modified to verify a different segment model i.e., Truck Model in a similar pattern.

C) The values are refined by performing multiple tests of the system at different values to find the best working setup.

Controller Design-

PID Controller Tuning-

The control parameters inside the controller were tuned to find out the optimum gain values of the controller to find out the case were maximum performance with respect to energy source usage either fuel cell or the battery (Benali Tifour et al., 2021, p. 2). The main intention is to verify that both the sources are working properly and there is no degradation of either of the sources.

The value which was selected at the end of the multiple iterations were K_p=5000 and other two parameters were considered zero as it didn't show much significant change in the measurements or plots.

Fuzzy Logic Controller-

As discussed previously about the control mechanism for the following in the above section, the boundary conditions must be set and values for MFs and Range was updated. The Range values for the first input i.e., Power required (P_{rqd}) was calculated [P_{rqdmin}, P_{rqdmax}] and the membership functions for each subset TL, L, M, H, TH were updated. The same was done to find out the values for individual subsets at the output side for Power needed from the fuel cell (P_{FC}) was also measured (Robert L et al., 2022, p. 3). This was done by multiple iterative runs to find out the effective Fuel Cell current value through which proper utilization of multiple sources was achievable.

The final parameters considered in the model are as follows-

Input1- SOC of the Battery

The values of subsets of the MFs (L, M, H) were considered as the following mentioned below in Figure 12.

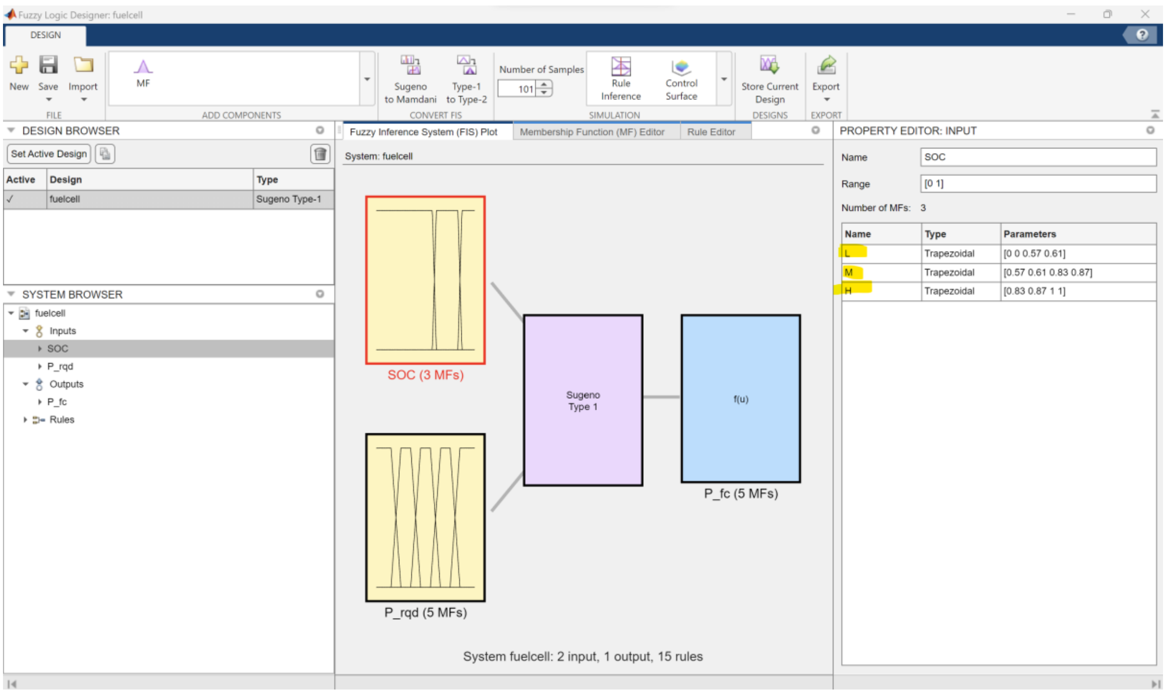

Figure 12 SOC MFs Parameters

Input2- Power required by the Wheels.
The Range for the following inputs is [0, 10000]. The values of subsets [TL, L, M, H, TH] is mentioned in the below Figure 13. Both the inputs considered here are of Trapezoidal shape.

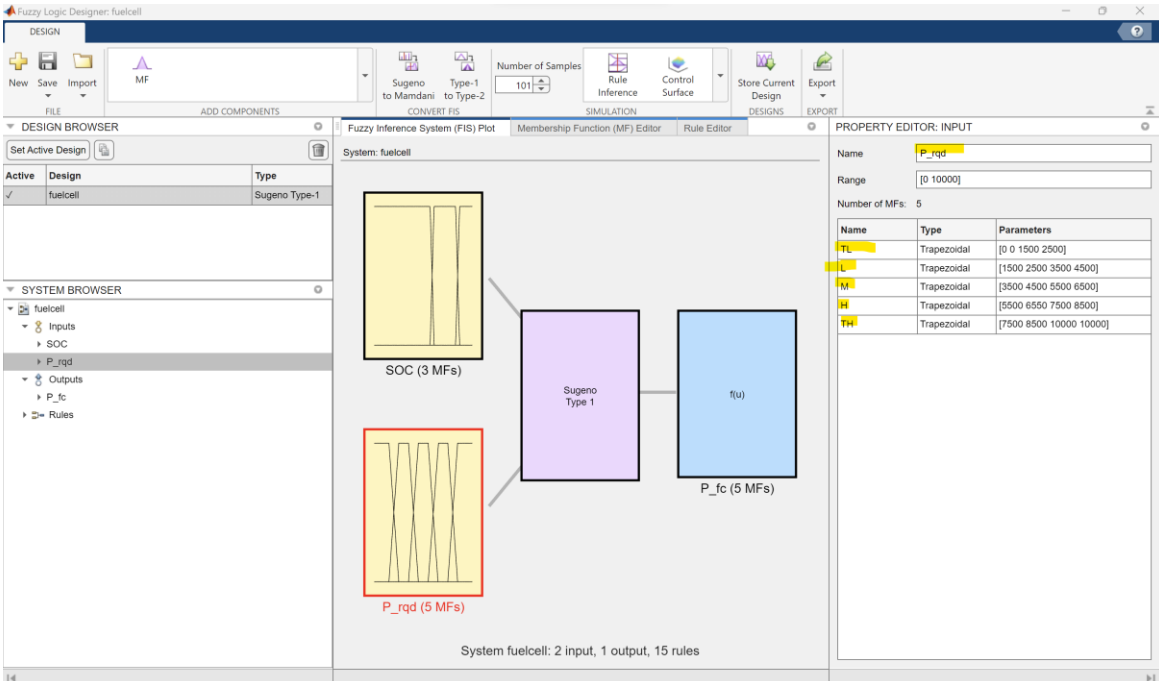

Figure 13 Power required MFs Parameters

Output-Power delivered by Fuel Cell
The Range considered for the output is same as that of the Input2. The output subsets {TL, L, M, H, TH] are of type constant hence are provided constant values as mentioned in the below Figure 14.

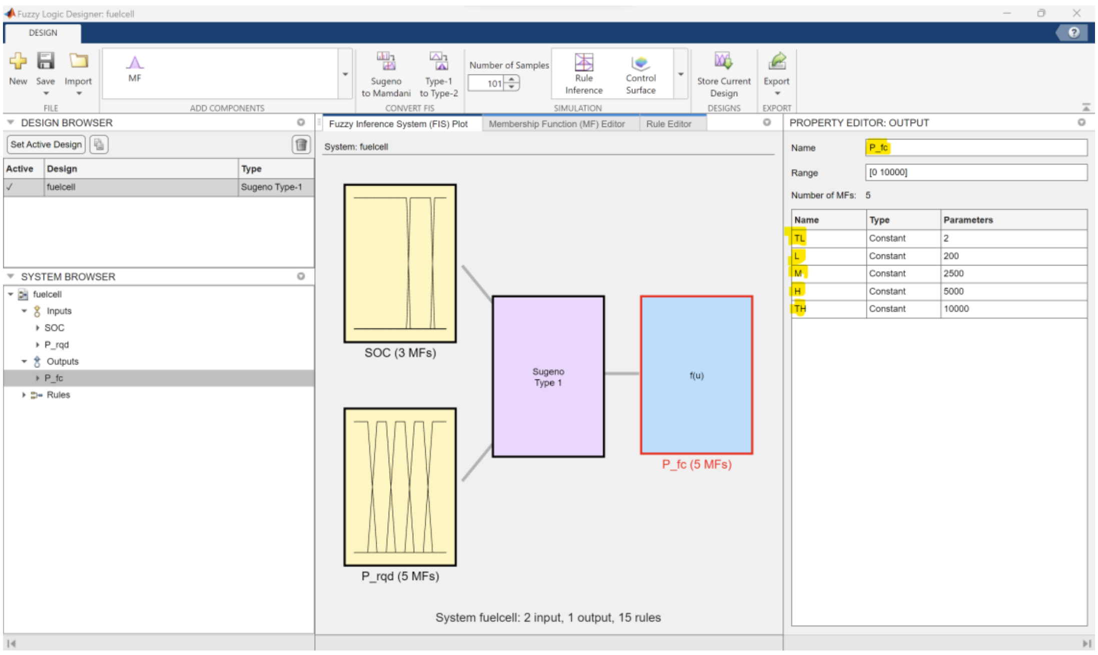

Figure 14 Power output MFs

Vehicle Parameters Measurement –

Multiple Drive Cycles such as FTP75, UDDS were considered to measure the following characteristics. The model was verified at the output side via a Dashboard which considered multiple parameters such as Vehicle Speed (Target, Actual), Motor Speed, Motor Torque, Battery SOC, Battery Current, Battery Power, Fuel Cell Current, Fuel Cell Voltage.

The final findings of each driving cycle can be found in the below given Figure 15, 16, 17 and 18. From the Images we can find out that in case of PID Controller the Fuel Cell is providing major amount of power whenever it needs by varying the fuel cell current. The additional power required by the vehicle is provided by battery whenever needed to compensate the fuel cell. In the case of Fuzzy Logic controller, a major amount of time similar amount of power from the fuel cell and battery requirements are manipulated as and when additional power is needed. Considering the SOC of the battery parameter, in case of PID controller the SOC value is tried to be maintained in and around 60 percent whereas in case of FLC the value is more varying as here the effective utilization of the battery is more compared to PID.

Finally considered in the following section is the economical aspect, the values obtained for both the controllers is somewhat close to each other for both the drive cycles and can't proclaim one controller to be better than the other in terms of the economical constraint.

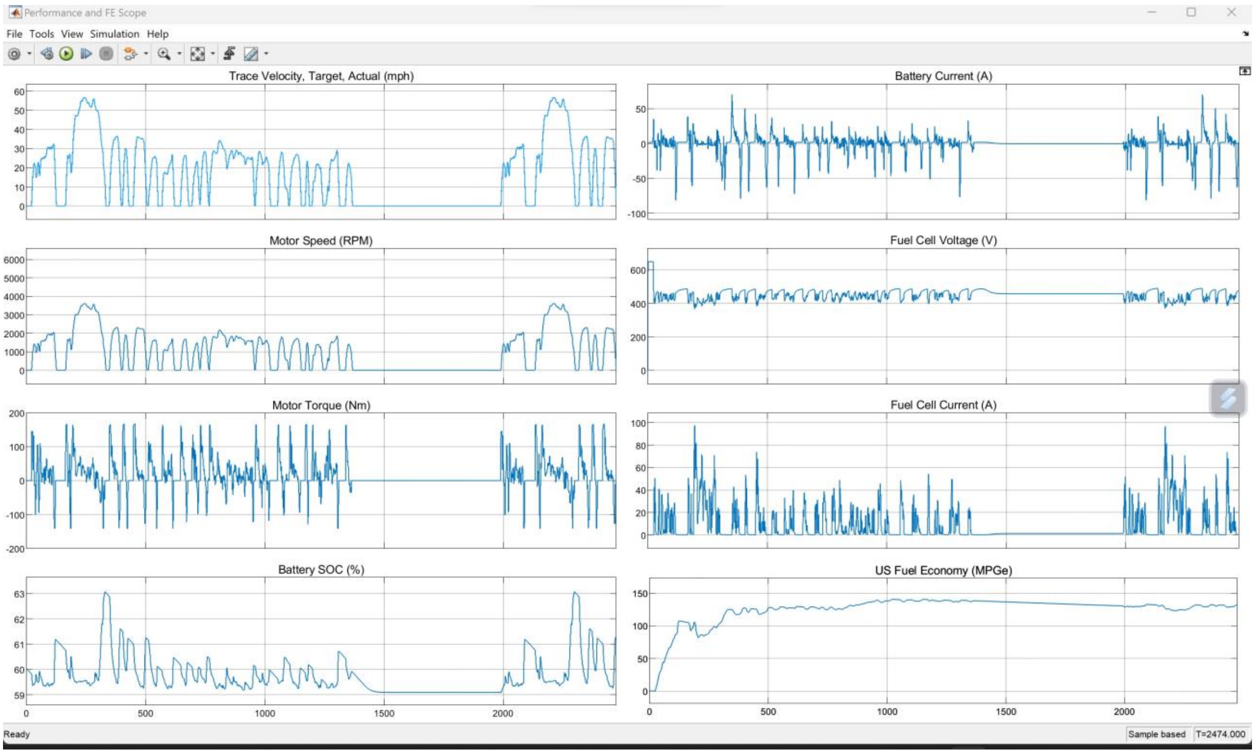

Figure 15 FTP75 PID Controller Plot

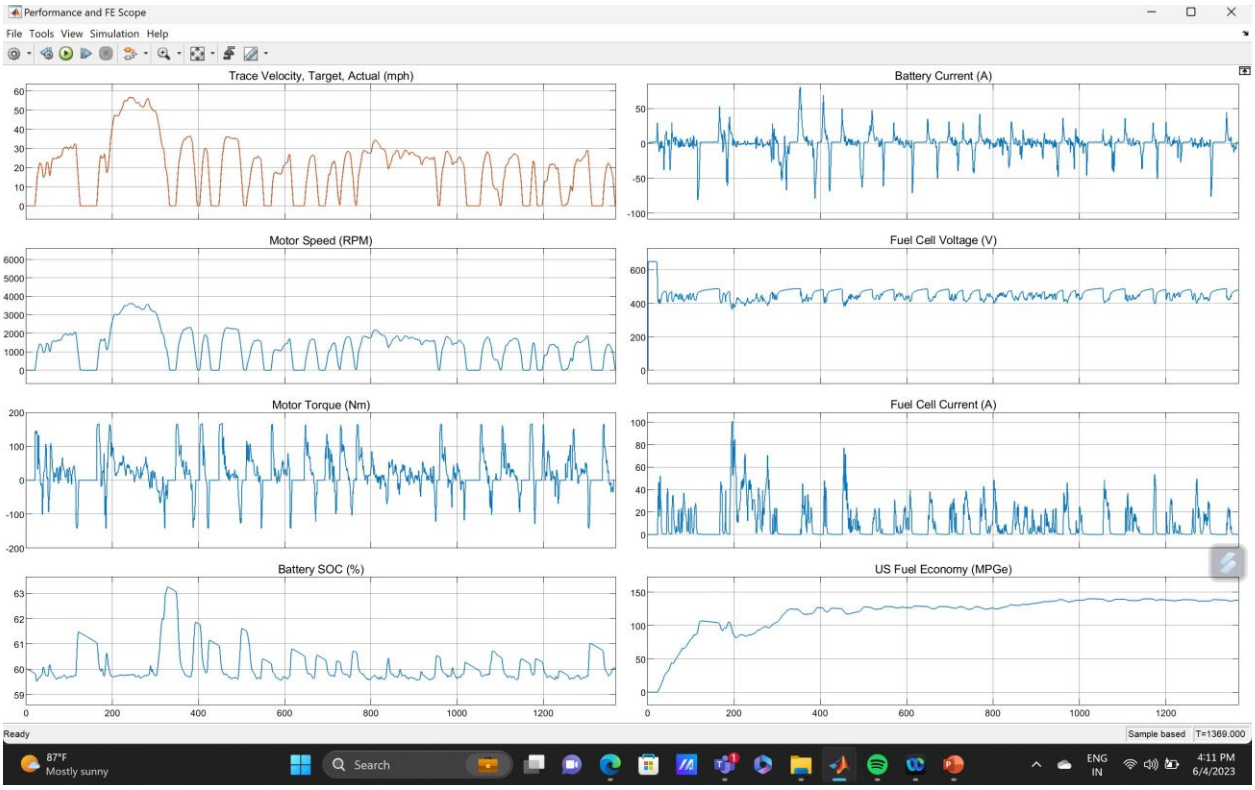

Figure 16 UDDS PID Controller Plot

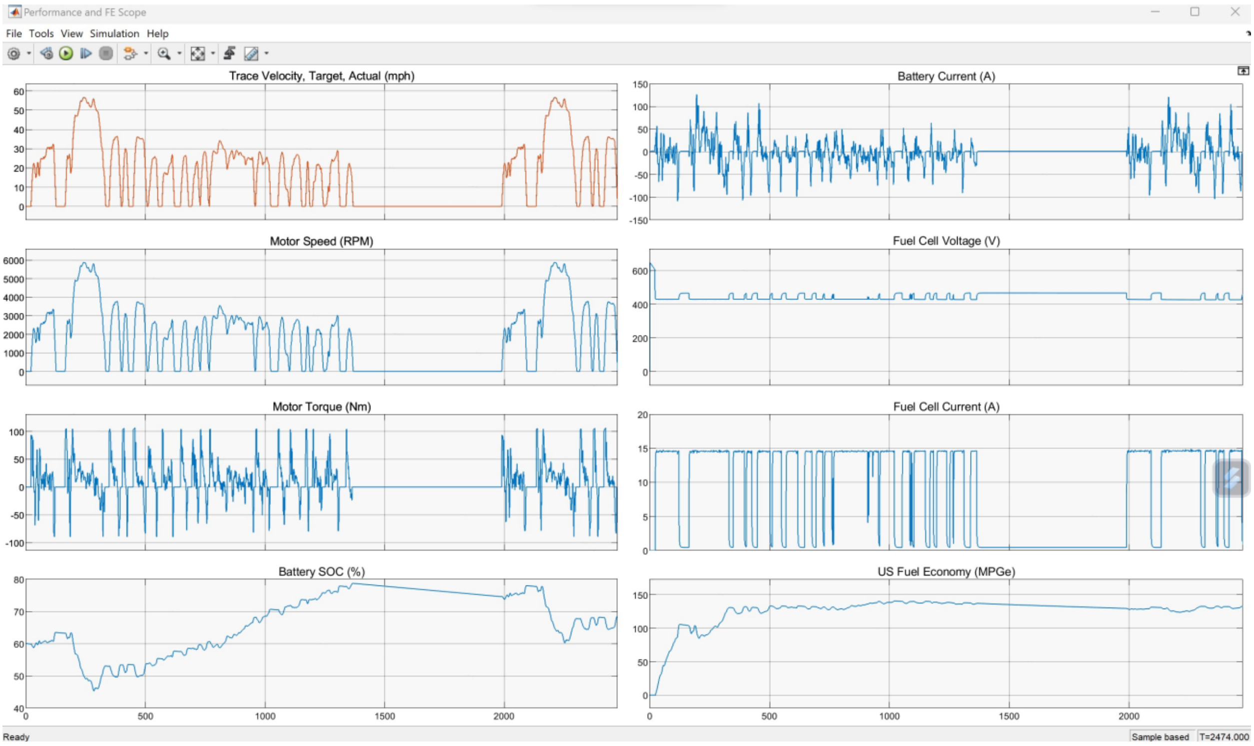

Figure 17 FTP75 Fuzzy Logic Controller Plot

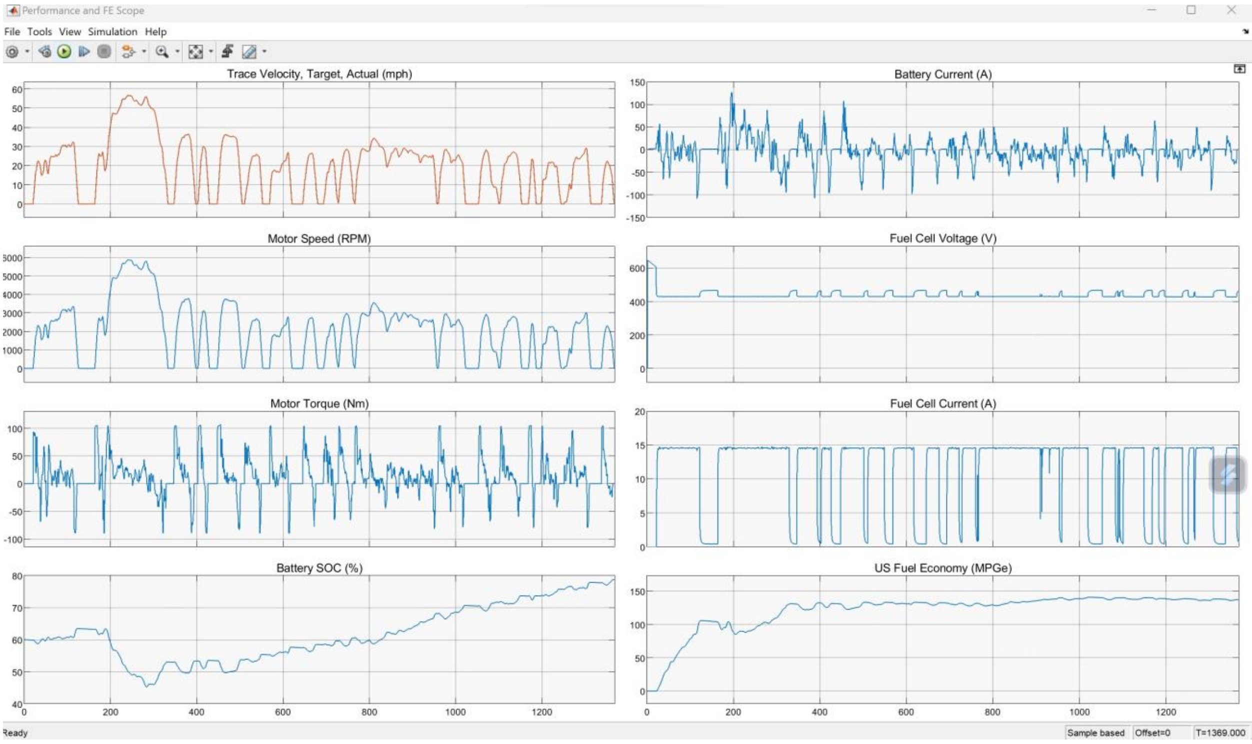

Figure 18 UDDS Fuzzy Logic Controller Plot

Energy and Efficiency Measurement-

The Energy consumption was measured for individual components inside the system such as Electric Plant and Drivetrain which consists of multiple sub-components inside it. The amount of energy input, energy loss, energy stored, and energy output is measured and based on the values of the following parameters the efficiency of the Individual components is calculated. The overall efficiency of the system is also found out by using the following formula mentioned below.

Overall Efficiency = [(Energy Output - Energy Losses) / (Energy Input + Energy Stored)] * 100

Thus, after running the model in multiple drive cycles the following values are obtained which you can see in the below Table 4 for both the controllers. From the tabulation you can observe that the PID controller has comparatively better efficiency as compared to that of fuzzy logic controller in the current model.

	Parameters	**Drive Cycle**	
		FTP75	**UDDS**
	Fuel Economy (MPGe)	131.9	138.2
	Electric Plant Efficiency (%)	71	72
	Drivetrain Plant Efficiency (%)	57	58
PID Control	**Overall Efficiency (%)**	27.5	28.4
	Fuel Economy (MPGe)	132.8	137.2
	Electric Plant Efficiency (%)	76.5	78
	Drivetrain Plant Efficiency (%)	57	58
Fuzzy Logic Control	**Overall Efficiency (%)**	22	25.8

Table 4 Energy Efficiency (Passenger Car)

Model Adaptability check-
As from the above analysis it could be seen that the effectiveness of the PID control mechanism in energy management aspect was better and overall efficiency value is somewhat better. Now by considering the PID control mechanism the parameter values were modified for the Truck segment to achieve required power rating values as the mass considered for the vehicle is more hence amount of Power required to drive the vehicle will also be higher. Here the weight considered is around 10500kg.

In the similar part for simulating the updated model, the NYCC cycle was considered to measure the vehicle characteristics. The vehicle parameters were again measured using a Dashboard plot which you can see in the below Figure 19. Here the behaviour observed was like that of Passenger car PID control mechanism.

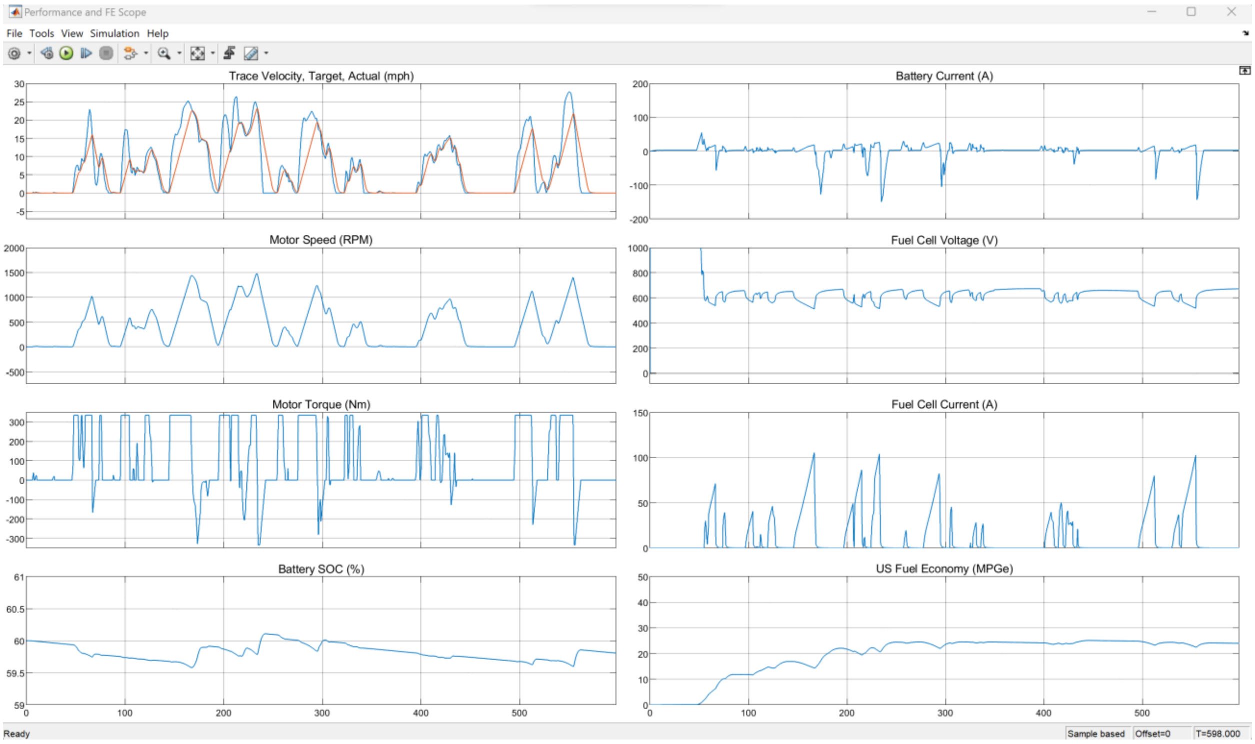

Figure 19 NYCC PID Controller Plot

The Energy and efficiency values were also calculated for the following model which you can see in the Table 5. Also, the fuel economy was measured, and it was found out to be 24MPGe as the drive cycle considered was only for 598 sec. The overall efficiency calculated was comparatively high as the drive cycle considered was for small duration of time.

Parameters	Drive Cycle
	NYCC
Fuel Economy (MPGe)	24
Electric Plant Efficiency (%)	71
Drivetrain Plant Efficiency (%)	61
Overall Efficiency (%)	39

Table 5 Energy Efficiency (Truck)

9 Project Management

9.1 Project Schedule

Phase1 (February-March)- Understanding the System Requirements of the Project

Plan of Action-Input, Process and Output of the system needs to be Identified. Understanding and developing the Block Diagram based on that requirements will be the next step. Another step will be to Identify the ratings of the different components which is being used in the work like capacity, power, current, voltage etc.

Outcome- Identified the key aspects of the model to be developed and the current vehicle parameters were found out by checking the real-world data. The base model to be used was identified and vehicle parameters and ratings were captured and tabulated.

Phase2 (April)- Theoretical Analysis and Performance measurement

Plan of Action-After understanding the system requirements, we need to perform some theoretical calculations and understand the system constraints to be set up for each device being used like Battery, Fuel Cell SOC, and current limits to be set. Also, need to understand what maximum power is supplied individually by fuel cell and battery as per power demand, the maximum speed which can be achieved and the range which can be travelled.

Outcome- The performance analysis was done based for Truck Parameters on multiple speed values and acceleration to verify the individual sources power consumption. Also, the energy losses data was captured to measure the efficiency of the system. Thus, the vehicle characteristics were measured and understood in the following phase.

Phase3 (May-June)- Simulation Model Development and Verification

Plan of Action-The next step is to develop a controller model in MATLAB/Simulink software. This includes considering a Plant Model for Vehicle Powertrain part and developing a controller model for the control strategy part. To validate the plant/controller specific set of Inputs such as Drive Cycle and vehicle dynamics (Environmental conditions) will be considered. Also, to measure the different parameter values calculated as per the driving cycle requirements, a dashboard model will be designed to verify the values obtained for different parameters at different time zones of the drive cycle.

Outcome- The following part was done initially by considering the passenger car model and parameters were correspondingly adjusted to match the current vehicle segment. The model was verified by considering multiple controllers PID and Fuzzy Logic controller to understand the energy performance aspects with each type and found out the better solution.

Additional thing which was performed in this phase was modifying the system for a Truck Segment vehicle by modifying plant model and control parameters and simulating it with a PID controller to find out the Energy Performance.

Phase4 (July)- Report Preparation and Submission

Plan of Action- The final part is to develop a proper report as per the Coventry template provided and required sections to be captured.

Outcome- The required sections of the report were prepared as per the Coventry template and referenced the data which was used from research articles. Special care was taken to keep the content as original as possible and prevent any plagiarism.

9.2 Risk Management

Multiple Risks which have been considered are as mentioned below-

Data Integrity Risk:
Risk: Data is damaged, inaccurate, or lost during data collection, analysis, and transfer.
Mitigation:

1. Use reliable tools and measurements such as MATLAB Simulink to ensure data is accurate.
2. Regular backup and secure storage/security of data to prevent loss or corruption.
3. Cross-validate data with various parameters available and verification techniques.
4. The data collection process must be documented in an effective manner to ensure data traceability.

Scheduling Risk:
Risk: Delays or interruptions in the research process cause project deadlines to extend.
Mitigation:

1. Detailed information on planning and scheduling, considering risks and allocating sufficient time for each phase.
2. Regular progress monitoring and communication with professors to identify and resolve deviations or delays in a timely manner.
3. Collaborate and co-ordinate with assigned supervisors to ensure quality and timely execution.

9.3 Quality Management

Proper Fuel cell hybrid electric vehicle (FCHEV) quality management is necessary to make sure the model is good, and it is important to obtain accurate results. The following quality control measures were taken to ensure the integrity and validity of the model.

1. Methodology:
    a. The methodology designed was carefully documented so that it could be re-used later. The process includes parameter selection, test conditions, data collection procedures, and analysis procedures.
    b. The process was carefully reviewed prior to investigation and supervisors were consulted to ensure it met industry standards or real-world data applicability.
2. Data Quality Assurance:
    a. Establish certain procedures to ensure the quality and accuracy of data collection. These guidelines define specific procedures for data collection, processing, and storage.
    b. Use data validation techniques such as fact checking or cross-verification of data by another person to identify and correct errors or inconsistencies in the collected data.
    c. The data analysis process includes the analysis of calculations, units, and conversion factors.
3. Data documentation and Traceability:
    a. Data collected throughout the investigation, including all aspects of the work such as methodology, experimental setup, data collection, analysis procedures, review process, and planning process.
    b. This following documentation ensures that the research can be replicated and analysed by other researchers.
4. Peer Review and Validation:
    a. The project report was carefully reviewed by the supervisors allocated with experience in the FCHEV or Powertrain field. This external review process helps validate the research methodology, data analysis process, and interpretation of results.
    b. Additionally, the feedback and suggestions provided by the supervisors were also considered in the final report.
5. Continuous Improvement:
    a. Lessons learned i.e., the negative aspects or areas to work upon moving further were also recorded so that they improve future research. This includes identifying areas for improvement in procedures, data collection, and review procedures.
    b. Additionally, opinions of supervisors can be sought to improve the quality of future studies.

These measures help ensure the overall integrity and reliability of the research topic and provide a good literature background to others for further development in the field.

9.4 Social, Legal, Ethical and Professional Considerations

The decisions mentioned below ensure that research adheres to societal values, laws, ethical standards, and professional practice. The following are considered:

1. Social decision:

   a) Environmental impact: Research shows the importance of reducing greenhouse gas emissions and supporting transportation solutions. FCHEVs have the potential to reduce emissions and increase energy efficiency, helping to reduce environmental impact and create a cleaner, greener future.
   b) Accessibility and Affordability: The survey recognizes the importance of making transportation accessible and affordable for many people. The cost-effectiveness and scalability of FCHEV technology has been determined, increasing the potential for wider use.

2. Legal considerations: This includes obtaining appropriate permissions, following ethical guidelines for human research (wherever applicable) while referring through the research articles, and complying with data protection laws and regulations.

3. Ethical considerations: No Primary data was collected (surveys/polls) was taken to cover this aspect and hence mentioned in ethics certificate.

4. Professional conduct:

   a) Objective and Integrity: Research is conducted with a commitment to fulfil the objective, accuracy, and integrity. Special care was taken to reduce bias and conflict of interest through transparent reporting processes, data collection, analysis, and interpretation.
   b) Citations: The necessary citations were provided to all materials/sources used in the research, to ensure that recognition is given to previous research works done in this area.

10 Critical Appraisal

In the following project the main aim was to measure or investigate the energy performance of fuel cell hybrid electric vehicles. Thus, to verify that the main evaluating parameters considered here are methodology, data collection and analysis, limitations, and future implications.

1. Methodology:
    - Benefits Achieved- The research methodology chosen provides a way to investigate and ensure that research objectives are met. The use of hybrid architecture in the model and the selection of parameters such as fuel cell and battery ratings such as power, operating limit and SOC values demonstrate that there is thought process which was considered before development of the model in simulation.

    - Drawbacks- However, the consideration of the multiple parameters or ratings can sometimes be hypothetical and not available in the real world and thus the system can have limitations based on further prototyping of this model. Further investigation of other system architectures or system configurations by checking with the currently available vehicles data can provide further insight and improve the quality of the research.

2. Data Collection:
    - Benefits Achieved- The data collection process involved collecting key performance indicators such as power consumption, power output, fuel economy and Energy consumption and Efficiency. Choosing the right parameter values as per the segment of the vehicle which is either the passenger car or truck was verified before simulating the model so as get the precise and accurate values of all the above-mentioned parameters and its real-world acceptance was verified.

    - Drawbacks- However, there may be limitations in the values calculated specially in case of the economy and efficiency due to the parameter values considered in simulation and because of the drive cycle patterns considered which may not be the case always. The data collected can be improved by changing and verifying the model in multiple drive cycles to be representative of real-life situations.

3. Data Analysis:
    - Benefits Achieved- Data analysis techniques, included numerical/statistical analysis of the model architecture considered and comparative analysis between multiple controllers to understand the advantages/disadvantages of each, provided a rigorous assessment of FCHEV's model considered in the project. Proper data was measured, plotted, and tabulated to make the user understood better the properties of the system.

    - Drawbacks- However, additional analysis such as rigorous testing may be performed which considers multiple re-runs of system in various drive cycle scenarios to determine/measure the impact of uncertainty of benefits achieved. In addition, the use of advanced modelling techniques can increase the accuracy and precision of the analysis.

4. Limitations: Some limitations were discovered during the model development.
    - Firstly, the data collected from the Truck parameters data has shown some significant improvement in Fuel economy as compared to the real-world data probably because of the drive cycle considered. Secondly, research often focuses on urban and highway driving cycles, perhaps ignoring changes in energy efficiency in extreme climates or mountainous regions as such drive cycle exploration was not possible. Future studies may explore these factors to better understand the energy efficiency of FCHEVs.

    - Secondly, the investigation was based on an FCHEV passenger vehicle or truck sample data collected and updated in model, which may limit the generality of the findings. Repeating the same modelling process using multiple models or different FCHEV models will increase the reliability and validity of the results.

5. Implications for future research:
    - Critical evaluation of this project suggests possibilities for future research. Exploring alternative design methods, modifying model parameters and ratings, including additional drive cycles for different geographical conditions, and considering various driving conditions will strengthen the scope of the project and improve understanding of FCHEV's energy performance.

    - Additionally, future research could focus on the development of quality control strategies which are further optimized and measure the durability and reliability of FCHEV systems. This will help advance the latest FCHEV technology and its potential for widespread use in transportation.

In conclusion, analysis of FCHEV's performance confirmed its quality, data collection and analysis strengths, while its limitations and improvement potential need to be validated.

Addressing these limitations and exploring future research directions will increase the understanding of FCHEV energy efficiency and contribute towards solving transportation problems.

11 Conclusions

11.1 Achievements

In this project, the optimum energy management strategy was developed to measure the energy performance of the system. Multiple Parameters like Energy Efficiency, Power Output and Fuel Economy were measured to tabulate the vehicle performance metrics. Based on the analysis we found out the following conclusions-

1) Energy Efficiency- The overall efficiency of the system was verified in multiple drive cycles (FTP75, UDDS) in case of Passenger Segment vehicle, The overall efficiency value was higher in case of PID controller i.e., close to 28 percent average whereas in case of Fuzzy Logic controller it was somewhere around 24 percent. Hence for Truck Segment, we verified the model using PID controller and achieved an overall efficiency of 39 per cent as we had considered NYCC drive cycle for the same. Overall, the efficiency was significantly improved in a FCHEV due to effective utilization of multiple energy sources fuel cell and battery,

2) Power Output- The required power output was provided to the wheels based on the user demands as per the vehicle type. In case of Passenger vehicle where power requirement was less offered relevant power demands of around 40-50kW whereas in case of Truck segment which has more power demands of around (80-100kW) was delivered properly. Hence proper acceleration and manoeuvrability was achieved even with this hybrid powertrain architecture.

3) Fuel Economy- The Fuel Economy was calculated in miles per gallon equivalent (MPGe) which is the unit specifically considered for electric and hybrid electric vehicles. We were able to achieve a very high fuel economy in case of Passenger car segment with respect to both the controllers and the value obtained was approximately in the range 132-138 MPGe which is considered remarkably good. In the case of the Truck segment, we were able to achieve an economy of 24 MPGe which is also high as a lower time period-based drive cycle was considered. Overall, from the findings the range the vehicle can travel in a single charge is higher than the conventional engine vehicle. Also, the emissions aspects are drastically reduced here as we are considering the FCHEV system.

11.2 Future Work

Even though through the investigation multiple valuable points were addressed there are still some gaps in the findings which must be worked upon. Some scenarios which can be explored are alternative design methods, enhancing model parameters and ratings, including additional drive cycles for different geographical conditions, and considering various driving conditions will strengthen the scope of the project and improve understanding of FCHEV's energy performance.

Additionally, the development of quality control strategies which are further optimized and measure the durability and reliability of FCHEV systems. This will help advance the latest FCHEV technology and its potential for widespread use in transportation. Finally, validation on a hardware prototype will be the future scope of the work after fixing above mentioned points.

12 Student Reflections

Overall, the project work was done in a precise manner as per the required deadline and the justification of topic considered for the project work was validated. There were multiple phases of the project which were determined at the start of the topic. So, proper care was taken of the time limitations for each individual phase to be completed in the correct time. In the initial phase secondary data was collected properly from the journals, conference papers etc., to verify the need for working on this specific aspect of the Energy Performance investigation. In the next phase, identification/defining the architecture to be used was found out. Also, the parameters to be used in the project were found out.

Then further down, numerical analysis was done to find out the energy performance in multiple scenarios of speed and acceleration. In the following phase some issues were faced initially with respect to finding out the exact split up between multiple energy losses and how to find a way to numerically check that but with some guidance of the supervisors it was understood and then measured. Then in the later phase, the model was developed in the simulation environment. One of the problems faced in the following phase was with respect to configuration of parameters for fuzzy logic controller using the fuzzy logic designer. After multiple background research, it was rectified and were able to use the control mechanism and simulate the model with this controller. Another aspect of simulation in which problem was faced was the control parameters considered in the fuzzy controller. The SOC of the battery was either getting underutilized or vice-versa. After multiple re-runs the following problem was identified and parameters were modified to obtain optimum results. These were some of the points from the lessons learnt at the end of the project.

As in the current project, in the simulation model development and verification phase, initially the parameters considered were with respect to Passenger car segment and comparative analysis was done with respect to that segment. But, with respect to the Truck segment vehicle only with the PID controller and single drive cycle the energy performance was measured due to the shortage of time. It could have been possible if the work in the passenger car was done in a better manner without the issues being faced and could have possibly got a better clarity for Truck segment energy performance also.

Even though with the all the above points mentioned, some of the aspects mentioned in the future scope need to be worked upon to improve the quality or impact of the current project work and in a manner be more helpful for others.

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Appendix A – Project Proposal

11911005_Project_Proposal.pdf

Appendix B – Monthly Progress Reports and Work Artefacts

Presentations-

PPT_Review_April.pptx PPT_Review_July_Final.pptx PPT_Review_March.pptx PPT_Review_June.pptx PPT_Review_May.pptx

Numerical Analysis/Calculations-

Numerical_calculation_check.xlsx

Work Artefacts GitHub Repository Link-
https://github.com/Sayuj0303/11911005_Project.git

Appendix C – Certificate of Ethics Approval

Certificate of Ethical Approval

Applicant:	Sayuj M Warrier
Project Title:	Investigation on Energy performance of Fuel Cell Hybrid Electric Vehicle (FC-HEV)

This is to certify that the above named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Low Risk

Date of approval:	17 Mar 2023
Project Reference Number:	P150332