Effects of Degree of Hybridization and Vehicle Driving Cycle on the Performance of Fuel Cell-Battery Hybrid Electric Vehicle

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Abstract - *Automobile manufacturers and end users are exhibiting interest in Electric Vehicles (EVs) due to the threats posed by fossil fuel driven vehicles mainly rising air pollution levels. As EVs are yet to play vital role and larger penetration into markets, hybrid electric vehicles especially Fuel Cell Hybrid Electric Vehicles (FCHEVs) are showing promising signs. Moreover, this is also creating interest among researchers to find better performing and affordable EVs. The problem with battery electric vehicle is long charging time, less travel range and high Battery cost. Fuel cell hybrid electric vehicles would solve these limitations to some extent. In the present work, the Advanced Vehicle Simulator (ADVISOR) has been used to investigate the impact of the degree of hybridization (DOH) on the performance an FCHEV (Toyota Mirai 2021 model). The fuel economy, acceleration performance and Gradeability performance of the various configurations (different DOHs) are compared with the original vehicle's findings. The vehicle configuration with maximum degree of hybridization (DOH = 68.7%) showed a 16.3% improvement in fuel economy. Furthermore, the best vehicle configuration is recreated across a variety of driving cycles in order to investigate its performance under various driving conditions.*

***Key Words*: Fuel Cell, Battery, Hybrid Electric Vehicle, Driving Cycle, ADVISOR Software, Range**

1. INTRODUCTION

As per the reports of IEA (International Energy Agency) in 2016, the transportation sector contributed for 33.7 percent of energy used worldwide and 24.4 percent of CO_2 emissions [1]. Vehicles driven by traditional IC Engines get their energy from fossil fuels. The price of fossil fuels has been increasing day by day and also emissions emitted by the traditional IC engine driven vehicles are affecting the environment drastically.

Both researchers as well as manufacturers are trying their best to cope with the stringent emission norms being legislated periodically. It has become mandatory to comply with EURO VI norms since April 2020 all over the world. In the process of meeting emission norms either focus is being shifting to include cost intensive engine modifications adopting exhaust aftertreatment device or employing alternative combustion techniques or alternative fuels [2]. However, owing to the persistent problem of harmful emissions due to various reasons and also to look for other alternatives for fossil fuelled ICE vehicles, interest is growing towards electrification of the transport sector both in heavy duty and passenger domains.

Automobile makers are being forced to develop innovative solutions as the public's desire to safeguard the environment grows. As a result, automakers are becoming more interested in EVs-Electric Vehicles and HEVs-Hybrid Electric Vehicles [3,4]. But the problem with full electric vehicles is large refuelling time, shorter drive range and availability of charging stations. So hybrid vehicles can be the best alternative option provided with a better energy management system. Hybrid vehicles are characterized based on drive train arrangement and source of energy. The power supplied by the ICE engine would either be directly utilized to drive the wheels or be used to replenish the battery, which in turn aids in the rotation of the motor in ICE hybrid cars. There are mainly three versions under which two power sources could be connected to propel the vehicle, in a way how the ICE and the battery or other than ICE is connected such series, parallel and series-parallel versions.

Though battery and ICE combined hybrids have started emerging but the issue with battery charging has remained as an issue. In this direction, fuel cell powered energy storage has started emerging in hybrid electric vehicles.

The fuel cell is the principal source of energy in fuel cell hybrid electric vehicles (FCHEV) [5]. Fuel cell is an electrochemical device that transforms chemical energy available [mostly in hydrogen] directly into electrical energy. They are categorized as PEMFC, AFC, MCFC, SOFC, and PAFC depending on the kind of electrolyte utilized in the fuel cells [6,7]. The attractive features of Proton Exchange Membranes (PEM) fuel cell that make its applicability in hybrids are; the simplicity, viability, quick start, better power density, lower temperature operation [8-11]. Oversize of FC does not hinder its use in transient conditions. However, it becomes an expensive option for hybrid vehicles. The contribution from FC is frequently reduced and hybridized with some other energy storage technology to minimize cost rise. The fuel cell enabled hybrid power-train system essentially comprises of batteries or ultracapacitors for energy storage and an electric motor [12]. Only particular circumstances allow the electrical energy storage devices to function. The fuel cell is the primary power source for the electrical motor in this investigation. When the fuel cell's power is insufficient to operate the motor during sudden acceleration, a battery system is used.

Turkmen, et al [13] built a fuel cell hybrid electric car model using ADVISOR software and studied the impact of fuel power and fuel cell type on vehicle performance. Ahmadi and Bathaee [14] to regulate the energy in the fuel cell hybrid car proposed two energy management methods have been developed (FCHV with fuzzy logic control (FLC) and operational mode control (OMC) are the two. These methods are compared to other methods that are available in advisor software. Maxoulis et al [15] explored how modifying design factors including maximum stack power, catalyst activity, and water concentration in the fuel cell stack's channels affected the overall performance and fuel consumption of a fuel cell electric car. Degliuomin et al [16] suggested a method for on-board hydrogen production from bio-ethanol that is used in conjunction with a Proton Exchange Membrane Fuel Cell aboard the vehicle. The car is put through its paces on typical driving cycles and determined to be adequate. It was also proposed that the components be resized to increase fuel economy. Das et al [17] in their review paper discussed various FCHEV configurations and power converter topologies. The advantages and disadvantages of each topology, safety standards, current situation and environmental impact of FCHEV were also discussed. Zhang et al [18], made use of ADVISOR software, created a fuel cell drive train model for a locomotive, featuring a fuel cell as the primary energy source and a lead-acid battery as secondary energy storage. As an energy management system, a fuzzy logic-based control method is designed, and the efficiency of the FC improves by 6.8%, while the gradeability at 36 km/h increases from 8.9% to 11.1%. Feroldi et al [19] proposed a methodology for scaling of fuel cell and number of supercapacitors in fuel cell hybrid electric vehicles integrated with supercapacitors. By enlarging the fuel cell and adjusting the energy management strategy's parameters, vehicle performance is investigated. Wipke et al [20] gave a clear insight about how ADVISOR software works and explained about backward and forward approach techniques used in the software. Advantages of ADVISOR software over other software's worked based on forward facing techniques are also presented. In comparison, with other forward-facing vehicle model software, ADVISOR mimics vehicle performance on regular driving cycle around 2.6 and 8.0 times faster.

Chris et al [21] emphasized the importance of simulation and modelling in the development of electric and hybrid vehicles discussed the methods (i) physics-based Resistive Companion Form technique and (ii) Bond Graph method for the powertrain component system. They briefly listed out the capabilities of other modelling tools in addition to ADVISOR for simulation of EVs and HEVs. They stressed the importance of numerical oscillations in dynamic simulations involving power electronics.

In the present work, an FCHEV mid-size car is modelled and simulated in ADVISOR (Advanced Vehicle Simulator-designed by the National Renewable Energy Laboratory, US) [22,23]. with varying fuel cell stack power battery pack by keeping maximum total power of the vehicle as constant and performance parameters such as power consumption, acceleration performance, Gradeability, driving range, fuel economy etc., are compared among each model. Studies were done related to tank-to-wheel and well-to-wheel and discussed the energy consumption and greenhouse gas emissions for the chosen engine configuration. Urban and cruising driving conditions for chosen for the simulation. Also, a Wankel engine would be an appealing choice for a plug-in hybrid electric vehicle's range extender [24].

Avanish Kumar and Thakura [25] felt that electric vehicles would be alternative to ICE vehicles. They were of the opinion that hybrid electric vehicles would be immediate option in place of EVs due to issues such as shorter range and longer recharging periods for electric vehicles as HEVs would exhibit better efficiency and reliable operating modes . Using the ADVISOR software, they evaluated the performance of a tiny HEV pure ICE with series HEV , and parallel HEV configurations. The acceleration performance and gradeability test and vehicle emissions were studied. To combat issue of poor quality in urban areas, that hybrids, specifically, Battery Electric Vehicles and Fuel Cell Electric Vehicles were becoming important source of automobiles [26].

For the present study, specifications of the new 2021 Toyota Mirai fuel cell hybrid Electric Vehicle is considered. The improved model is simulated across different Degrees of Hybridization and multiple driving cycles.

1.1 Vehicle Description and Driving Cycles:

Toyota Mirai FCEV Sedan-2021 Product Information was chosen for the investigation. The power-train is modelled with reference to the 2021 Toyota Mirai FCEV's vehicle specifications. Power drivetrain comprises of hydrogen tank, fuel cell stack, dc/dc converter, battery, electric motor, dc/ac inverter. Table 1 shows the essential vehicle characteristics for this kind of vehicle. In general, combining an FC energy system with battery storage increases the vehicle's performance and its fuel efficiency. The hybridization ratio is defined as the ESS power to total power. FCHEVs engine economy, recovery from braking energy, and fuel cell life-span can be improved by using hybridization. The importance of hybridization leads to higher fuel efficiency in urban(transient) and accelerated driving circumstances. The fuel cell produces primary power for steady-state driving, whereas the battery boosts power in acceleration surges and peak load conditions and recovers kinetic energy during braking. The equivalent internal resistance of the battery, which has a higher energy density, is a critical limitation for hybrid power management. In the present work, at different degrees of hybridization conditions Fuel cell system power and the battery capacity are varied by keeping maximum total power 174 kW as constant to calculate the fuel efficiency and acceleration performance in each case.

The characteristic of vehicle speed versus time illustrates a typical *Vehicle Driving Cycle*. It can be treated as a replication or simulation of driving conditions on the road. Different nations and organizations develop driving cycles to evaluate a vehicle's performance in a variety of ways, including fuel efficiency, the range of an electric car, and emissions. Driving cycles are also used for simulations to predict imposing road and driving conditions for arriving at vehicle's performance and emissions .

The popular driving cycles include- the UDDS (Urban Dynamometer Driving Schedule), NREL2VAIL Urban Driving Cycle (UDC) and the Extra Urban Driving Cycle (EUDC) cycles, are combined to form the New European Drive Cycle (NEDC). In the context of India, Modified Indian driving cycle (MIDC) is used to test vehicles operated in India. The NEDC depicts high-speed driving circumstances with fast speed variations, as well as driver behavior. The WLTC (Worldwide Harmonized Light Vehicle Test Cycles) are the tests on chassis dynamometers, used to determine energy consumption and emissions from light-duty vehicles. It represents the driving conditions for a span of 14.41 miles (23.2 km) with 8 stops in between and total test time is around 1800 sec. The whole cycle is divided into low, medium, high, extra high i.e., 4 parts with respect to speed and achieves a maximum speed of 81.65 mph (131.4 kmph).

1.2 Degree of hybridization (DoH) of HEV:_

The ratio of the batteries maximum power to the drivetrain total power is the degree of hybridization for an FCHEV.

$$\text{DoH} = \frac{p_{B,max}}{p_{FCS,max}+p_{B,max}}$$

Where $p_{B,max}$ is the battery maximum power and $p_{FCS,max}$ is the fuel cell maximum power. In the present work, $p_{FCS,max}$ and $p_{B,max}$ are varied accordingly maintaining the vehicle's total power unaltered (174 kW).

1.3 Degree of hybridization

FCEVs must satisfy the following requirements [20]

i. FCS must be able to keep the vehicle moving at 55 mph (88.5 km/h) at a 6.5 percent gradient for 20 minutes on its own.

ii. The vehicle should be able to accelerate from 0 to 96.6 km/h in 12 seconds, according to the PNGV.

Performance of vehicles with various DoH (degrees of hybridization) will be evaluated, but only for automotive models that adhere to the aforementioned requirements.

Table -1: Vehicle Specifications

Variable	Description	HEV (Toyota vellfire)
fc_max_pwr	Fuel cell max power in kW	114 KW
ess_moduel	no of battery moduel	37
ess_nom_voltage	nominal voltage of battery moduel	248 V
mc_max_power	max power required by battery	113 KW
fc_coolant_init_tmp	initial coolant temperature	28
veh_CD	coefficient of aerodynamic drag	0.29
veh_FA	vehicle frontal area	2.79
veh_wheelbase	distance between front and rear axle	2.78
wh_mass	total mass of all wheels	32
wh_radius	radius of the wheel	0.33
veh_glider_mass	weight	1840
	Drive Type	FWD

2. METHODOLOGY

Vehicle configurations with varied DOHs are studied in ADVISOR software, to see how the degree of hybridization affects vehicle performance. ADVISOR makes use combination of forward-facing and backward-facing combination for simulation features. It's developed for quick comparisons of traditional, electric, and hybrid vehicle performance and fuel efficiency. ADVISOR also serves as a foundation for extensive simulation and analysis of user-defined drivetrain components, as well as a source of validated vehicle data and algorithms from which to fully use SIMULINK's modelling freedom and MATLAB's analytic capabilities. In our current work, overall power of the powertrain is kept constant across all configurations, with just the percentage of power available from the battery and the fuel cell system altering.

Uses of Advisor Tool

i. To investigate how energy is used and lost across the drivetrains of conventional, hybrid and electric vehicles.

ii. To see the operation of an energy management plan for the fuel converter in your hybrid car.

iii. Calculate the tailpipe emissions from a variety of cycles.

iv. To adjust the gear ratios in the transmissions in order to reduce fuel consumption or increase performance, for example.

v. To learn about the fuel efficiency of automobiles that have yet to be produced.

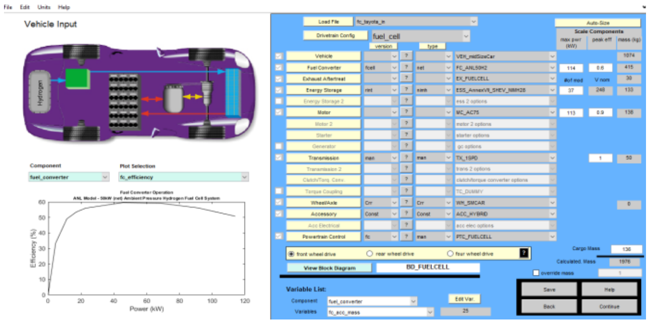


Figure 1: Input window of ADVISOR software

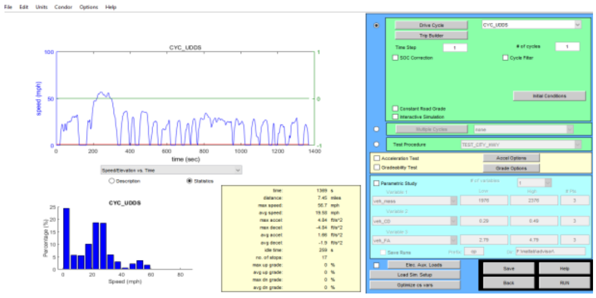


Figure 2: Simulation setup window in ADVISOR

Figures 1–4 illustrate the input, setup, simulation sample results interface and vehicle block diagram respectively.

The driving cycles are coded in MATLAB as detailed below:

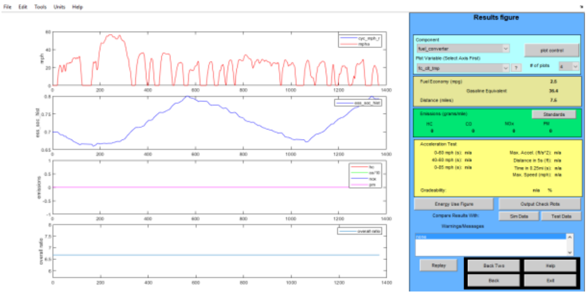


Figure 3. Results window in ADVISOR

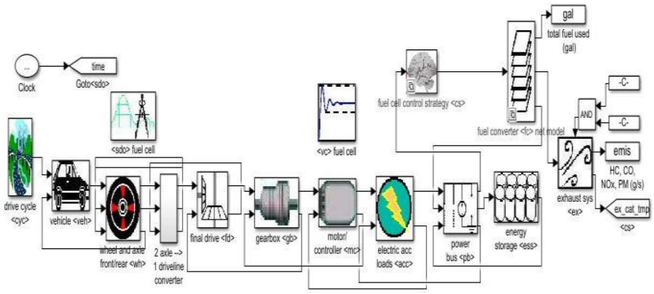


Figure 4: FCHEV Block diagram in ADVISOR

3. RESULTS AND DISCUSSION:

As described in the previous section, the simulation resolution results obtained through ADVISOR for the Toyota Mirai vehicle are presented and discussed.

Effect of the Degree of Hybridization (DoH):

This section discusses how the degree of hybridization affects FCHEV's performance. Table - 2 summarizes the acceleration and gradeability findings for each setup. In the acceleration test the time taken to reach 60 mph, 85 mph from 0 and 60 mph from 40 mph are noted.

Table-2 Acceleration, Gradeability performance results

DoH (%)	**Acceleration test (Time Taken to reach)**			**Gradability test at 55 mph for 20 mins (%)**
	0-60 mph	**40-60 mph**	**0-85 mph**	
29.89	12.1	6.5	25.6	16
31.03	12	6.3	25	15.2
34.5	10.7	6	23.4	14.6
44.83	9.8	51	20	12.5
50	9.3	4.7	18.7	11.3
59.77	8.5	4.2	16.8	8.7
64.94	8.1	4	15.9	7.3
67.8	7.8	3.8	15.4	6.5
68.4	7.7	3.7	15.3	6.3

Table-3 Maximum speed, fuel economy, Initial travel distance results

DoH (%)	**Maximum Speed (mph)**	**Distance travelled in 5 sec (ft)**	**Gasoline equivalent**
29.89	97.9	163.4	-
31.03	97.9	165.6	63.8
34.5	97.9	168.6	65.1
44.83	97.5	176.6	68.9
50	97.5	182.1	71.1
59.77	97.3	187.5	72.9
64.94	97.2	190.2	74.9
67.8	97.2	192.5	75.7
68.4	97.2	192.8	-

It is observed that with rising DoH, there is a decreasing tendency in acceleration time. With increase in battery power, the acceleration time should decrease due to the battery's greater reaction to power increase than that of the fuel cell. The Gradeability test determines the maximum grade that the vehicle can travel at 55 mph for 20 minutes. As the DoH moves away from the initial DoH, the maximum grade supported by the FCEV in the Gradeability test at 55 mph decreases.

Table-3 summarizes the maximum speed, fuel economy, travel distance in first 5 secs findings for each setup. Max speed remains almost constant with change in DoH. Distance traveled in the first 5 sec is increasing as the vehicle DoH is increasing since in the initial condition's battery is solely used to run the motor. Maximum acceleration remained constant. Fuel economy of FCHEV is determined for UDDS cycle at all configurations. 34.5% is the DoH corresponding to the original Toyota Mirai, the fuel economy corresponding to this configuration is 65.1 mph, while Mirai's fuel economy is 67 mph, we can see a difference of around 2.8%. The lowest DoH configuration has a worse fuel efficiency, as shown in Table-3, while the vehicle with maximum DoH configuration has highest fuel efficiency. It is feasible to see an improvement in fuel efficiency with the help of DoH. When evaluating a vehicle's fuel efficiency with original DoH configuration to that of maximum DoH configuration, there is a 16.3 percent improvement in case of maximum DoH configuration's performance. But with increase in DoH the gradeability decreases significantly, maximum speed also decreases slightly. DoH for Toyota Mirai is restricted between 31%-67.8% (from Table-2). The vehicle configuration corresponding to 67.8 percent DoH has good acceleration performance and also has improved fuel economy so the corresponding vehicle configuration can be treated as optimum Toyota Mirai configuration.

3.1 Performance on different driving cycles:

i) Modified Indian Driving Cycle (MIDC):

Actual Toyota Mirai FCEV is simulated with respect to MIDC driving cycle. The simulation results for vehicle speed, battery state of charge, motor power requirement, fuel cell power, and battery power are shown in Fig.5. The battery SOC reduces from 70 percent to 56.4 percent during the first 810 seconds. During the first 810 sec the speed is very low due to this only the battery is producing the total power needed and fuel cell is in ideal state. After 810 sec, due to high speeds, the fuel cell system simultaneously recharges the battery i.e SOC increases as well as supplies power to motor. The fuel cell energy system completely compensates the peak demand of the motor, which is roughly 26.3 kW. Fuel cell is in off mode for most of the time. Between 810 sec to 1180 sec power generated by the fuel cell is utilized to charge the battery.

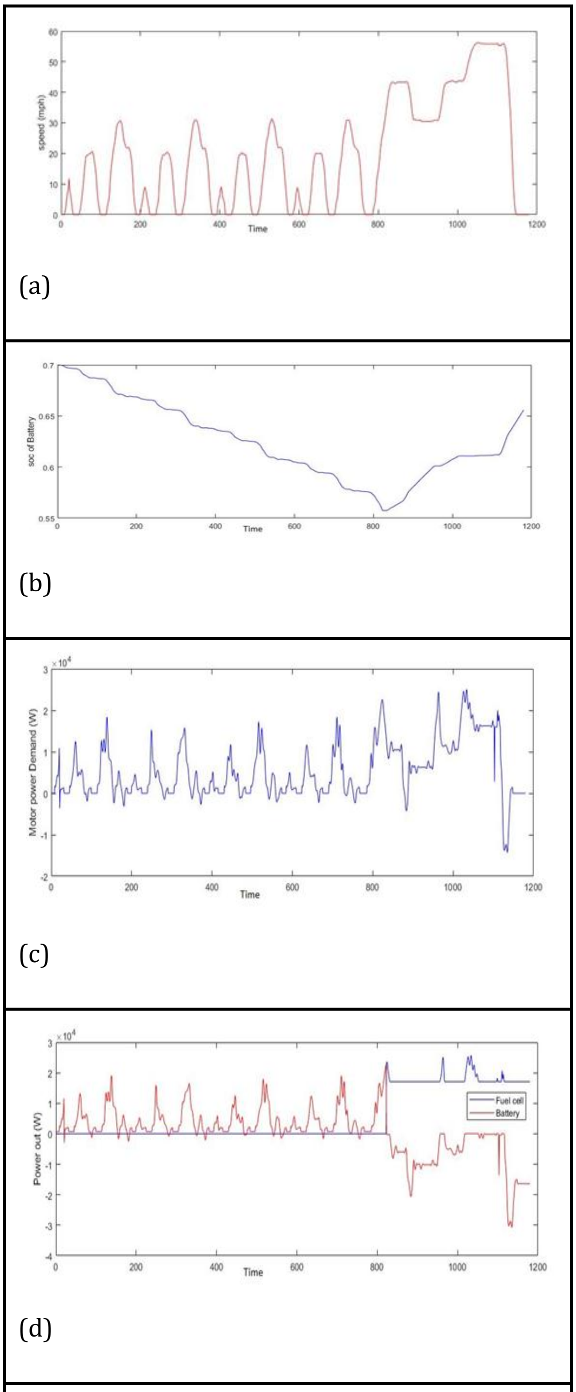


Figure: 5 Simulation results during MIDC cycle

ii) Urban Dynamometer Driving Schedules (UDDS)

Fig. 6 shows the simulation findings in relation to the UDDS. During the vehicle beginning phase of 100 seconds, the battery SOC reduces from 74.5 percent to 70.2 percent, before returning to its baseline SOC after 400 Seconds. To meet the motor peak power requirement of 47.2 kW, the fuel cell and battery provide 41.6 kW and 7.9 kW, respectively.

SOC of battery at the end of the cycle is 70.5 percent. Only the battery supports the motor during the vehicle's starting and low-speed situations. For the most part, the fuel cell is switched off.

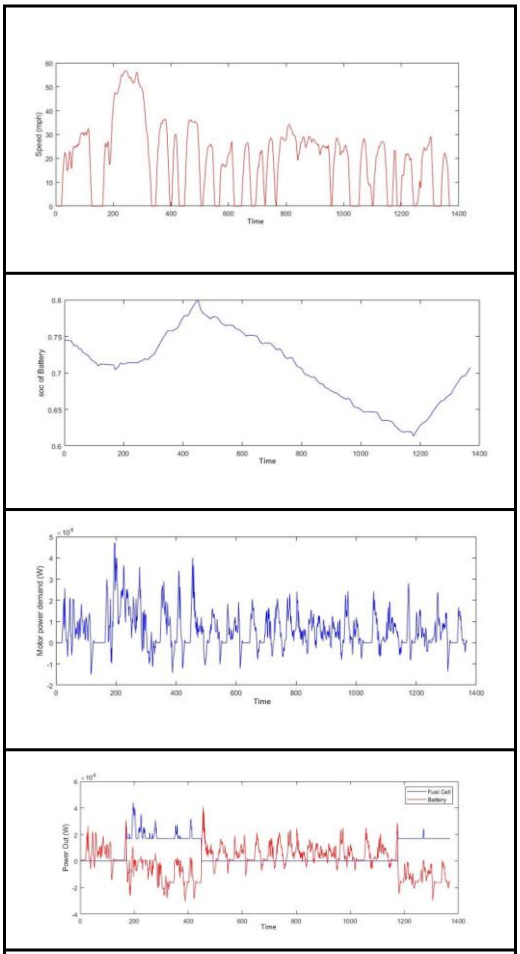


Figure 6: UDDS cycle simulation results

ii) NREL2VAIL (used to predict the performance at mountain areas)

The NREL2VAIL driving cycle is often used to estimate vehicle performance in off-road circumstances, particularly in mountainous terrain. The NREL2VAIL driving cycle is being used to forecast vehicle performance. It has both uphill and downhill sections. Between 1200 and 2800 seconds, uphill circumstances may be seen, with elevations ranging from 2270 to 3280 meters. The highest power consumption of the motor is roughly 78.3 kW, which is supported by both energy sources, namely the fuel cell (8.3 kW) and the battery system (71.4 kW). Most of the time, both the battery and the fuel cell work together to provide the power need. The battery's SOC has stayed stable at 70%. Between 4900 and 5700 seconds, downhill conditions may be seen, with elevations ranging from 3190 to 2520 meters. The battery system takes care of the majority of the motor's peak power requirement, which is around 43.7 kW.

Most of the time, the fuel cell is idle. Overall fuel cell system efficiency increases when the need for hybrid power control is low or negative. The simulation plots are depicted in Fig. 7.

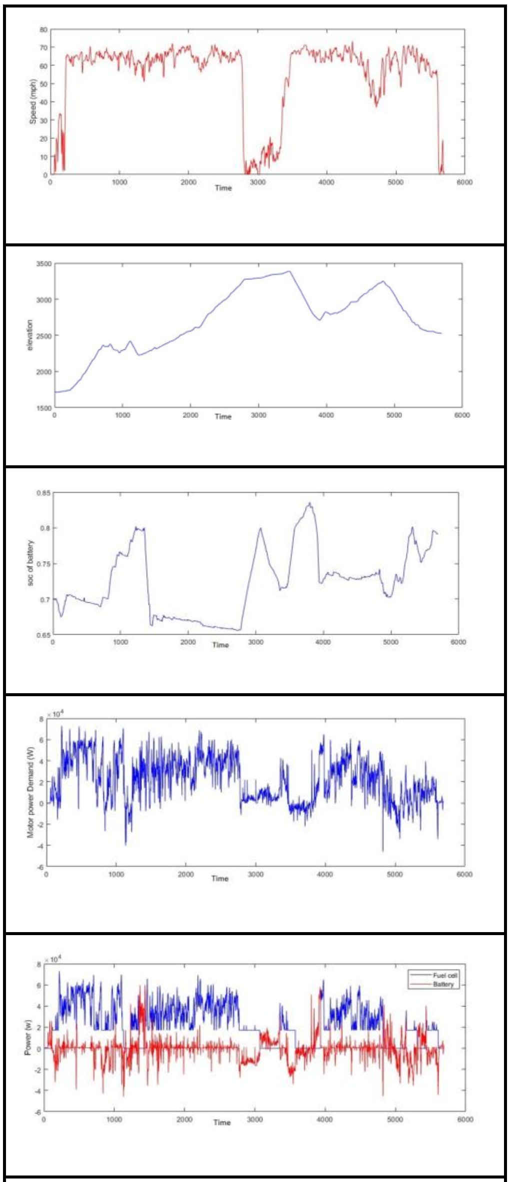


Figure 7: NREL2VAIL driving cycle simulation results

iv) Worldwide harmonized Light vehicles Test Cycles (WLTC)

Considered WLTC class-3 driving cycle for our present simulation. The battery SOC reduces from 70 percent to 64.4 percent during the first 280 sec, after this the fuel cell starts providing required power to the motor and reaches a maximum SOC of 80.5 percentage at around 600 seconds. It can be observed that the fuel cell alone provided motor peak power of 58.3kW and 79.5 percent is the SOC of battery at the end of the cycle. Only the battery supports the motor during the vehicle's starting and low-speed situations, during this situation the fuel cell is in idle state. The details are illustrated in Fig.8.

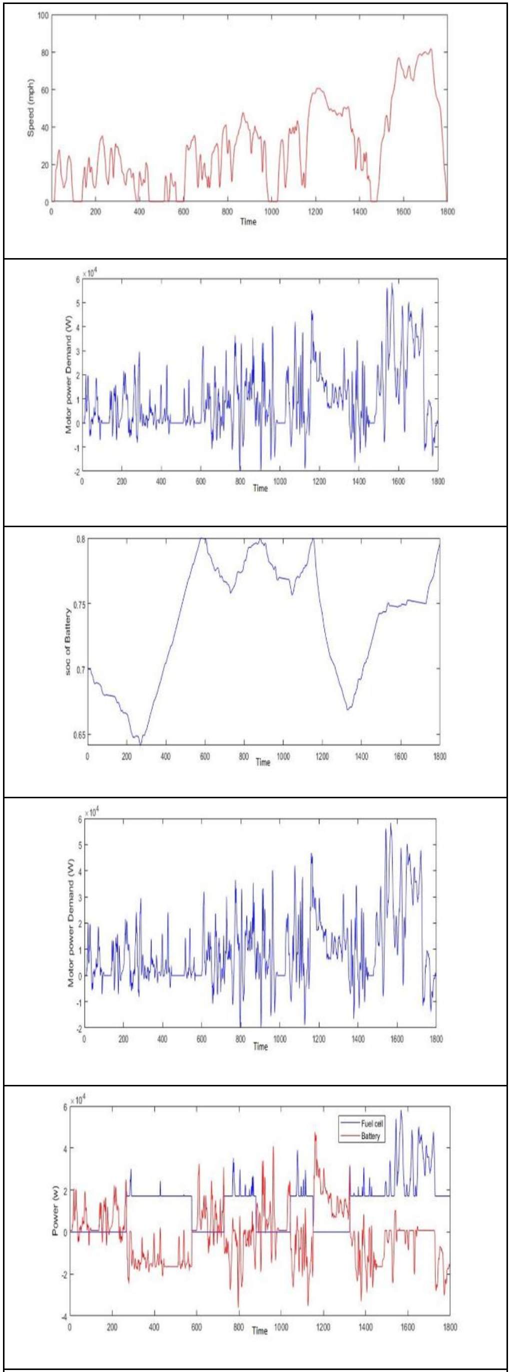


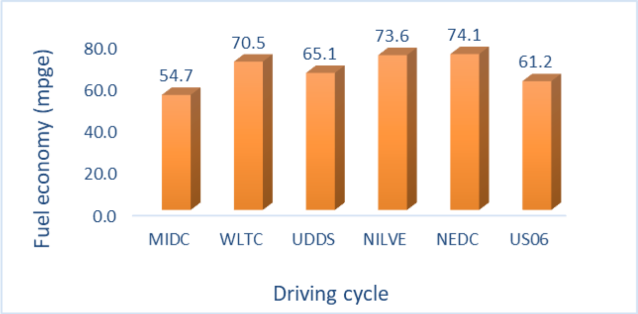
Figure 8: Simulation results for WLTC driving cycle

3.2 Comparison of performance on different driving cycle:

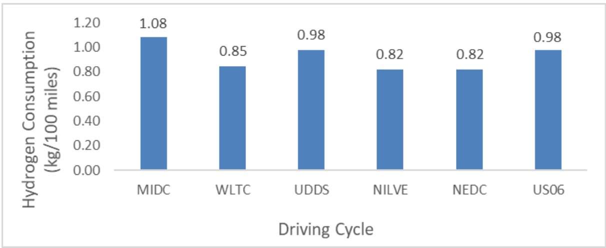
Table 4 represents the Toyato Mirai performance during different driving conditions. The vehicle performs better in NEDC, WLTC i.e its best suited for European and Japanese driving conditions. The comparison plots are shown in Fig.9.

Table-4 Simulation results of Toyato Mirai

S No	**Driving cycle**	**Hydrogen Consumption** (kg/100 miles)	**Fuel economy** (mpge)	**Driving Range** (miles)	**Energy Consumption** per 100 miles
1	MIDC	1.08	54.7	273	61.1
2	WLTC	0.85	70.5	352	47.4
3	UDDS	0.98	65.1	326	51.3
4	NILVE	0.82	73.6	368	45.4
5	NEDC	0.82	74.1	370	45.1
6	US06	0.98	61.2	306	54.6
7	IDC	0.82	73.2	366	45.6
8	HWFET	0.98	61.5	308	54.3



(a)



(b)

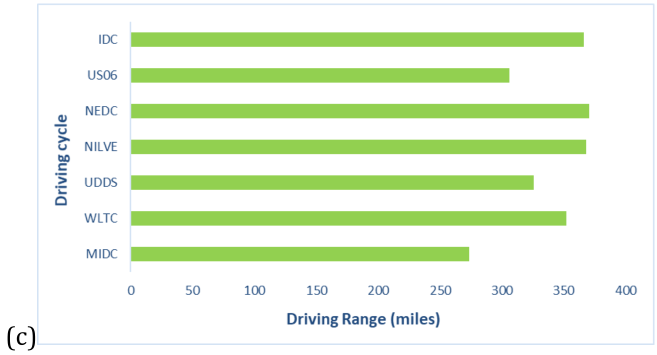


Figure 9: Simulated performance results under various cycles.

4. CONCLUSIONS

The simulation of actual FCHEV mid-size automobile modelling for different DoH and performance are discussed. The hybrid powertrain is modelled using widely used software-ADVISOR in a MATLAB/Simulink-based environment. It is observed that with increasing the DoH improved the vehicle's acceleration performance. The fuel economy result supports the DOH that it significantly enhances vehicle performance. If the fuel economy is similar, there is a 16.3 percent improvement when maximum DOH configuration's is compared to original DOH configuration. Significant improvement in acceleration performance can also be noticed. Lowering the fuel cell power and boosting the battery modules enhances the battery pulse power capabilities while also reducing the fuel cell stack size, cost, and improving vehicle acceleration. The actual Toyota Mirai FCHEV is simulated over different driving cycles and the vehicle configuration is found out to be performing well in European and Japanese driving conditions.

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