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Simulation-based Performance Analysis of Internal Combustion Engine, Electric Vehicle and Fuel Cell Electric Vehicle

Ankita Singh*, [1], Sanjay Mishra*, and Anirudh Gautan^

Abstract – *Rising awareness over climate change and worsening air quality have propelled the automotive industry to prioritize zero-emission powertrain innovations and promote sustainable fuels for the next generations. Among these advancements, electric vehicles (EVs) and fuel cell electric vehicles (FCEVs) have emerged as front-runners in promoting a green environment and more sustainable transportation. In this study, a simulation-based analysis has been conducted to compare the performance of Spark Ignition (SI), EV, and FCEV. The SI, EV, and FCEV models pre-existed as reference examples in the MATLAB/Simulink environment. The parameters such as motor speed, motor torque, battery State of Charge (SoC), battery current, fuel cell (FC) Voltage, FC current, fuel economy, brake-specific fuel consumption (BSFC), and emission have been used to evaluate the pros and cons of each propulsion system across Federal Test Procedure-75 (FTP-75) driving cycles. Our finding shows that stable SI, EV, and FCEV fuel economies are 35,150 and 120 miles per gallon equivalent (MPGe), respectively, with EV showing promising overall efficiency and FCEV outperforming longer driving range. This research highlights the key impact of sustainable technologies on advancing the future of transportation*.

Keywords – Electric Vehicle; Fuel Cell Electric Vehicle; Hybrid Electric Vehicle; MATLAB/Simulink; Spark Ignition Engine vehicles.

1. INTRODUCTION

The transportation industry faces a crucial phase as sustainable solutions and operational efficiency are becoming key in technological evolution. The transportation sector accounts for 28-29% of the GHGs (Green House Gases) emissions and 94% of the consumption of petroleum fuels [1]. The global transportation industry is catalyzing a sweeping transformation amid the pressing need to cut greenhouse gas emissions and lessen reliance on fossil fuels. Advancements in combustion, after treatment of the exhaust gas, start and stop technologies have significantly reduced harmful emissions from vehicles. These advancements are impactful in providing a clean atmosphere and reducing GHGs.

However, the above reductions in harmful emissions are largely negated due to the increasing population of vehicles. EVs and Fuel Cell Battery hybrid electric vehicles (FC-BHEVs) can be considered robust alternatives to internal combustion engines (ICE) based vehicles, provided GHG emissions in the manufacture of the batteries and hydrogen production from saline water with renewable energy can be achieved at reasonable costs. EVs and FCEVs can potentially have significant green benefits and eliminate dependence on fossil fuels.

This paper investigates the potential of EVs and FC-BHEVs to overcome the issues connected with conventional vehicle technologies, highlighting their importance in developing a more eco-friendly and efficient transportation system.

Extensive research has been conducted on a comparison of ICE-based and Battery and FC battery Hybrid power trains for Light-duty and heavy-duty vehicles through modeling and simulation. Offer et al. [2] compared the cost of different powertrains such as Battery Electric Vehicles (BEVs), Hydrogen FCEVs, and Hydrogen FC Plug-in Hybrid Vehicles (FCHEVs). Mallouh et al. [3] modified the standard urban duty for three-wheelers and developed a new duty cycle for Auto rickshaws. The ICE and FC hybrid Auto Rickshaw drivetrains are modeled using the Powertrain System Analysis Toolkit (PSAT) Software package and compared for performance and emissions. Mallouh et al. [4] compared the ICE and FC hybrid rickshaws based on running costs using a realistic drive cycle by using PSAT software. Emran et al. [5] have conducted a comparative analysis based on the performance and emissions of FCEVs and battery electric vehicles (BEVs) for the selected 42-ton truck, considering Indian driving conditions through modeling and simulations using GT Suite software. Yokoyama et al. [6] discussed the performance and emissions of FCHV-BUS2, which was developed through collaboration of Toyota and HINO Motors, Ltd. This bus is propelled by two Toyota FC stacks, two traction motors, and four secondary batteries. Wu et al. [7], analyzed the conceptual design of FC hybrid vehicles propelled by FCs and nano-phosphate lithium-ion batteries in London. Reddy et al. [8], comprehensively compared the four technologies namely solar vehicles, FC vehicles (FCVs), biofuel-

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powered vehicles (BPVs) and EVs based on technical factors, cost considerations, environmental impacts, and policy dimensions. McNicol et al., [9] have studied the environmental effects of automobile emissions, advantages and disadvantages of FC, manufacturing companies of FC, fuel used by FC, alternatives of FCVs, impact of FCVs on other industries. Chan et al. [10], have reviewed the state of electric, hybrid, and FC vehicles, and concentrated on architecture and modeling of energy management systems. Chan et al. [11] have examined the state-of- the-art of hybrid, electric and fuel hybrid vehicles. They discuss the model of different Hybrid EVs. Uzunoglu and Alam [12] have focused on the design and modeling of FC /ultracapacitor hybrid EVs. Youssef Mohamed, et al. [13] compared performance of ICE mid-sized vehicle with combined FC and battery powertrain using duty cycle used in Toronto (New York). Vidhya and Balaji's [14] objective is to convert the three-wheeled light EVs under Indian driving conditions with a Hybrid electric vehicle (HEV) powered by battery and ultracapacitor (UC).

From the literature review, it is evident that comparative studies of SI vehicles, EVs, and FCEVs have been conducted based on technical factors, cost considerations, environmental impacts, and policy dimensions. There is a significant gap in comparative studies based on simulation using the MATLAB/Simulink environment of these vehicles.

This paper seeks to conduct a simulation-based analysis of SI Engine vehicles, EVs, and FCEVs. These vehicles' models were already pre-built and were part of a reference example provided in the MATLAB/Simulink environment. The study is dedicated to the FTP-75 drive cycle to examine performance and fuel consumption. This study will uncover each propulsion system's strengths and weaknesses, offering insights and guidance for future advancements in vehicle design and energy management. The result will contribute to the ongoing efforts to assess viability and future developments in vehicle design and energy management.

2. MODEL DESCRIPTION AND SIMULATION FRAMEWORK

This study used pre-built models of SI Engine vehicles, EVs, and FCEVs as part of a reference example provided in the MATLAB/Simulink environment for a comparative study. These models were selected due to their close representation of the dynamic behavior of each vehicle type. The MATLAB/Simulink environment is chosen to simulate because it has robust capabilities in modeling complex vehicle systems and can accurately simulate real-world driving conditions. The FTP-75 (Federal Test Procedure) driving cycle was used as a standard simulation cycle developed by the U.S. Environmental Protection Agency (EPA) and reflects the typical urban traffic patterns. This drive cycle is designed for city driving conditions in which frequent stops, idling, accelerations, and a mix of low and moderate speeds, stops, and starts are included. The maximum velocity is approximately 25 m/s and 23 stops. The graph shown in Figure 1 shows the speed vs time of FTP-75. The primary parameters evaluated in this study were motor speed, torque, battery SoC, battery current, FC Voltage, FC current, fuel economy, BSFC, and emissions.

Figure 2 shows the MATLAB/ Simulink SI, EV, and FCEV models. The model consists of the a) Driving Cycle block, b) Longitudinal Driver block, c) Environment block, d) Controller block, and e) Car block. Power and Energy analysis block compares the power and energy requirements of the selected powertrains. Environmental factors such as ambient temperature, air pressure, gradability, etc., which directly affect the ICE, the battery's thermal management system, the FC stack, and hydrogen consumption, have been included in the environment block. A longitudinal Driver block is a virtual driver that controls the speed, acceleration, and retardation of vehicles. Controller block is the heart of model as it controls the power flow which ensures optimal engine performance and lower emissions. In SI model the engine control unit (ECU) is used to control the fuel injection, ignition timing, and air-fuel ratio; in EV model Battery Management System (BMS), motor controllers, and regenerative braking control are used to control the function of battery, motor and regenerative brake; in FCEV model the controller is used for FC management, battery management, regenerative braking control and motor control to split power between FC and battery. In the SI engine vehicle model, ICE, transmission, and drivetrain; in the EV model, electric motor, battery, and transmission; and in the FCEV model, FC stack, hydrogen tank, battery, and electric motor are represented. The visualization block shows the output or scope of various parameters. The specifications of SI Engine vehicle, EV, and FCEV are presented in Table 1, respectively.

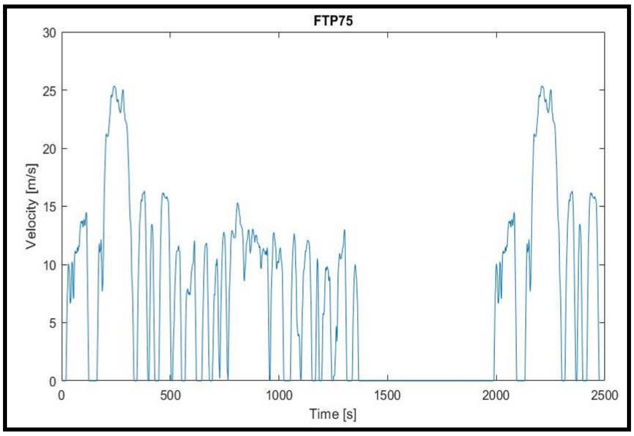

Fig. 1: FTP-75 Drive Cycle.

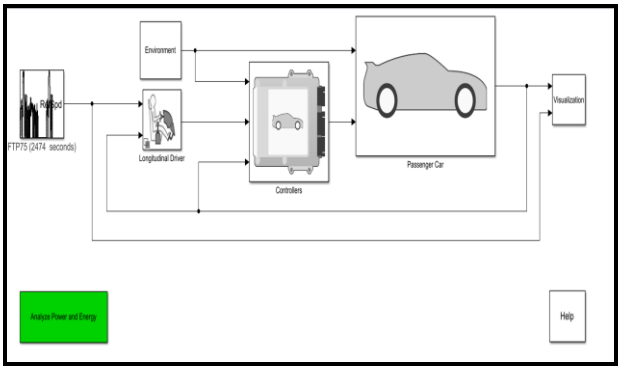

Fig. 2: MATLAB/Simulink models of SI, EV, and FCEV.

After the simulations, the performance parameters were analyzed and compared for each vehicle type. The aim is to see how each vehicle's powertrain performs and to show the strength/ weakness of each powertrain over the FTP-75 driving cycle. The schematic diagrams of SI, EV, and FCEV are shown in Figures 3 to 5.

Table 1. Specification of SI Engine, EV, and FCEV.

S. No.	Attribute	SI engine powertrain	Battery powertrain	FC-Battery powertrain
1.	Power train components	Internal Combustion Engine	Battery Pack, BMS, Inverter, Transmission, Thermal Management System, Permanent Magnet Synchronous Motor (PMSM)	FC Stack, Battery Pack, Power Control Unit, PMSM.
2.	Vehicle mass	1200 (kg)	1645 (kg)	1500 (kg)
3.	Environment Parameter	Temperature= 300 K Pressure= 101325 bar.	Temperature= 300 K Pressure= 101325 bar.	Temperature= 300 K Pressure= 101325 bar.
4.	Gradability of road	0 deg.	0 deg.	0 deg.
5.	Engine/ Battery/ FC	Displacement 1.5L and Number of cylinders four	Lithium-Ion	Proton Exchange Membrane FC and Lithium-Ion
6.	Exhaust after treatment devices	Catalytic Converter	N/A	N/A
7.	Braking System	N/A	Regenerative Braking System	Regenerative Braking System
8.	System Degradation	Assume ideal engine performance without considering wear and tear over time.	Assume ideal battery performance without any degradation with time.	Assume the ideal fuel cell stack and battery performance are without any deterioration in the long term.

Figure 3 shows the schematic of a typical IC engine-centric power train. Gasoline and air are supplied to the spark-ignition engine cylinder, and the fuel-air mixture ignition is initiated with the help of a spark plug fitted into the cylinder head. In modern spark ignition engines, fuel is injected into the air inlet port of each cylinder with the help of electronic fuel injectors, resulting in a faster response of the engine to load and speed changes. The volumetric efficiency of the air delivery system increases as fuel is injected into the inlet airport just before the cylinder. SI engines operate with stoichiometric air-fuel ratios. Gasoline direct injection SI engines have electronic fuel injectors that inject fuel directly into the cylinder, thus preventing knocking as the combustion mixing is controlled with higher compression ratios. Direct gasoline injection SI engines achieve higher power density. Formation of harmful emissions inside the cylinder is prevented by having air inlet pressure through turbocharger boosting, electronic fuel variable injection timing, variable valve drives, variable spark ignition timing, optimized combustion chamber through detailed 3-D combustion CFD simulations, etc. The three-way catalytic converter is used as an after-treatment device to control the emissions of CO, THC, and NOx.

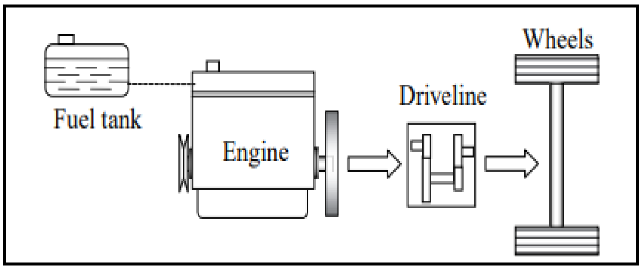

Fig. 3: Schematic diagram of SI Powertrain [15].

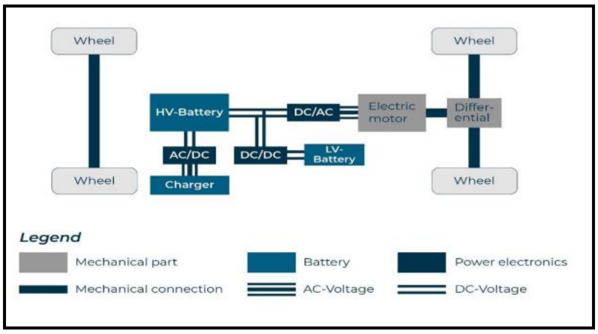

Fig. 4: Schematic diagram of EV Powertrain [16].

Figure 4 provides the schematic of an electric vehicle power train. In electric vehicles, high-voltage batteries are the power source, and traction motors transmit the torque to the wheels through a differential. Bi-directional DC-DC boost and buck converter feed the DC-bus and charge the battery, respectively. Battery voltage is boosted by the bi-directional DC-DC converter to the DC bus voltage. DC bus, which can be from 700 V to 2000 V, is the input to the DC: AC traction converter, which converts the DC voltage to three-phase AC voltage and controls the torque of the AC induction motor through Variable-Voltage: Variable Frequency (VVVF) control. An electric vehicle exhibits the highest transmission efficiency compared to the SI and FCEV power train. Regenerative braking captures the braking energy and charges the onboard battery. Main mode of battery charging is plug-in charging through a charging point. Electric vehicles have driving range issues due to the batteries' lower energy and power density.

Driving range issues of EVs have led to the development of FCEV power trains (figure 5) for highway driving and heavy-duty vehicles. FCEV powertrain consists of a Fuel Cell and Battery along with DC-DC converters, DC-AC traction converters, and a traction motor. Power trains are similar to the EV power train except that there is a power split between battery and fuel cell. Generally, Proton Exchange Membrane fuel cells (PEMFC) with hydrogen fuels are used in mobility applications. On-board FC is used to recharge the batteries in addition to the regenerative braking. The voltage output of the FC is low, and a boost DC-DC converter is used to enhance the FC voltage to the level of the DC bus. Other power electronics are similar to the EV. The power split between the fuel cell and the battery is decided based on the driving cycle.

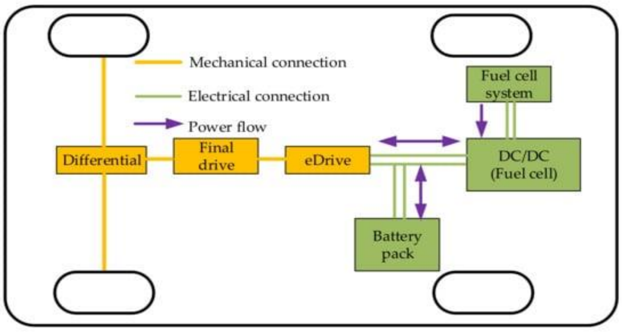

Fig. 5: Schematic diagram of FCEV Powertrain [17].

3. RESULTS

After completion of simulations, the simulation graph and performance parameters of SI Engine vehicle, EV, and FCEV were figured out in following as follows:

3.1 SI engine-based powertrain

The simulation result of SI based power train is illustrated in Figure 6. This is discussed below:

The produced engine torque (Figure 6) follows the duty cycle FTP 75, indicating the adequacy of the model. During vehicle acceleration and deceleration, a rapid rate of change of torque are required, and Figure 6 shows that the model can meet this requirement. The lower part of Figure 6 illustrates the fuel flow to the engine, and there is a strong correlation between the torque developed by the engine and the fuel flow.

Figure 7 displays the vehicle velocity attained by the vehicle vis-à-vis the target velocity as per FTP75. It is observed that the traced velocity can closely follow the FTP75 velocity profile. Engine speed (middle graph) is in line with the vehicle speed. The bottom graph establishes the correlation between the brake-specific fuel consumption of the engine and the engine speed. The lowest graph of Figure 7 demonstrates that the drive train model can maintain a constant fuel economy (MPGe) after the initial start-up.

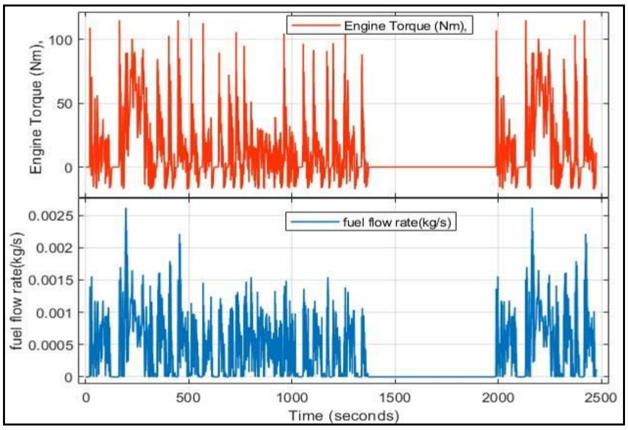

Fig. 6: Simulation graph of engine torque and fuel flow rate of SI engine vehicle.

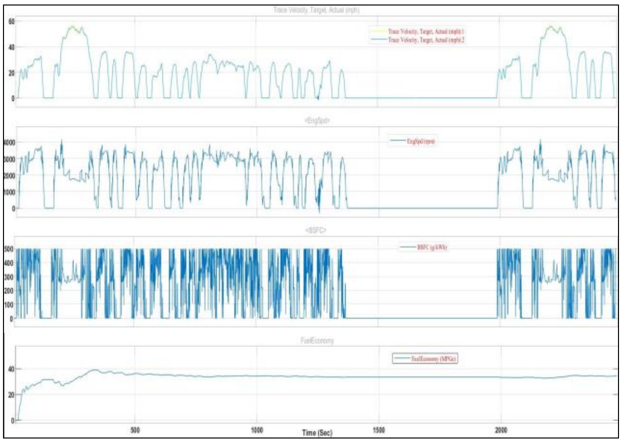

Fig. 7: Simulation of SI engine-based vehicle and engine.

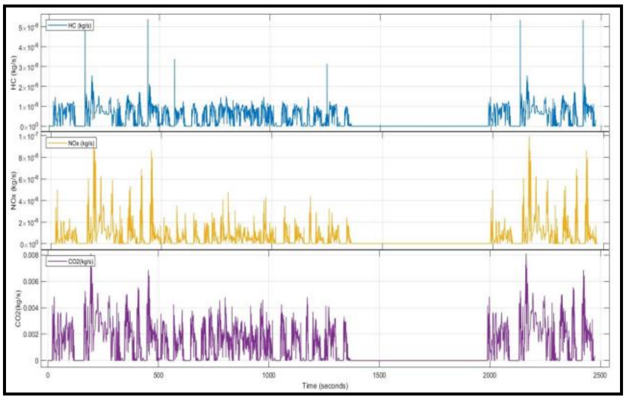

Fig. 8: Simulated emissions from SI engine.

Figure 8 shows a simulation of engine emissions. High HC and NOx emissions are observed during the engine's transient operation. This represents incomplete combustion due to a sudden change in the air-fuel ratio. The NO_x is high during acceleration and high engine speed due to higher temperatures. CO_2 is related to fuel consumption.

3.2 *Electric Vehicle (EV)*

Simulation results for electric vehicles are provided in Figures 9 and 10.

The simulated EV can effectively follow the FTP75 speed profile. This indicates that the model and the control system are adequate for simulating real-life driving conditions.

Rapid changes in vehicle speed, motor speed, and torque during acceleration and deceleration are directly proportional to the load demands. EV models show a large fluctuation in torque over a short period of time as EV torque is directly proportional to the current supplied, and electric vehicles produce maximum torque at the start.

The torque developed by the traction motor varies from +100 to -50 Nm (figure 9), whereas in the SI engine power train, this variation is from +100 to -10 Nm. This difference is due to the regenerative braking in the EV. During regenerative braking, the motor acts as a generator and charges the battery. In the SI engine power train, variation in the torque developed by the engine and the drive train on the negative side is due to braking leading to losses in the power transmission as the engine is brought to idle and the transmission applies reverse torque on the engine.

Battery SoC measures the remaining charge in the battery compared to its total capacity, expressed as a percentage. As we see from Table 2 and Figure 10, the SoC of an EV shows a continuous drop of approximately 75.5% to below 71% over the drive cycle. The EV is propelled solely by the battery, and a continuous drop is seen in the battery's SoC as power is drawn for traction.

The battery current (figure 10) of EV shows notable fluctuations as the demand for power increases. During acceleration or climbing a hill, the battery needs to deliver more current, which leads to higher variations in battery current to meet this load. This leads to significant variations in battery current. And during the deceleration of vehicles, the battery needs to deliver less current. The battery currents (Figure 10) have fluctuations from both positive and negative. The positive represents that current is drawn out from the battery to the vehicles, and the negative shows that the battery gets charged through regenerative braking.

Electric vehicles exhibit a high energy efficiency of 175 MPGe (figure 10) vis-à-vis 35 MPGe for the SI engine power train. The efficiency of batteries is much higher (95%) compared to 35% for SI engines. The efficiency of a battery is the ratio of the energy retrieved during powering to energy stored in the battery during charging. Inefficiencies in electrical power generation upstream of the battery charging are not considered. A SI engine generates power on-board, and therefore, conversion efficiency of fuel to useful power at the wheels is the measure of efficiency.

Due to these factors, there is a significant difference in the battery and the SI engine efficiency.

Battery power is represented in Figure 11. Variation in the power developed by battery ranges from -17 kW to 40 kW. Negative power indicates charging of the battery during regenerative braking. Power developed by the battery follows the FTP75 driving cycle.

Figure 12 shows the battery voltage with time. Battery voltage varies from 350 to 375 V. As power is drawn from the battery for traction, the battery is discharged, and battery voltage is lowered. During regenerative braking, the battery is charged and battery voltage increases. Battery management system can maintain the voltage within the design range.

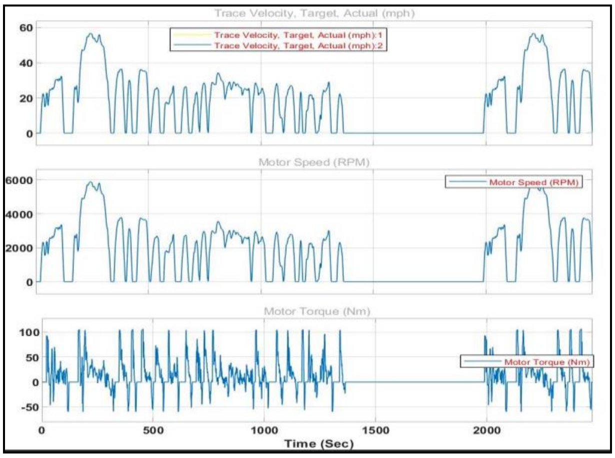

Fig. 9:Simulation Graph of EV.

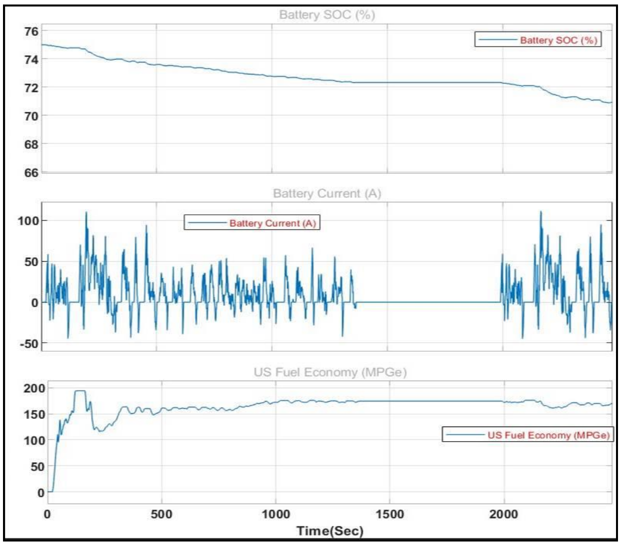

Fig. 10: Simulation Graph of EV

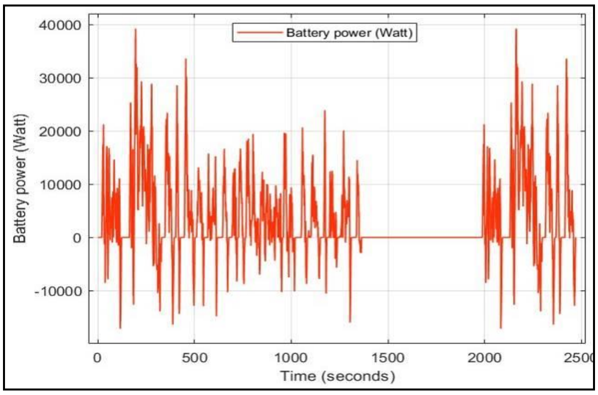

Fig. 11: Battery power of EV.

The lower graph of Figure 13 depicts the battery pack current, which follows the battery voltage (figure 12). The battery pack current is similar to the battery current (figure 10), exhibiting charging and discharging of the battery in line with the driving cycle. The lower graph of Figure 13 illustrates the BMS inverter voltage, which ranges from 350 to 375. BMS inverter is used for charging the battery during regenerative braking when it inverts the three-phase AC power output of the traction motor to DC bus voltage and then stepped down to the battery voltage by a bidirectional buck converter.

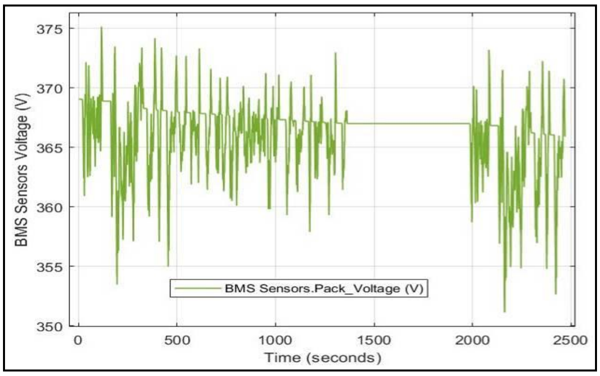

Fig. 12: Battery voltage of electrical vehicle

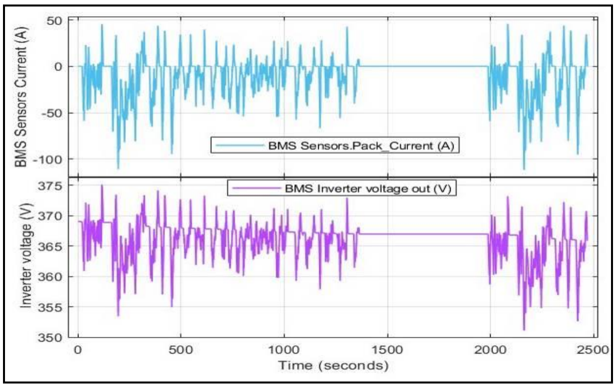

Fig. 13: BMS sensor current and inverter voltage of EV.

3.3 Fuel Cell Electric Vehicle (FCEV)

Simulation results for FCEV are shown in Figures 14 and 15.

The simulated vehicle speed closely follows the target speed as per FTP57. Motor speed aligns with the simulated vehicle speed (second graph of Figure 14. Motor torque (third graph of Figure 14) varies from +100 to -100 Nm, pointing to the motor and generator phase of the 3-phase AC induction motor. Battery SOC varies from 59% to 63% (last graph of Figure 14), unlike EV, where the SOC is reduced continuously as power is drawn from the battery. In the case of FCEV, onboard FC charges the battery whenever the vehicle requires less power. The energy management system of the FCEV decides and controls the battery's onboard charging by the fuel cell. Battery current (Figure 15) gives the battery current with time. The range of battery current is from -90 A to + 60 A. A negative battery current indicates charging of battery by on-board fuel cell. Fuel cells respond slowly to transients, and fast transients can damage the fuel cell electrodes and the electrolyte. Fuel cells provide steady power while the battery is utilized to power the fast transients. On a comparative basis, while a fuel cell has a response of 15 s, the battery response time is only 2-3 s. Fuel cell voltage is therefore maintained almost constant, i.e., 400 V, as shown in the second graph of Figure 15. In the third graph of Figure 15, FC current is plotted against time. FC current shows variations in tandem with the battery current. FC meets the power requirements of vehicles as the prime mover. However, fast transients are catered to by the battery. FC also charges the battery when power demand from the car is low and as programmed in the EMS of the power train. The last graph in Figure 15 illustrates the energy economy of the FCEV in MPGe. FCEV shows a fuel economy in the range of 100 – 150 MPGe, which is less than the battery (175 MPGe) and larger than the SI power train (35 MPGe). On-board conversion of hydrogen to electrical energy, as per the NERNST equation, has a lower efficiency than drawing power from the battery.

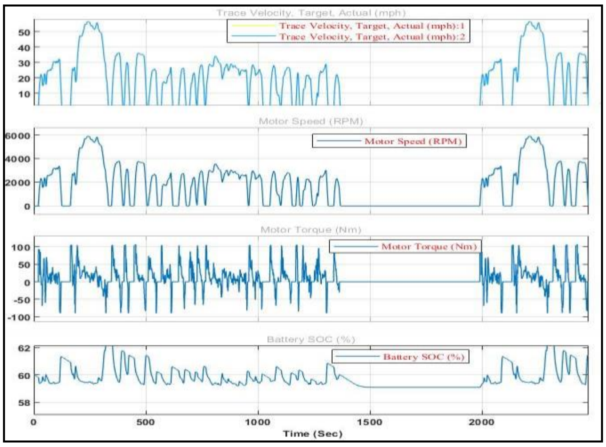

Fig. 14: Simulation graph of FCEV.

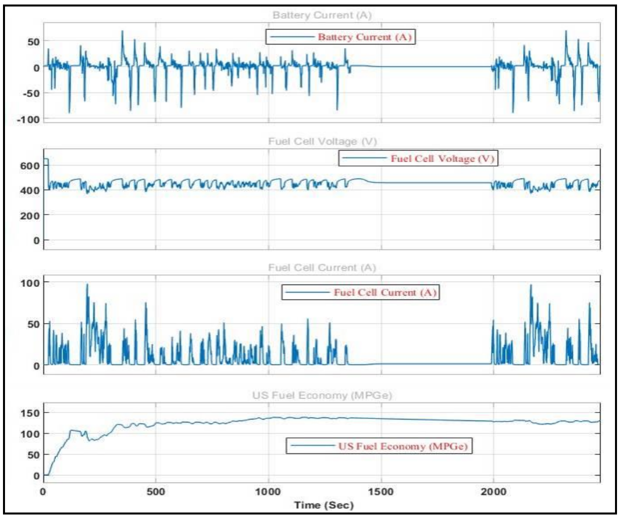

Figure 15: Simulation graph of FCEV.

Figure 16 demonstrates the power delivered by the battery and the vehicle's total power requirement. There are notable fluctuations in both battery and FC power (Figure 16). Battery power fluctuates between -20 kW and +20 kW, representing the fast charging and discharging cycles due to acceleration and regenerative braking. Total power demand varies between -10 kW and +30 kW, showing the integrated power dynamics of the battery and FC.

The hydrogen flow rate (Figure 17) remains minimal, showing efficient utilization, keeping the flow under 20% of the rated flow.

4. DISCUSSIONS

1. Due to the simple drive train and few mechanical parts in EVs, trace velocity shows a more consistent adherence to the target velocity, whereas due to the complex powertrains of FCEVs and SI, trace velocities show some fluctuations.
2. SI engines produce torque that fluctuates with speed and is less predictable. In contrast, EVs and FCEVs deliver a steady and immediate torque response, which results in optimal efficiency and responsiveness during operation.

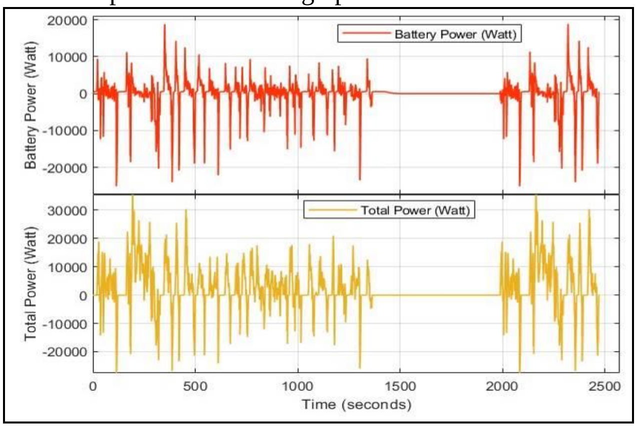

Fig. 16: Battery and total power of FCEV.

Table 2: Results of SI, EV, and FCEV.

Parameter	SI	EV	FCEV
Motor/ Engine Speed (RPM)	Peak: 4000, Steady: 1000-3000	Peak: approx. 5800, Steady: 2000-4000	Peak: 5000, Steady: 1500-3000
Motor Torque (Nm)	N/A	Peak: ±100, Fluctuates: ±50	Peak: ±100, Fluctuates: ±50
Battery SOC (%)	N/A	Start: 75%, End: 71%	Start: 64%, End: 60%
Battery Current (A)	N/A	Peak: approx. ±120, Fluctuates: ±50	Peak: approx. ±53, Fluctuates: ±50
Fuel Cell Voltage (V)	N/A	N/A	Stable: around 600
Fuel Cell Current (A)	N/A	N/A	Peak: ±100, Fluctuates: ±50
Fuel Economy (MPGe)	Start: 15-20, Stable: 35	Start: 200, Stable: 150	Peak: 140, Stable: 120
BSFC (g/kWh)	Fluctuates: 200-500	N/A	N/A
Maximum Brake specific energy consumption (BSEC) (kJ/kWh.)	38.75	3.84	4.39

3. The SoC of an EV steadily decreases as energy is consumed to propel the vehicle. But in FCEV, the dual-power approach maintains a more stable battery over time compared to an EV. This enhances the FCEV's range compared with an EV. The SI engine operates independently of the battery.
4. FCEV's energy management strategies are more complex than those of EVs. The interactions between battery and FC power sources contribute to variations in their current levels.
5. EV shows offer higher Fuel Economy. A stable fuel economy is achieved in EVs because EV powertrains are more efficient across various driving conditions. In SI, more significant variability is shown in fuel economy or fluctuations in fuel consumption according to engine loads due to the inefficiency of ICE. In FCEV, variations are shown, but this variation is more efficient than the SI model. Due to hybrid arrangements, complexity is introduced to energy management. In Figure 18, the EV maintains the highest fuel economy, above 160 MPGe, which shows a higher efficiency than SI and FCEV. The FCEV fuel economy increased more rapidly initially but gradually declined later. The SI fuel economy remains below 50 MPGe throughout the period and shows low performance and lower fuel efficiency than the other two power trains.
6. As we see from Table 2, BSEC is higher for SI, which means more fuel energy is required to produce the same amount of work. The energy loss

in SI engines is due to heat, friction, and combustion inefficiency. In FCEV, BSEC is slightly higher than EV but lower than SI. The energy loss in the FCEV engine is due to the conversion of hydrogen to electrical power and mechanical power. However, FCEV results are better than SI. The EV has the lowest BSEC and is the most efficient in converting electrical to mechanical energy. EV provides higher fuel economy, which results in lower BSEC. The lower BSEC is due to low mechanical losses, high energy conversion efficiency, and reduced waste heat production. This shows the advantages of electric powertrain over FCEV and SI.

7. EVs and FCEVs use eco-friendly fuel, which leads to zero emissions, but SI emits HC, CO_2, and NO_x emissions.

Table 3 compares the costs and Environmental Impacts of IC Vehicles, EVs, and FCEVs. It highlights that IC engines have low initial costs but higher long-term costs and harmful effects on the environment, while EVs and FCEVs provide a greener choice

Table 3. Comparison of costs and environmental impacts of IC vehicles, EVs, and FCEVs.

SN	Cost	SI engine powertrain	Battery powertrain	FC-Battery powertrain
1.	Production Costs	Low initial costs are due to mature manufacturing processes. For example, the Cost of an entry-level Petrol Car is Rs. 5.5 Lakh (approximately).	Battery cost is higher, but the drivetrain is simple, cutting down other costs. e.g., cost of an entry-level EV is Rs. 10 Lakh (approximately).	Fuel cell and hydrogen production costs and infrastructure increase the costs. E.g. Cost of energy level FCEV is Rs. 25 Lakh (approximately).
2.	Maintenance Costs	Higher cost due to thousands of parts and regular service and mechanical wear and tear.	Cost is lower due to few parts of mechanical cost is lower, but battery replacement cost is high.	Moderate cost but catalyst degradation over time.
3.	Energy Costs	Higher cost due to fossil fuel	Lower electricity cost generated with renewable energy.	Higher due to production cost of hydrogen.
4.	Environmental consequences	High emission is generated	Operational emissions are low, but battery manufacturing has ecological effects	No harmful Tailpipe emission but Full lifecycle emissions depend on hydrogen production.

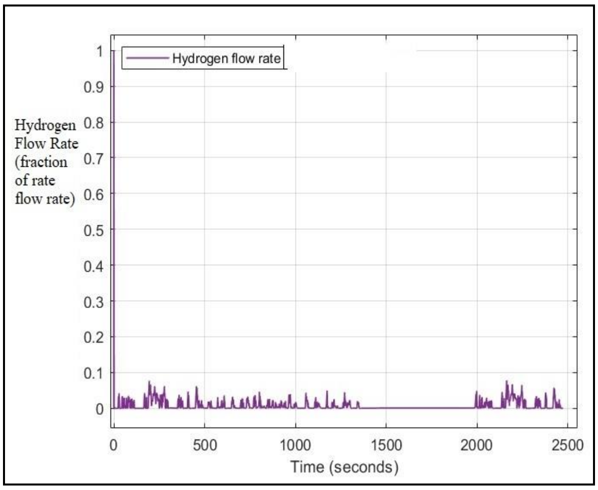

Fig. 17: Hydrogen flow rate of FCEV.

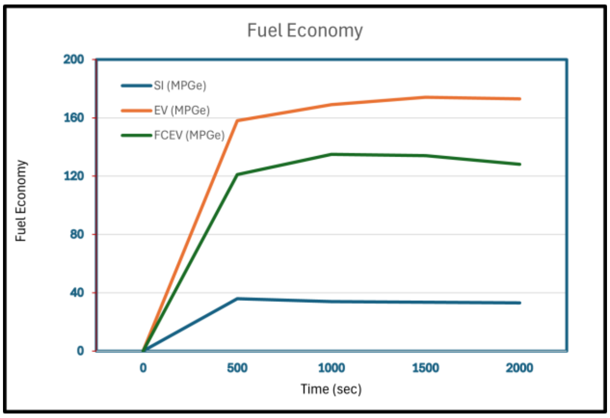

Fig. 18: Fuel Economy (MPGe) of SI, EV, and FCEV.

5. CONCLUSION

Electric Vehicle (EV) powertrain performs best, offering the highest efficiency, superior fuel economy, a quick torque response, velocity alignment, and smooth decrease in State-of-Charge (SoC). A lower range of driving with EVs is its weak feature. Therefore, EVs are used in urban areas for transportation. For long-distance transportation and heavy-duty vehicles, EVs are not preferred. FCEVs are the second-best choice in terms of efficiency. The FCEV has advantages such as faster refueling speed and more extended driving range over EVs; the motor speed and torque of FCEV are like EVs, but its fuel economy lags when compared with EVs. Emissions from FCEV are in the form of water vapor, and no emissions of harmful pollutants have been noted. The cost of the FCEV powertrain is highest due to the extremely high cost of the fuel cell. Also, the availability of green hydrogen and its high cost are barriers to the large-scale adoption of FCEVs. The SI engine is the least desirable powertrain due to several factors: low fuel economy, uneven torque output, less responsiveness, and lower overall efficiency than EV and FCEV. SI engine power train produces harmful pollutants like CO, NO_x, THC, etc. The large-scale availability of lost-cost gasoline fuel is the biggest strength of SI vehicles. Also, the lowest cost amongst all three power trains makes it still the choice of transport for most users.

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