Hybridization and Performance Analysis of mid-sized Fuel Cell Hybrid Vehicle using Standard Driving Cycles

A dissertation submitted in partial fulfillment of requirement for

the award of the degree of

Doctor of Philosophy

in

Mechanical Engineering

by

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January–2020

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CERTIFICATE

This is to certify that the thesis entitled **"Hybridization and Performance Analysis of mid-sized Fuel Cell Hybrid Vehicle using Standard Driving Cycles"**, which is being submitted by **Mr. Venkata KoteswaraRao.K** (Roll No. 714019), is a bonafide work submitted to National Institute of Technology, Warangal in partial fulfilment of the requirement for the award of the degree of **Doctor of Philosophy** in Department of Mechanical Engineering.

To the best of my knowledge, the work incorporated in this thesis has not been submitted elsewhere for the award of any degree.

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Dedicated to my Parents

Shri. Rama KoteswaraRao and Smt. Sanjivamma

and

All my Teachers

DECLARATION

This is to certify that the work presented in the thesis entitled "**Hybridization and Performance Analysis of mid-sized Fuel Cell Hybrid Vehicle using Standard Driving Cycles"** is a bonafide work done by me under the supervision of **Dr. G. Naga Srinivasulu,** Department of Mechanical Engineering, National Institute of Technology, Warangal, India and was not submitted elsewhere for the award of any degree.

I declare that this written submission represents my ideas in my own words and where others ideas or words have been included; I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/date/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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ACKNOWLEDGEMENTS

It gives me immense pleasure to express my deep sense of gratitude and thanks to my supervisor **Dr. G. Naga Srinivasulu,** Associate Professor, Department of Mechanical Engineering, National Institute of Technology Warangal, for his invaluable guidance, support, and suggestions. His knowledge, suggestions, and discussions helped me to become a capable researcher. He has shown me the interesting side of this wonderful and potential research area. His encouragement helped me to overcome the difficulties encountered in my research as well in my life.

I am very thankful to **Prof. N. Selvaraj** Head, Department of Mechanical Engineering for his constant encouragement, support and cooperation.

I take this opportunity to thank all my Doctoral Scrutiny Committee members, **Prof. N.Selvaraj** Professor, Department of Mechanical Engineering, **Dr. A.Veeresh Babu,** Associate Professor, Department of Mechanical Engineering, and **Dr. P.V. Suresh,** Associate Professor, Department of Chemical Engineering for their detailed review, constructive suggestions and excellent advice during the progress of this research work.

I also appreciate the encouragement from teaching, non-teaching members, and fraternity of Department of Mechanical Engineering of NIT Warangal. They have always been encouraging and supportive.

I wish to express my sincere thanks to **Prof. N.V. RamanaRao**, Director, NIT Warangal for his support and encouragement.

I wish to express my sincere and whole hearted thanks and gratitude to **Dr. M. Raja Vishwanathan**, Assistant Professor, Humanities and Sciences, NIT Warangal.

I convey my special thanks to my colleagues Dr. Venkateswarlu Velisala, Dr. Venkata Phanindra Bogu and contemporary mechanical department research scholars Mr. Srinivasa Reddy Badduri, Mr. Murali Krishna Boni, Mr. Ganesh Rupchand Gawale, Mr. Ramesh Rahul Jammy (EEE) and Mr. Naresh Yadav (CHE).

I acknowledge my gratitude to all my teachers and colleagues at various places for supporting and co-operating with me to complete the work.

I gratefully acknowledge my wife **Mrs. Swathi** for her continuous support and encouragement, towards my research work and success in life.

My special, sincere acknowledgement, heartfelt gratitude and indebtedness are due to my parents **Shri. K. Rama KoteswaraRao** & **Smt. Sanjivamma** and my beloved sister **Mrs. Annapurna** for their sincere prayers, blessings, constant encouragement, shouldering the responsibilities and moral support rendered to me throughout my life, without which my research work would not have been possible. I heartily acknowledge all my relatives for their love and affection towards me.

Above all, I express my deepest regards and gratitude to the "**ALMIGHTY**" whose divine light and warmth showered upon me the perseverance, inspiration, faith and strength to keep the momentum of work high even at tough moments of research.

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Abstract

Hybridization and component sizing of hybrid energy storage systems (HESS's) has a huge impact on the performance of any hybrid vehicle because it decides the operating point of almost every component associated with the powertrain. This means that its optimization is a remarkable task which must influence fuel consumption, driving range, component degradation, acceleration and gradeability performance. Hybridization and component sizing for Fuel Cell Hybrid Electric Vehicles (FCHEVs), is essential not only to minimize fuel consumption, but also to reduce powertrain cost and the electrical stress on the fuel cell and increase its lifetime. This is because the durability and cost of the fuel cell stack is one of the major problems preventing FCHEVs from being competitive with conventional vehicles.

In this work, a fuel cell hybrid (FCH) mid-size car is modeled and simulated in Advanced Vehicle Simulator (ADVISOR) by downsizing the fuel cell stack power by 30% with corresponding increase in the battery pack size to achieve equivalent performance in terms of fuel economy and better acceleration performance in comparison with 2017 Toyota Mirai Fuel Cell Electric Vehicle (FCEV). In order to model the downsized vehicle, the parameters are adopted from 2017 Toyota Mirai FCEV and are investigated for different standard driving cycles to verify the performance. The aim of this analysis is to understand the energy interactions of the fuel cell and batteries and to identify an optimal energy management. It is found that an estimated powertrain cost reduction of 26% and equivalent fuel economy of 67.67 miles per gallon equivalent (MPGe) is achieved for this class of fuel cell mid size car in comparison with benchmark vehicle. This work is believed to be the first of its kind to estimate the effect of downsizing the fuel stack power on the fuel economy, vehicle dynamic performance and powertrain cost.

In addition to the hybridization and optimal sizing of hybrid energy components, the new real time advanced drive cycle World harmonized Light Vehicle Test cycle (WLTC) is embedded into the ADVISOR tool and the driving performance of the downsized Fuel Cell Hybrid Electric Vehicle (FCHV) is estimated.

In this work, the performance of hybridization, cold start ability, maximum speed conditions and energy consumption of downsized FCHV for WLTC and NEDC is estimated. Finally, downsized FCHV performance is compared with Toyota Mirai 2017 FCEV ANL test data. UDDS cycle consumes approximately 7% less for downsized FCHV in comparison with Toyota Mirai FCEV. US06 drive cycle consumes approximately 27% less fuel energy consumption (i.e. Wh/mile) for downsized FCHV in comparison with Toyota Mirai FCEV.

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ACRONYMS

AC - Alternating Current

ADVISOR - Advanced Vehicle Simulator

ANL - Argonne National Laboratory

Bat - Battery

C65 - Constant 65 mph Speed Cycle

DC - Direct Current

DOD - Depth of Discharge

ECMS - Equivalent Consumption Minimization Strategy

ESS - Energy Storage System

FC - Fuel Cell

FLC - Fuzzy Logic Control

FCHV - Fuel Cell Hybrid Vehicle

FCEV - Fuel Cell Electric Vehicle

GM - General Motors

HESS - Hybrid Energy Storage System

HEV - Hybrid Electric Vehicle

HiL - Hardware in the Loop

HPPC - Hybrid Pulse Power Characterization

HPSS - Hybrid Power Supply System

HWFET - Highway Fuel Economy Test

ICE - Internal Combustion Engine

IDC - Indian Driving Cycle

MPGGE - Miles Per Gallon Gasoline Equivalent

MPGe **-** Miles Per Gallon Equivalent

NASA - National Aeronautics and Space Administration

NEDC **-** New Europian Driving Cycle

Ni-MH - Nickel Metal Hydride

NREL - National Renewable Energy Laboratory

OCV - Open Circuit Voltage

PBS - Pneumatic Braking System

PEM **-** Proton Exchange Membrane

PMR - Power to Mass Ratio

RBS **-** Regenerative Braking System

SOC **-** State of Charge

UC **-** Ultracapacitor

UDDS **-** Urban Dynamometer Driving Schedule

US06 (SFTP) - Supplementary Federal Test Procedure

WLTC **-** World Harmonized Light Duty Test Cycle

1015 **-** Japanese Driving Cycle

CHAPTER - 1

INTRODUCTION

Depletion of earth's petroleum resources, green house gas emissions, and global warming issues are caused by conventional vehicles around the globe. In recent years, automotive industries have focused on emerging alternative energy sources to mitigate the reliance on fossil fuels so as to reduce harmful emissions. Researchers have focused on different aspects of hybrid and battery electric vehicles, such as energy management, regenerative braking control and architecture of power electronics.

Fuel cell hybrid vehicles provide high-efficiency and zero-emission alternate vehicles compared with conventional vehicles [1]. Hybridization requires an energy management system which optimizes among the main and auxiliary power sources enabling the provision of regenerative braking, leads to improvement in efficiency. Fuel cells are generally integrated with auxiliary energy storage units such as rechargeable batteries and ultracapacitors to develop hybrid power topologies storage systems. The batteries and ultracapacitors characterized with high energy and power densities respectively are coupled to DC bus to generate transient power demand which leads to reduction in fuel cell stack size, cost and to supply average energy demand in a drive cycle [2].

Moreover, the integration of various energy sources in hybrid electric vehicle enhances the reliability and efficiency of the system. However, proper energy management control strategies are necessary to regulate power flow among the energy sources. Fossil fuels provide the main source of power to drive the internal combustion engine (ICE) based hybrid electric vehicle (HEV). Vehicles like Honda Insight and Toyota Prius are some of the good examples falling under the class of HEV's. Now a days fuel cell technology has drawn the attention of numerous researches, because of its two important features. i.e. zero pollution and high energy efficiency in the tank to wheel process. These two features of fuel cell technology lead to the replacement of IC engine. Hybridization of energy component control source with two other secondary energy sources. For example, batteries and ultracapacitors will assist the fuel cell (FC) for a long time.

1.1 Background

A Brief History of Fuel Cell Vehicles

The invention of fuel cells is usually credited to Sir William Grove in 1839. However, it was initially only considered as an interest due to the imperfection in electrical technology. Almost a century later, in 1932, Francis Thomas Bacon developed the first practical hydrogen-oxygen fuel cell, and in the 1960s The National Aeronautics and Space administration (NASA) began using fuel cells on the Apollo space program. Fuel cells were chosen because of their compact size and weight compared to conventional batteries and solar power was used because of its, relative safety compared to nuclear power. Later, alkaline fuel cells continued to be used throughout the Apollo and Space Shuttle missions.

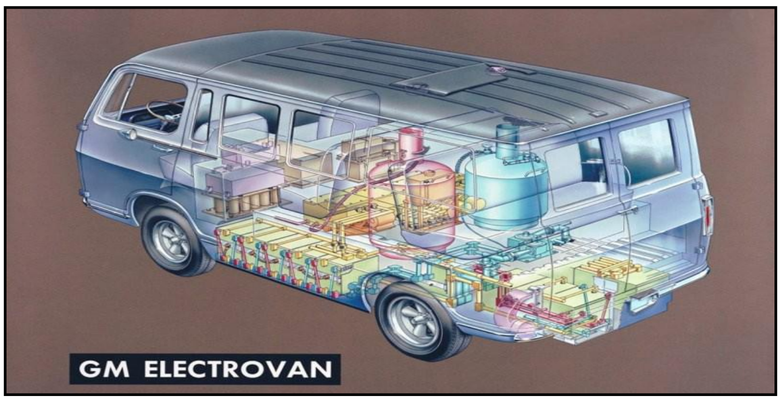


Figure 1.1 1966 GM Electrovan Fuel Cell System Layout - Qin et al. [3]

In the automotive industry, the world's first Fuel Cell Hybrid Electric Vehicle (FCHEV) was the "Electrovan" (Figure 1.1) developed by GM in 1966 which also used an alkaline fuel cell and cryogenic liquid hydrogen (and oxygen) storage [4]. It had only two seats due to the 1800 kg fuel cell system and storage tanks taking up most the rear of an originally 6 seater Handivan and weighed 3220 kg . The 160 kW(peak) Union Carbide fuel cell stack was rated for 1000 hours of use and drive the van to maximum speeds of 70 mph with a driving range of 100-150 miles [5].

The Proton Exchange Membrane (PEM) fuel cell was invented during the 1960s by Willard Thomas Grubb and Leonard Niedrach of General Electric. The Nafion film electrolyte utilized in PEM fuel cell components is sensitive to temperature and in this manner high amounts of platinum catalysts are required so as to make response rates viable for power production. These key issues stifled further improvements of fuel cell vehicles for an additional three decades until advancements in packed hydrogen storage, computer-based controllers and low platinum loading catalysts reduced the expense and complex nature of fuel cell module stacks, making the improvement of the FCHEV feasible again.

These improvements harmonized with the conclusion of the Apollo program which saw numerous NASA specialists move to privately owned businesses and accordingly another time of advancement in FCHEVs was inaugurated in 1994, Daimler-Benz AG introduced NeCar I, the world's first PEMFC HEV powered by a 50 kW fuel cell stack developed and supplied by Ballard Power Systems [6]. The vehicle was based on a MB-180 van and used compressed hydrogen stored at 300 bar. This was followed by NeCar II, a passenger minivan in May 1996; the Ne Car III, based on Mercedes's B-Class passenger car, and the NeBus, a fully functioning city transit bus in 1997. The most recent model NeCar IV was presented in 1999, with a 70 kW Ballard fuel cell system, a top speed of 90 mph and a range of 280 miles bringing fuel cell hybrid vehicles a lot nearer to current creation vehicles as far as ease of use and execution was concerned. Meanwhile, Toyota, GM, Mazda, Ford, Honda, Nissan, and Volkswagen additionally started technical improvements on their own fuel cell-powered vehicles with fuel cell stack powers ranging from 10 to 75kW and demonstrated ranges of up to 310 miles.

This era of FCHEVs was significantly nearer to that of ICE partners; be that as it may, various issues still introduced themselves. Ferdinand Panic [6] states that gravimetric and volumetric densities of the framework still required trade off regarding traveler and gear space with NeCar III, and records this as a need focus for NeCar IV, in light of the Mercedes Benz A-Class. Panik additionally referenced the staggering expense of the framework to be a noteworthy disservice contrasted with regular innovation. The GM HydroGen undertaking was begun in the late 1990s.

Early forms utilized an Opel Zara MPV body style with fluid hydrogen stockpiling, yet GM later moved to 700 bar compacted hydrogen stockpiling with HydroGen4 (presented 2007) which was fitted to a Chevrolet Equinox crossover with a number of structural modifications to the chassis for safety reasons [7]. This gave the vehicle 4.2 kg of Hydrogen and a scope of around 250 miles.

Eberle et al.[4] express that a large number of these disappointing strategies can be handled by the control technique because of perfect working conditions in a research center, where power device stacks can work for a few thousand hours. Accordingly, they exhibited various straightforward adjustments which could improve the 50% disappointment time to 3500 hours. The new thousand years has seen a major push by major car producers to develop hydrogen and energy component innovation with the presentation of HydroGen venture by General Motors (GM) and the main restricted renting of Toyota's FCHV in 2002 to the ongoing presentation of the financially accessible power device vehicles, the Hyundai ix35 Fuel Cell, and the Toyota Mirai despite these, GM, Honda, Daimler AG, Nissan, Renault and Ford are for the most part additionally intending to discharge FCHEVs 5 years from now. In any case, there are as yet various specialized issues that must be defeated before FCHEVs will be really focused with customary innovation.

1.2 Current Challenges for Fuel Cell Vehicles

Despite the recent launch of Honda FCX-Clarity, Hyundai ix35 FCEV and the Toyota Mirai, there are a number of issues obstructing the FCHEVs from being challenging with ICE vehicles. These are the cost and durability of the fuel cell stack itself, and the supply, hydrogen storage, infrastructure and transportation of hydrogen fuel.

In summary, fuel cell vehicles are just emerging on the automobile market; although, they are not yet honestly competitive with traditional technology and these are available in limited regions only due to cost, credibility, range, and insufficient infrastructure. Consequently, these vehicles are aimed at the luxury automotive market as a second car similar to early BEVs. Over the next 10 years, through additional advancements in technology, and nominal cost reduction due to enrichment of the technology and peak production volumes, many of the technical objectives are predicted to be met and FCHEVs will begin to become more competitive with current ICE hybrid powertrains. In hybrid power source, the FC power module provides the main power consistently during the acceleration phase, while other secondary power source gives supplementary power increasing speed and peak load operation and captures the regeneration braking energy during vehicle deceleration.

Hence, the stress on FC power module and cost will be diminished. The transient performance of the power train and the energy storage efficiency will be improved. Ultracapacitor has the nature of more power density and moderately less energy density. It can permit many years of cycle life and overall increased performance of the batteries. The capacitance of ultracapacitor is more than that of conventional capacitors, permitting enough energy requirements for increasing acceleration performance [8,9]. The energy storage capacity of ultracapacitors is 75–150 Wh. The fuel economy benefit with the ultracapacitors is 10–15% higher than with the equivalent weight of batteries due to higher efficiency of ultracapacitors and more efficient engine operation [10]. Two hybrid power sources such as fuel cell–battery hybrid source and fuel cell– ultracapacitor hybrid source are designed and simulated using Advanced Vehicle Simulator (ADVISOR) to achieve better performance and higher fuel economy [11]. Large sport-utility vehicle (SUV) is modeled with FC power module as main power source and battery as a secondary energy source for hybrid electric power train in ADVISOR by utilizing individual approved part models and this achieved improved energy efficiency by varying degrees of hybridization for different drive cycles [12].

In this chapter, a prediction type power management approach for FC/battery plug-in hybrid vehicles with the aim of developing overall system efficiency during its operation is adopted to achieve optimal hybridization value. The main objective of the suggested strategy is that if the absolute amount of energy demand to complete a certain drive cycle can be reliably desired, then the energy stored in the energy storage device can be consumed in an optimal aspect that allows the FC power device to operate its most efficient regime [13].

Toyota has outlined as FC electric vehicle in view of F/B hybrid utilizing a nickel–metal hydride (Ni–MH) battery pack as an auxiliary energy source, and Honda has made another model on F/UC hybrid utilizing ultracapacitor cells as power barriers. It is expected that FC/battery/ultracapacitor (F/B/C) hybrid can result in outstanding system performance and energy efficiency [14]. A control standard is set for using proton exchange membrane FC energy as fundamental power source and supercapacitors as the secondary power source for hybrid electric vehicle applications. The technique depends on DC interface voltage control, and FC component is basically working in steady-state conditions in order to limit the mechanical stresses of FC power module and to ensure decent synchronization between fuel stream and FC current [15].

Assurance of the hybridization degree is as per drivability necessities, the examination of the energy flows, and the calculation of the ideal hydrogen utilization. The outcomes demonstrate that hybridization permits a noteworthy change in the hydrogen economy through recouped energy from braking. The entire study is performed with a detailed model of the fuel cell hybrid system in ADVISOR [14].

1.3 Fuel cell hybrid vehicle simulation using ADVISOR

Fernandez et al. [17] proposed a hybrid powertrain with fuel cell and secondary energy storage as Ni-MH battery associated with a typical DC-DC converter to assist power demand for tramway loads. He et al. [18] proposed and verified a control strategy based on fuzzy logic for a hybrid powertrain system used for hybrid vehicles. An investigation to confirm the energy execution strategy in Urban Dynamometer Driving Schedule (UDDS) is revealed. The limit utilization of hybrid energy system can be cut down by 4.1% with fuzzy logic control strategy contrasted and run based on control technique. Odeim et al. [19] studied power management strategy using optimization technique for fuel cell/battery HEV and examined both simulation results and experimental tests. Torreglosa et al. [20] minimized hydrogen usage by using fuel consumption minimization technique for an original tramway driven by a hybrid powertrain with fuel cell and battery. A versatile monitoring control system for a dual Proton Exchange Membrane Fuel Cell (PEMFC) stack hybrid city bus with an evaluated net power of 40 kW and a

Ni-MH battery was proposed by Chan, et al. [21]. Abu Mallouh et al. [22] reported a hybrid fuel cell/battery vehicle for various standard driving schedules. The conventional model of mid-size vehicle is validated with experimental tests. The behavior of the hybrid powertrain arrangement is beneficial in comparison with conventional vehicle in terms of efficiency, fuel economy, emissions and speed tracing error. Fletcher et al. [23] analyzed a Stochasting Dynamic Program (SDP) technique to minimize fuel cell running cost, including fuel consumption and lifetime of battery to develop a low speed vehicle.

The optimal control of the suggested technique gives 12.3 % reduction in fuel cell degradation cost and 14 % increase in fuel cell stack life. Xu et al. [24] proposed an adaptive supervisory control technique based on Equivalent consumption minimization strategy (ECMS) for a city bus powered by fuel cell/battery. It enables an increase in fuel economy, durability and simplicity in control. Sovran and Blaser. [25] investigated the amount of energy consumed during braking period in the total disbursed energy under three diverse driving schedules (UDDS in USA ,ECE in Europe and 10–15 in Japan) were 43.3% ,60.1%, and 52.5% individually. Qi et al. [26] applied fuzzy logic control (FLC) to minimize fuel exhaustion of hybrid powertrain with fuel cell and battery-ultracapacitor dual energy storage combination developed in ADVISOR software. Bernard et al. [27] explored hybrid powertrain sizing to shrink hydrogen use by adopting effective power sharing strategy between the fuel cell unit and energy storage system (ESS) based on acceleration and driveability conditions. The powers of FC, secondary battery and electric motor were optimized to increase the dynamic and fuel economy performance of the locomotive described by Zhang et al. [28] A fuel cell hybrid vehicle powertrain was modeled in ADVISOR using PEMFC and lead acid battery and determined using minimum hydrogen consumption; the maximum speed and better gradeability performance were achieved at 59.7 % hybrid ratio by Huang et al. [29].

Zhang et al. [30] described a hybrid power tram powered by fuel cell stack assisted by Li-ion battery pack and ultracapacitor pack using ECMS (Equivalent Consumption Minimization Strategy) which reduces the hydrogen consumption by 3.5 %. Same et al. [31] explored different hybrid drivetrain structures such as series, parallel and through-the ground respectively and determined an optimal hybrid configuration. Zhang and

Zhou. [32] developed a set of fuel cell, battery and DC-DC converter system model to know the transient performance of fuel cell stack, power converter and battery systems based on system model controllers and to regulate the power system to accomplish the actual performance. Ettihir et al. [33] investigated optimal power sharing between the fuel cell and supplementary battery pack in order to achieve better efficiency and evaluate the performance during peak power conditions for fuel cell hybrid vehicle using Pontryagins Minimum Principle.

1.4 ADVISOR Simulink models of Fuel cell hybrid power components

Advanced Vehicle Simulator ADVISOR was established by National Renewable Energy Laboratory (NREL) at the end of 1990s. Firstly, they were utilized for modeling and analysis of hybrid systems. It was designed to make either forward or backward modeling. It is useful for the test and assessment of traditional vehicle, electric vehicle and hybrid vehicle; it combines backward- and forward-facing approaches creatively. This program is used widely by automobile manufacturers, researchers in universities or the industry.

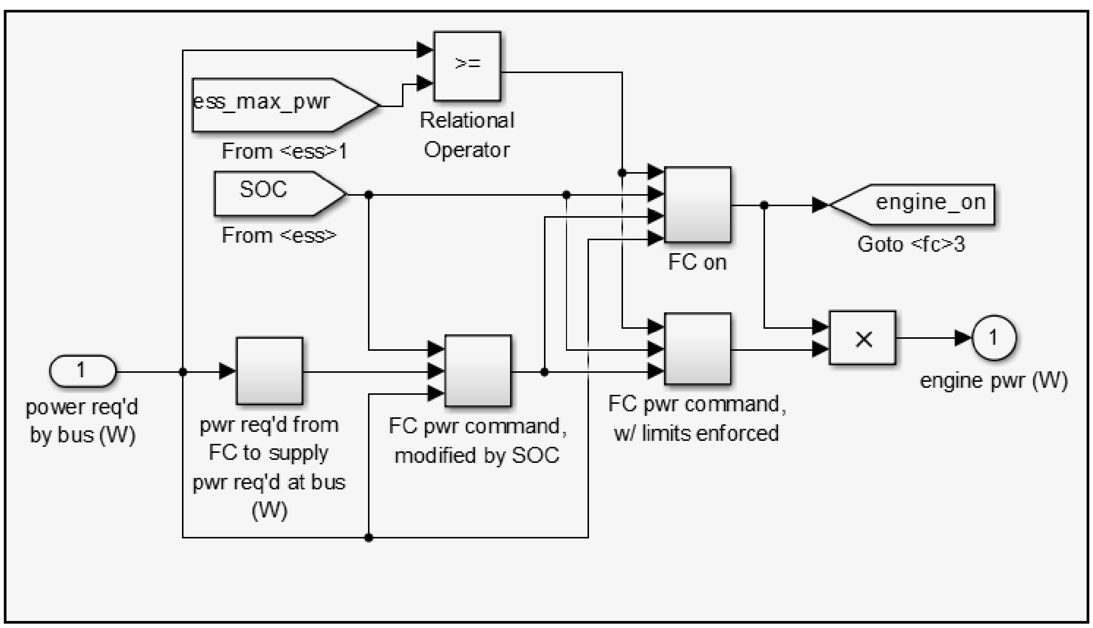


Figure 1.2 Schematic of ADVISOR fuel-cell control strategy system

Simulink models of the fuel cell power control strategy system, fuel cell system, battery and ultracapacitors systems are shown in Figures.1.2 - 1.5 respectively. All these existing modules are designed in ADVISOR library using MATLAB/Simulink environment. This software is open-source and used offline. It has friendly graphical user interface. In order to make modeling and simulation in ADVISOR, a module of Matlab/Simulink was used. That module is used to perform dynamical system analysis in Matlab/Simulink. Furthermore, this software was developed to support either instantaneous, linear, non-linear system in time domain systems or hybrid systems [34].

ADVISOR Benefits

- Reduces testing time to evaluate various vehicle powertrain alternatives;
- Provides a shared simulation tool for government and industry;
- Assists the automotive industry to develop fuel-efficient vehicles and components;
- Flexibility of making vehicle model, control strategy, and easiness to make changes on algorithm such as breaking algorithm;

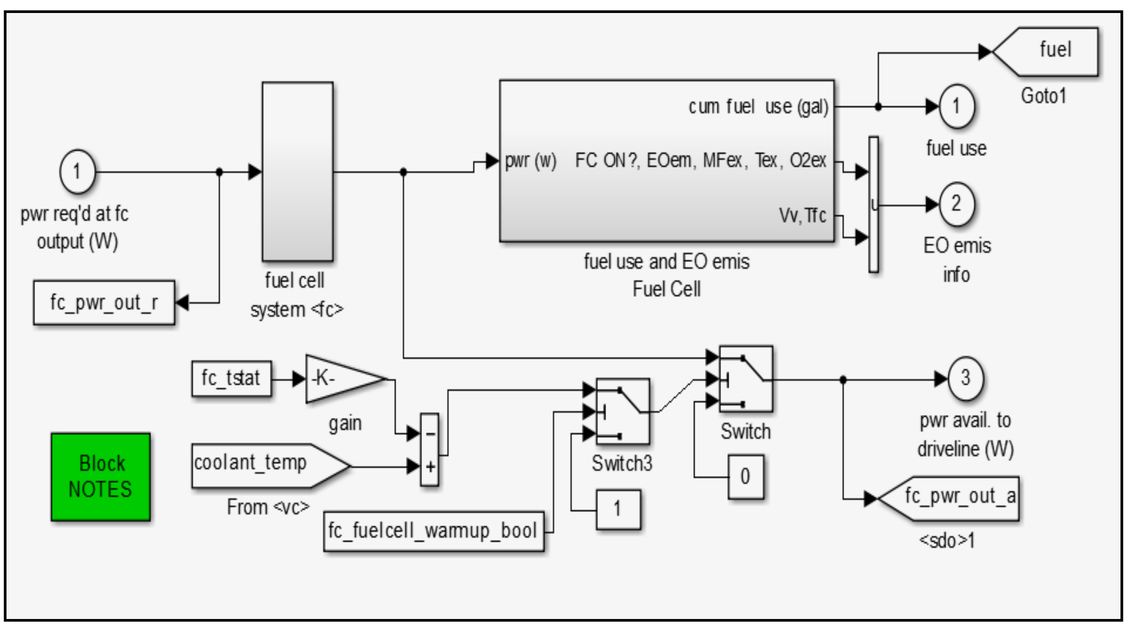


Figure 1.3 Simulink model of fuel cell system

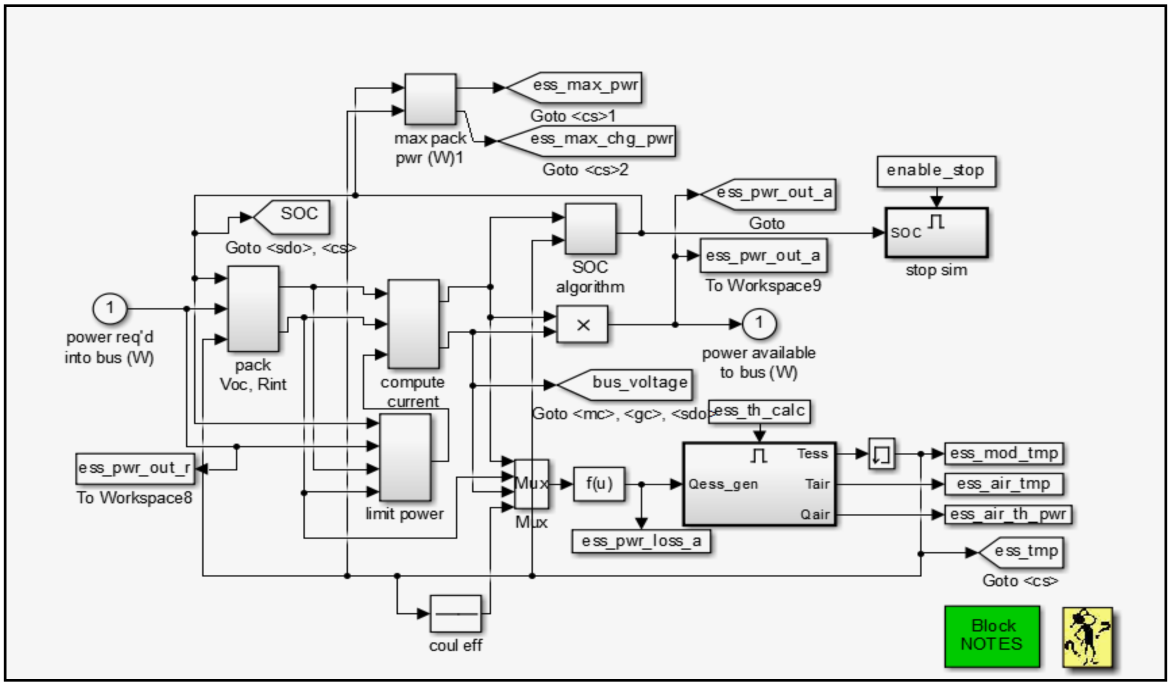


Figure 1.4 Simulink model of battery

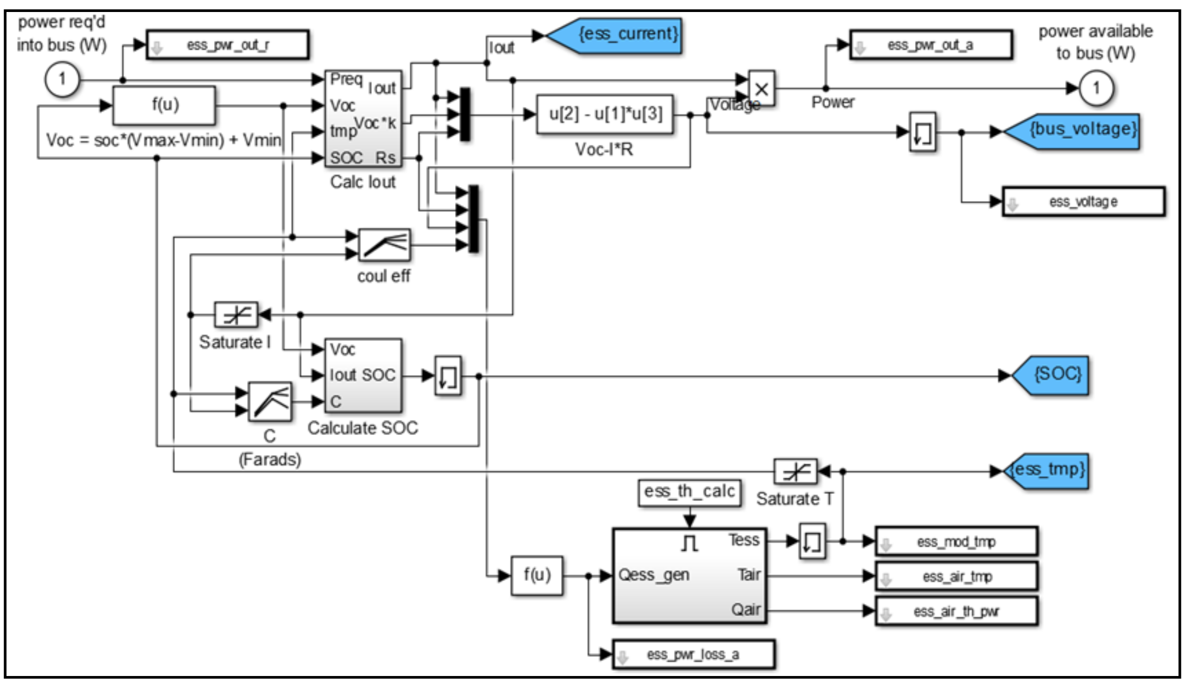


Figure 1.5 Simulink model of ultracapacitor

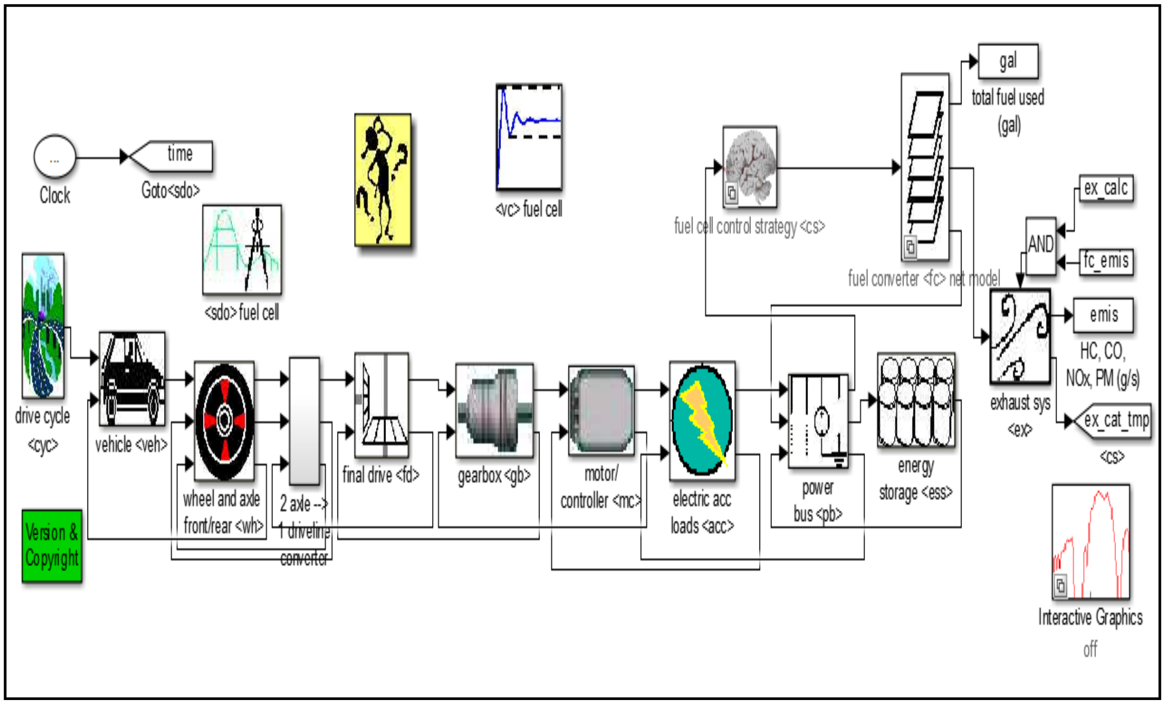


Figure 1.6 Block diagram of the fuel cell hybrid vehicle

Assembling all the models to build a whole fuel cell hybrid electric vehicle block diagram is as shown in Figure 1.6. It consists of drive cycle model, vehicle dynamics model, wheel axle model, vehicle power transmission model, hybrid power components models, power electronics model, and control strategy model. All the models are interlinked to build a single hybrid vehicle model. One of the advantages of using Matlab/Simulink interface in ADVISOR is the flexibility of making vehicle model, designing control strategy, and ease of making changes on algorithm such as breaking algorithm. As a consequence of these advantages, it is easy to analyze vehicle configurations and attain results of the systems in graphical format [35]. ADVISOR uses driving graphic first. From that graph, it derives the relationship between torque and velocity of wheel or between wheel and energy sources. The energy source could be electricity in battery or the fuel in hybrid power unit. The robustness of the model and relevance of the model with other vehicle simulators are crucial for determining authenticity of the ADVISOR. NREL has been signing agreements with universities to encompass more accurate data for models. Additionally, ADVISOR has also been having agreements with some of commercial automobile manufacturers, so that using the algorithms in industry, minimum uncertainty can be achieved [36].

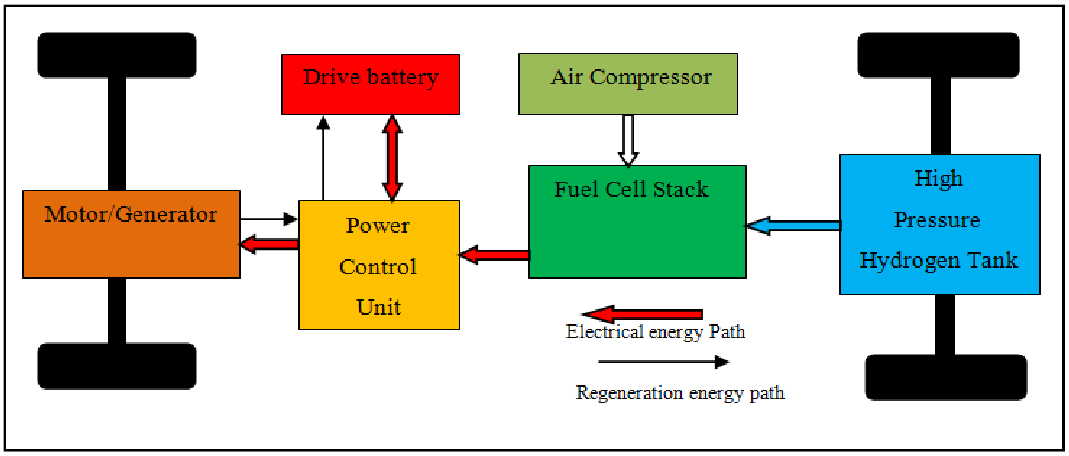


Figure 1.7 – Toyota Mirai FCHV Hybrid Powertrain

Figure 1.7 represents the structure of Toyota Mirai FCHV powered by PEM fuel cell-battery hybrid system. The hybrid powertrain structure consists of motor, power control unit, drive battery, air compressor, fuel cell stack and high pressure hydrogen tank. Pure hydrogen gas is stored in the tank at a pressure of 70 Mpa and it is supplied to the fuel cell stack which generates the desired electrical power to the hybrid powertrain via power control unit. Both motoring and regenerative power flows are controlled by power control unit of the hybrid powertrain.

1.5 Fuel cell Vehicles

Fuel cell vehicles are alternate fuel vehicles, In general, fuel cells in vehicles generate electricity to power the motor by using oxygen from the air and compressed hydrogen. As compared to conventional vehicles, they are zero emission vehicles, which emit only heat and water as byproducts. Some of the hydrogen fuel cell vehicle are listed in the Table.

Table 1.1 Comparison of fuel economy for hydrogen fuel cell vehicles [37]

Vehicle	Model year	Combined fuel economy (MPGe)	City fuel economy (MPGe)	Highway fuel economy (MPGe)	Range (miles)	Annual fuel cost (US$)
Hyundai Tucson Fuel Cell	2017	49	48	50	256	1700
Toyota Mirai	2017	67	67	67	312	1250
Honda Clarity Fuel Cell	2017	67	68	66	366	-
Hyundai Nexo	2018				370	-

1.5.1 Fuel cell vehicle benefits

Low Greenhouse Gas Emissions

Fossil fuel powered vehicles emit greenhouse gases (GHGs), mainly carbon dioxide (CO_2) that results in environmental pollution. Fuel cell vehicles, which are powered by fuel cells, produce power using pure hydrogen and atmospheric air. These are mostly zero emission vehicles. The only byproducts from these vehicles are heat and water.

Reduce the dependence on fossil fuels

Fuel cells do not need fossil fuels or gas and can therefore, reduce economic dependence on oil producing countries.

Fuel efficient vehicles

Fuel cells have higher efficiency than diesel or gasoline engines. Hydrogen fuel cells are capable of generating electricity with up to 60 % efficiency.

1.5.2 Fuel cell vehicle issues

Onboard hydrogen storage

Some Fuel cell vehicles store adequate hydrogen to travel as far as gasoline vehicles. The hydrogen storage containers are still too large, bulky, and very expensive. Hydrogen contains three times more energy per weight compared with gasoline. However, hydrogen gas contains only 33% of the energy per volume basis, making it hard to store enough hydrogen to travel similarly as a gasoline vehicle on a full tank, at least in terms of size, weight, and cost imperatives[38].

Vehicle Cost

Fuel cell vehicles are right now too expensive to compete with hybrid vehicles and conventional gasoline and diesel vehicles. Automakers must cut down production costs, particularly the costs of the fuel cell system and hydrogen storage.

Fuel Cell Durability and Reliability

Fuel cell systems are not yet as durable as internal combustion engines and do not perform as well in extreme environments, such as sub-freezing temperatures. However, specialists accept a 150,000-mile expected lifetime is essential for FCVs to contend with gas vehicles. The cold-weather operation can also be problematic since fuel cell systems consistently contain water, which can solidify at low temperatures, and the operation must arrive at a specific temperature to accomplish full execution. Contaminants can reduce fuel cell performance and durability, so it is hazy what level of purity of hydrogen and intake air will be required for FCVs to work dependably in real-world driving conditions.

Hydrogen infrastructure

New facilities and systems must be constructed for producing, transporting, and dispensing hydrogen to consumers.

Competitive with other Technologies

Automakers are as yet improving the productivity of gas and diesel-fueled engines, hybrid vehicles are popular, and advances in battery innovation are making plug-in and electric vehicles progressively alluring. FCVs should offer buyers a suitable other option, particularly in terms of execution, durability, and cost, to get by in this ultra-demanding market.

Safety

Hydrogen, similar to any fuel, is dangerous and must be used with caution. Designers must improve fuel storage and conveyance frameworks for safe regular use, and customers must get comfortable with hydrogen's properties and dangers.[]

Public acceptance

Fuel cell technology must be grasped by consumers before its benefits can be realized. Consumers may have concerns about the dependability and safety of these vehicles.

1.6 Thesis Organization

This thesis is organized into 6 chapters.

The **first Chapter** provides a brief introduction to hybridization and the state of art of fuel cell hybrid vehicle configurations and the energy storage systems. The necessity of integration with fuel cells is also discussed. The scope of the work has been highlighted and the author's contribution to the research area has been summarized.

The **second Chapter** presents the literature review of existing energy management strategies and methodologies for fuel cell hybrid vehicles. This sets the motivation for research work carried out in this thesis.

In the **third Chapter**, ADVISOR simulation methodology, governing equations, boundary conditions for simulation study and definitions of parameters are presented followed by the new configuration of Fuel cell-ultracapacitor hybrid powertrain system is based on hybridization of power sources. The description of vehicle and the hybrid component size ratio are presented. The large sport utility vehicle (SUV) chosen for this simulation analysis is based on a four-wheel drive Chevrolet Suburban light truck converted to a fuel cell hybrid electric vehicle (FCHEV). In addition, the fuel economy performance for different drive cycles are presented and also the component converter efficiencies are verified.

In the **fourth Chapter**, a downsized Fuel Cell-Battery Hybrid Electric Vehicle powertrain is proposed. In this study, a fuel cell hybrid mid-size car is modeled and simulated in ADVISOR by downsizing the fuel cell stack power by 30% with corresponding increase in the battery pack size to achieve equivalent performance in terms of fuel economy and better acceleration performance in comparison with 2017 Toyota Mirai Fuel Cell Electric Vehicle (FCEV). In addition, the fuel economy performances like, miles per gallon gasoline equivalent (MPGGE), hydrogen consumption, miles per gallon equivalent (MPGe) and driving ranges are estimated.

In the **fifth Chapter**, The real time advanced drive cycle World harmonized Light Vehicle Test cycle (WLTC) is embedded into the ADVISOR and driving performance of downsized Fuel Cell Hybrid Electric Vehicle is estimated. In addition, the performance of hybridization, cold start ability, maximum speed conditions of Fuel cell- battery HEV and Fuel cell- ultracapacitor HEV for WLTC, NEDC, and Indian driving conditions are presented and also estimated the energy consumption analysis is also calculated.

In the **sixth chapter**, the downsized Fuel cell- battery HEV performance is compared with **Toyota Mirai 2017 FCEV ANL test data. The** Vehicle energy level consumption and the performance of vehicle for low and aggressive speed driving conditions are presented.

In the APPENDIX A the comparison table A1 for the downsized fuel cell hybrid vehicle (FCHV), gasoline hybrid electric vehicle (HEV) and conventional gasoline vehicle is included. Table A2 describes the fuel economy performance of different drive cycles for different hybrid configurations.

CHAPTER - 2

LITERATURE REVIEW

Among existing hybrid powertrain structures, advanced fuel cell (FC) advanced technologies were considered as a possible and preferable solution for automotive applications because of zero emissions from the use of sustainable power source. Fuel cell hybrid vehicles enable better feasibility due to its high energy density and provides better mileage when compared to battery driven EV. In any case, energy components can't help a snappy response to the heap because of low power density batteries. Accordingly, a hybrid powertrain system made out of fuel cell power device, battery and ultracapacitors are a promising answer to accomplish both high energy density and high power density. Hybridization of fuel cell with energy storage systems (batteries and ultracapacitors) are essential to reduce hydrogen consumption, fuel cell size and powertrain cost. Paladini et al. [39] presented an optimal control strategy to power a hybrid vehicle with both fuel cell and battery to reduce fuel consumption. Hybrid electric vehicles (HEVs) including auxiliary power source, for example, battery and ultracapacitor are intended to assist transient power request, during uphill driving condition or acceleration. Acceleration performance of HEV rely on both high power density and high energy density storage devices [40]. Energy sharing occurs between battery and ultracapacitor connected to DC bus voltage via bidirectional DC-DC converter which is used to control the DC bus voltage and optimize the power distribution between main source and secondary source.

Xie et al. [41] developed a test station sourced by 1 kW PEM fuel cell, Li-ion battery pack of 2.8 kWh and ultracapacitor bank of 330 F/48.6 V. Experimental results concluded that the fuel cell is responsible for slow dynamic variation and the output of the battery pack and ultracapacitor are regulated to meet fast dynamic variations. Hardware in the loop comprises simulated system and hardware components and acts as a powerful technique in testing vehicle energy control methodologies. Hybridization of FC combined with auxiliary energy storage devices like batteries and ultracapacitors can offer FC reliability and improved efficiency. Lithium-ion batteries are preferred among the existing rechargeable batteries due to its high energy density and low cost. However, batteries are associated with disadvantages such as low power density, reduced life cycle and more charging duration. Therefore, utilization of a battery alone as an ESS in FCHEV may not provide effective performance. In order to enhance the performance of FCHEV, ultracapacitor is integrated with batteries to alleviate the above said disadvantages [42]. UCs exhibit higher power densities in comparison with batteries, and feature higher energy densities when compared to electrolytic capacitors However, the energy densities of UCs are usually less than battery structures [43]. Battery-ultracapacitor combination as ESS is recommended for vehicular applications as it inherits the features of high energy densities of lithium-ion batteries and high energy densities of ultracapacitor [44].

Incorporation of regenerative braking mechanism in energy source hybridization is a key innovation in hybrid electric vehicles. In general, the electric engine can be controlled to work as a generator changing over the vehicle's kinetic energy into power during regenerative braking [45]. Regenerative braking system can enhance the fuel economy and durability of fuel cell system, which leads to increased lifespan of the fuel cell system and decrease hydrogen consumption. The potential effects of regenerative braking system on fuel economy of the vehicles can be exceptional. The rate of the utilized energy during deceleration in the total expended energy for three diverse driving cycles (ECE in Europe, UDDS in USA and 10–15 in Japan) can accomplish 60.1%, 43.3% and 52.5% reduction individually [46].

The energy administration of hybrid electric vehicle, which chooses power undertaking between the fuel cell power device and secondary energy buffer system is an imperative strategy. Lately, an assortment of control techniques for energy management has been utilized for hybrid electric vehicle. The fundamental destinations of the energy governance methodology are to oversee control sharing between different segments and to ensure the power sources execution. The principle goal of EMSs is to enhance the execution, bringing down hydrogen utilization all through the driving cycle. Energy management systems (EMSs) are calculations which choose at each testing time the power fraction among the principle control source and the energy storage systems (ESS). The true objective to accomplish power distribution between the requested power and power source. Thounthong et al. [47] proposed DC connect voltage control by directing power converters. However, they did not concentrated on the system proficiency. Equivalent Consumption Minimization Strategy has shown itself be vigorous under a range of working conditions. An EMS strategy is based on controlling the hybrid vehicle by connecting PI controllers in series to generate proper reference signal energy source [48]. Na et al. [49] applied a predictive control to fuel cell hybrid vehicle. Erdinc et al. [50] and Ferreira et al. [51] suggested an EMS based on fuzzy logic control to regulate the demanded load by the hybrid vehicle.

A parallel energy sharing control of fuel cell, battery and ultracapacitor has been reported by Wong et al. [52] voltage of the ultracapacitor is controlled with respect to vehicle speed to secure ample energy for a vehicle speeding and also enough space for vehicle braking energy. A novel hybrid powertrain comprising fuel cell unit and Li-particle battery utilizing a snappy parallel structure with a ultracapacitor bank was reported by Xie et al. [53]. In this audit, a test station is controlled by a 1 kW fuel cell power module control gadget system, Li-particle battery pack of 2.8 kWh and an ultracapacitor bank of 330 F/48.6 V formed and based on the introduction of stay singular module. FC framework is controlled to fulfill the moderate dynamic variety and the ultracapacitor pack is regulated to meet quick unique load necessities. The assessment of auxiliary sources like batteries and ultracapacitors in a FCHEV was investigated by Schaltz et al [54]. Furthermore, analyzed fuel cell volume, mass, productivity, and battery constancy were analyzed because rating of the energy storage systems was introduced. The authors suggested that better outcomes can be achieved by overrating Li-ion battery pack storage device.

In the hybrid powertrain system, battery/ultracapacitor and FC have been used as power sources. Among the available power sources, FC generates low grade DC voltage, and it is converted into useful constant voltage by double DC/DC converters. One power converter transfers electrical power to the ancillary loads of the vehicle. Second converter sends power to inverter traction motor via DC bus. The battery and ultracapacitor are connected to the DC bus via bidirectional converters.

Table 2.1 Summary of power conversion configurations of FCHEV

Configuration	Energy component	Controller	Description	Advantage	Author
C1	PEMFC/UC	PWM controller	FC is interfaced directly with energy storage system without power converter and DC Bus connected with inverter drive motor	Suitable for single stage conversion	Azib, et al. [56]
C2	PEMFC/Battery	Thermostat and Fuzzy logic controllers	FC is coupled with boost DC-DC converter. Battery is directly coupled with DC bus and the electric motor connected with inverter	Power split control on fuel cell and energy storage systems	Mallouh et al.[57]
C3	PEMFC/Battery/Ultracapacitor	PI controller	FC system directly interfaced with DC bus and energy system linked with DC-DC converter	minimized the bidirectional dc/dc converter loss by maintaining soft switching operation during sudden load conditions	Wang et al. [58]
C4	PEMFC/Battery	Fuzzy logic controller	Both FC and storage devices are interfaced with DC-DC converters	Provides stable DC voltage	M.C. Kisacikoglu, et al.[59]
C5	PEMFC/Battery/Ultracapacitor	Fuzzy logic controller	FC is linked with boost converter and energy storage devices interfaced with a bi-directional converter	Integration of high power and high energy storage devices	D.Gao et al [60]
C6	PEMFC/Battery/Ultracapacitor	Wavelet and fuzzy logic control	All the power sources connected via DC-DC converters	Effective control of DC bus voltage. Ultracapacitor can regulate the sudden power demands and battery to store braking energy efficiently	Erdinc et al.[46]

The inverter converts high voltage DC to useful high voltage AC from the DC bus generated by FC , battery and ultracapacitor. Hybrid powertrain arrangement employs regenerative braking energy of the traction motor, which is stored in drive battery. The battery assists as power source during the initial cold condition of FC, while ultracapacitor assists the power for transient load conditions. Figure 2.1 depicted different types of power conversion configurations and the summary of these configurations included in Table 1.

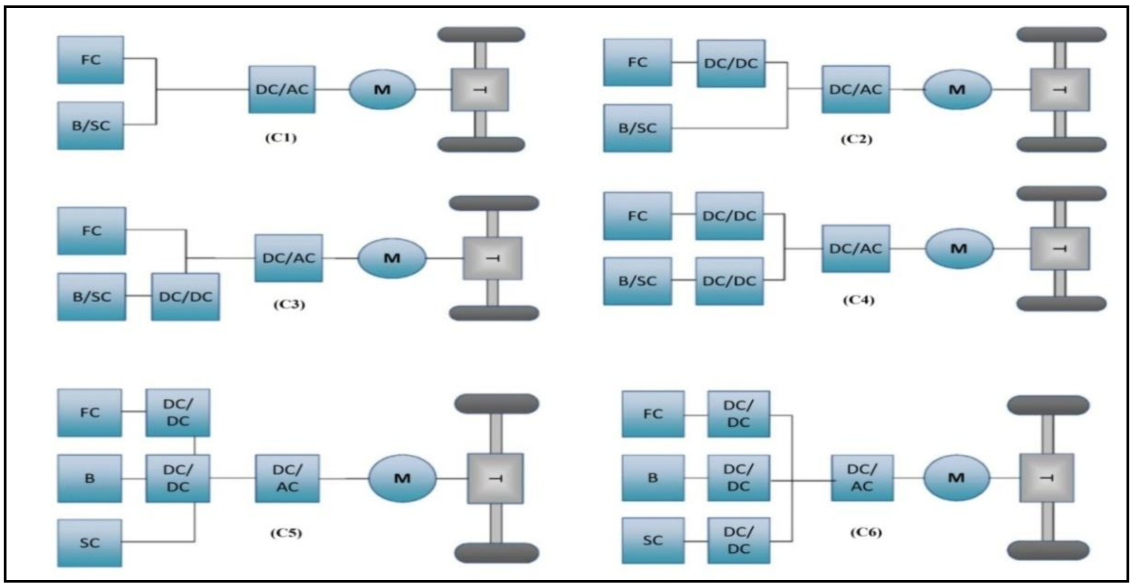


Figure 2.1 - Power conversion configurations of FCHEV. [55]

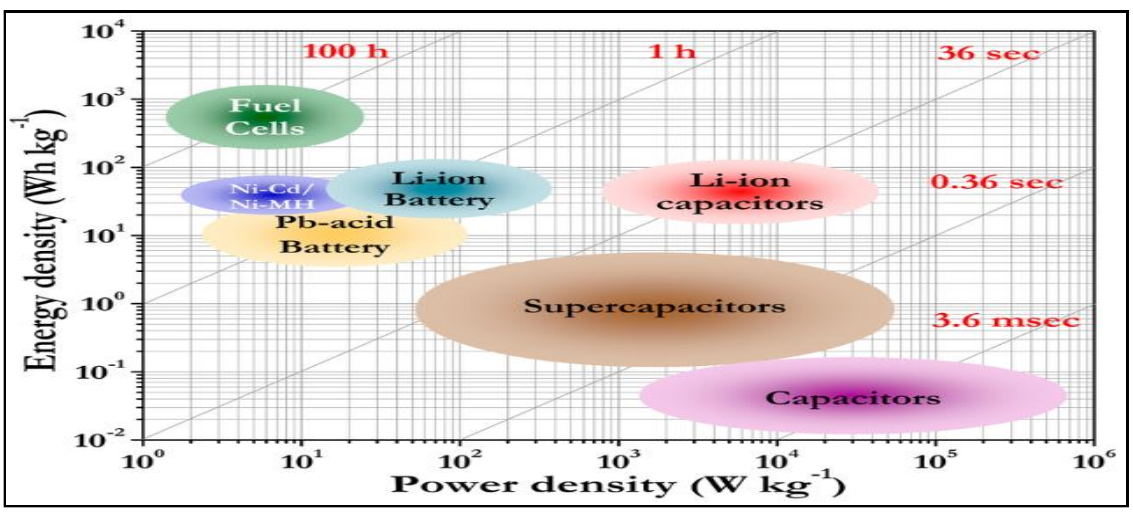


Figure 2.2 Specific energy against specific power of energy storage system (ESS) [61]

Figure 2.2 depicts, the comparison between different energy sources as a function of time. Among all the energy sources, fuel cell and battery show useful high energy content but with low power density. Batteries show more discharge time, whereas ultracapacitors have low energy density but deliver high power densities for a short duration of time, especially suitable for sudden power demands. Figure 2.3 shows various energy densities of energy carriers for a vehicle range of 500 km using present technology. Moreover, for mid-size hybrid car applications, 220 Wh capacity of ultracapacitor pack required less weight compared to other three energy sources as shown in Figure 2.3 [62].

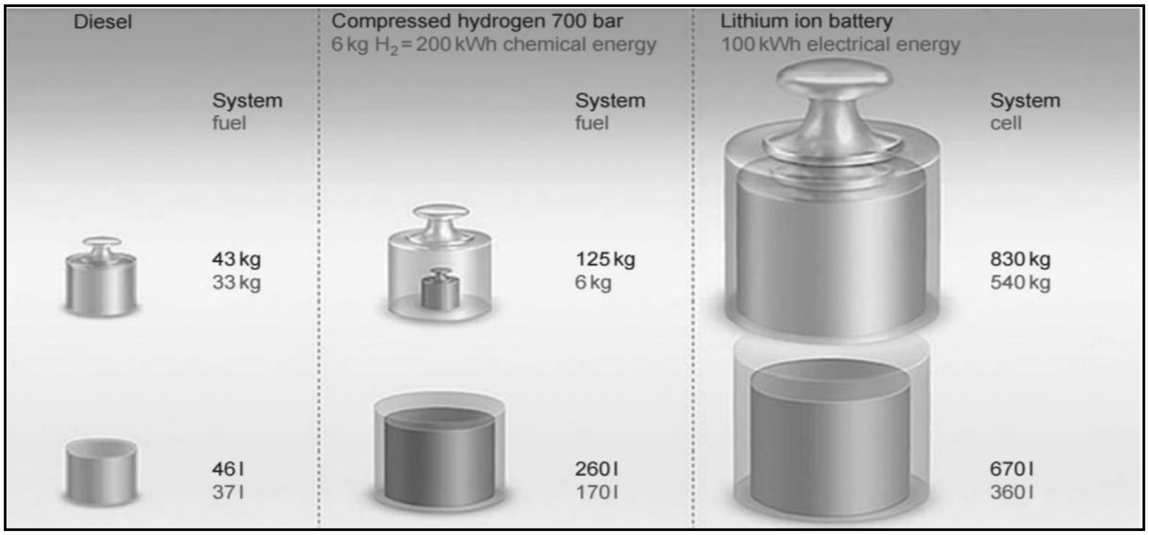


Figure 2.3 Energy Storage System weight and volumes for various energy carriers [63]

Bauman et al. [64] concentrated top to bottom approach and itemized correlation of close ideal fuel-cell–battery, fuel-cell–ultracapacitor, and fuel-cell–battery–ultracapacitor vehicles. Quickening time, mileage, and cost were considered in the target work and they reported that fuel-cell–battery–ultracapacitor mix has higher efficiency and can expand the battery lifetime because of low battery stress. Bauman et al. [65] proposed a new architecture to cut down fuel consumption and to reduce the cost of the powertrain. The proposed new topology only needs one high-power DC/DC unidirectional converter to step-up the fuel cell voltage. It produces a higher performance path to maintain the battery cycle efficiency. The design confirmed that the ultracapacitor can manage variable power demands, thus lowering battery use and enhancing battery endurance.

Table 2.2 Comparison of Energy sources for Fuel Cell Hybrid Vehicles [66-69]

Power source	Pros	Cons
Fuel cell	Directly converts chemical energy into electrical energy	Expensive to fabricate due to the high cost of catalysts (platinum)
	Zero harmful emissions	Lack of infrastructure to support the distribution of hydrogen
	More energy efficiency compared with ic engine	Highly inflammable
	Compact and robust	Storage of hydrogen gas
	Silent and smooth operation	
	Environmental friendly	
	Renewable energy	
	Higher part load efficiency	
	Only water vapour as bi-product	
Li-ion Battery	High specific energy	Batteries cannot be charged or discharged at high currents
	Self discharge is much lower than that of other rechargeable batteries	Batteries have less cycle life
	Low maintenance	Low specific power
	Cell voltage: 3.6 V nominal	Requires protection circuit to maintain voltage and current within safe limits.
	Charge time: 10 to 60 minutes	
	Specific energy (Wh/kg): 120 to 240	
	Specific power (W/kg): 1000 to 3000	
	Cycle life: 5 to 10 years	
	Cost per kWh: $200-1000 (large system)	
Ultracapacitor	High specific power and low resistance enables high load currents	Low specific energy
	Ultracapacitors can produce sudden burst of powers with better performance and unlimited cycle life	Low cell voltage requires series connections with voltage balancing
	Ultracapacitors can charged and discharged at high currents	High cost per Watt
	Cell voltage: 2.3 -2.75 V	High self-discharge, higher than most batteries
	Charge time: 1- 10 seconds	
	Specific energy (Wh/kg): 5 (typical)	
	Specific power (W/kg): up to 10000	
	Cycle life: 10 to 15 years	
	Cost per kWh: $10000	

In a report by Zhao et al. [70], using different hybridization configurations, energy storage technologies, and power split control strategies were modeled and evaluated. They reported that fuel economy improvements are greater using ultracapacitors than batteries. Meanwhile, for energy storage technology, improvement was achieved when the size of the energy storage unit is increased. Meanwhile Castaings et al. [71] explored real-time energy control procedures for a blend of energy buffering framework, which consists of a battery and ultracapacitor for an electric vehicle. The minimization of the battery current RMS esteem increases the lifetime of battery. In a report, Hsieh et al. [72] developed a hybrid control source with a direct current (DC) supply structure for electric forklifts. The power source includes an energy unit fuel cell (FC) structure, lithium-ion batteries, and ultracapacitor modules. The power yield might be isolated into power for raising and power for moving. The main purpose of this hybrid power source is a drop in the wattage of the fuel cell and to reduction in overall system cost.

In the interim, Bunbna et al. [73] studied the possibility of uniting ultracapacitors to a power module - battery hybrid travel transport tested on two driving cycles (Manhattan Bus Cycle and UDDS). Simulations were driven using linear frequency modulated (LFM) powertrain test framework which was made in MATLAB/Simulink programming. Simulation outcomes demonstrate that the adding ultracapacitors extraordinarily enhances execution parameters for example, battery C-rates. They contemplated that the coordination of ultracapacitors into the ESS licenses the shrinking of the battery pack which can decrease the cost and weight and extend battery lifetime.

Kim et al. [74] presented the regenerative braking control of a permanent magnet motor in a light fuel cell hybrid electric vehicle by using prototype experimental test-bed and the results are discussed. However, the DC bus voltage was limited to 60 V for the regeneration during the braking operation. On the other hand, Cao et al. [75] proposed a new battery/ultracapacitor hybrid energy storage system (HESS) in which a smaller DC-DC converter was used to regulate the voltage of the ultracapacitor higher than the battery. The new topology has the ability of utilizing the system configuration for fast charging via ultracapacitor. They concluded that the new topology was highly beneficial in reducing the cost of the design and increasing the battery life. Maxoulis et al. [76], studied the effect of temp variation during the drive cycle using lumped semi empirical dynamic model using ADVISOR. Gao et al. [77] presented two hybrid powertrains using battery and ultracapacitor. The authors concluded that the ultracapacitor combination can more effectively assist the fuel cell to meet vehicle dynamic power demand and fuel economy.

2.1 Experimental evolution

Bo Long et al. [78] illustrated power circuit structure of the hybrid power supply system (HPSS). They reported energy allocation between the battery and ultracapacitor. A practical DC-DC converter was designed based on H-infinity and proportional integral derivative (PID) controllers. They concluded that the average charging power for H-infinity is 10 kW and 9.5 kW for PID controller. Therefore H-infinity can achieve 5.3% more braking energy than conventional PID controller. J. Bernard et al. [79] proposed an ongoing control technique to decrease the hydrogen utilization by utilizing efficient power sharing between the fuel cell unit and energy storage system (ESS) and they approved the system with a Hardware-in-the loop (HiL) test bench based on 600 W fuel cell system. They reported that the hydrogen consumption is reduced by 3.5% for simulation and 4% in a test bench respectively. Odeim et al. [80] investigated an experimental fuel cell/battery/ultracapacitor hybrid system for power management and optimization of fuel consumption, battery loading and acceleration performance. Two power control strategies were used in this analysis and an advantageous feature like charge exchange between battery and ultracapacitor was avoided and battery power demand was estimated based on ultracapacitor state.

Amjadi et al. [81] proposed 4-quadrant SC Luo converter control strategy based on traction motor power flow and battery current variation. Both Voltage buck-boost capability and bidirectional power flow were attained in a single circuit and tested with experimental prototype. They reported that the advantage of the proposed strategy was that it enables the lower source current ripple, simpler dynamics and control. Thounthong et al. [82] conducted experiments on a test bench with (a PEMFC: 500 W, 50 A; a battery bank: 68 Ah, 24 V; and a ultracapacitor bank: 292 F, 30 V, 500 A). Hybrid energy was unbiased by the dc bus voltage control. They used three voltage control loops such as DC bus voltage controlled by ultracapacitor bank, ultracapacitor voltage influenced by battery bank and battery voltage influenced by FC. They presumed fast change of FC and battery powers and after that lessening of FC and battery stresses. Hongwen et al. [83] developed and verified the fuzzy logic control methodology for a hybrid power framework utilized for crossover vehicles. They uncovered a trial examination to affirm the energy administration under Urban Dynamometer Driving Schedule (UDDS). The limit utilization of hybrid energy system can be brought down by 4.1% with fuzzy logic control methodology and run based control technique.

Meanwhile, Zandi et al. [84] presented an energy administration strategy, for example, using electric hybrid power control source (EHPS) in view of flatness control method (FCT) and fuzzy logic control (FLC). EHPS is consolidated with energy unit source as principle source and two assistant sources being a bank of ultracapacitors and a bank of batteries. By hybridizing the two secondary sources with the fundamental source, the span of EHPS can be minimized. An EHPS has been furnished with ongoing framework control utilizing digital signal processing and control engineering (dSPACE). FCT is connected to deal with energy between the fundamental source and secondary source and FLC is connected for energy sharing amongst battery and ultracapacitor. However, the study was limited to energy sharing between main and auxiliary sources only, and the performance of SOC variation for two auxiliary sources were not mentioned and it is observed that the maximum load was restricted to 780W.

When integrating batteries and ultracapacitors to hybrid system, its volume and system mass can be decreased. In this regard, the high energy density of the batteries and high power density of the ultracapacitors are used as key energy storage devices for vehicle accelerating demands [85]. Both battery and ultracapacitors are essential for hybrid powertrain systems. The battery exhibits low power density and high energy density while the ultracapacitor exhibits vice- versa. The energy drawn from the main source and auxiliary source is supported into DC transport voltage and into the inverter which can change the voltage from direct current (DC) to alternating current (AC) voltage and after that AC voltage was prepared to move AC electric motor [86].

Gauchia et al. [87] presented a fuel cell–battery-ultracapacitor multi storage energy system based on Energetic Macroscopic Representation (EMR) of the multisource powertrain system. The tests were conducted on 1.2 kW fuel cell, (Nexa Ballard), 22-50 V source with a 50 A peak current. The stack model was scaled to show a 300 cell in series with a voltage bound between 138 -318 V. Hannan et al. [88] designed an energy regulation for light duty hybrid vehicles, that comprises of a fuel cell, battery, and ultracapacitor separately. Vehicle speed results were in contrast with that of battery power source only; multiple sources (fuel cell–battery–ultracapacitor) were tested for ECE-47 test drive cycle. The powertrain showed 94% productivity in contrast with battery power source, which exhibited 84.9% proficiency, whenever the vehicle was tried in elevated driving condition. Li et al. [89] developed a tramway hybrid configuration with dual FC stacks along with batteries and ultracapacitors, and proposed a state machine control strategy to integrate the power sources and reduce sudden power demands. The control strategy improved hydrogen consumption as well as power source efficiency.

Marzougui et al. [90] described an energy management algorithm for fuel cell hybrid electric vehicle (FCHEV) using MATLAB/Simulink and validated them experimentally with real-time controller with dSPACE. Zhou et al. [91] proposed an online energy management based on optimized offline fuzzy logic controllers with data fusion approach for three different types of road conditions. A Probabilistic Support Vector Machine (PSVM) online controller results was compared with Hardware-In-the –Loop (HiL) tests. Fathabadi [92] proposed a novel FC/Battery/ultracapacitor hybrid power source for hybrid electric vehicle. Experimental verifications were made with prototype of FC/Battery/Ultracapacitor and they achieved 96 % power efficiency at rated power. The proposed powertrain achieved better performance in terms of maximum speed, acceleration and cruising range of the vehicle. Shin et al. [93] analyzed PEMFC and ultracapacitor hybrid system and demonstrated the break- even point of hybrid system to reduce the fuel cost at extra cost of hybridization level.

In any case, the review was restricted to simulation results only, and the energy restoring and releasing capacities of the battery and ultracapacitor were not obvious. Yu et al. [94] proposed an energy component battery-ultracapacitor control portion methodology which was done in Matlab/Simulink. Energy regulation was divided by two blocks, fuel cell-battery and battery-ultracapacitor and the energy allocation schedule was done in Matlab/Simulink programming. The range of battery SOC was set between 40%-90%, though the range of ultracapacitor was inside 25-100%. However the present review was centered around city and expressway level roads. Subsequently, driving uphill and downhill was not considered. Souleman et al. [95] reported en energy control for a fuel cell–battery–ultracapacitor hybrid electric vehicle, and that contemplated five particular control methodologies: (1) state machine design methodology, (2) fuzzy logic control-rule based (3) traditional proportional integral control technique, (4) frequency decoupling and fuzzy logic control, and (5) equivalent consumption minimization strategy (ECMS). All these simulations were carried out by means of Matlab/Simulink utilizing Sim Power Systems tool box, and the simulations were additionally tried progressively through Lab VIEW on NI-PXI 8108, that showed a DC transport voltage of 280 V. The exploration for a 15 kW fuel cell–battery–ultracapacitor HEV created comes about for every one of the methodologies, concentrating the hydrogen utilization and stress examination of every system; in any case, there was no obvious review on speed and load control profile.

Paladini et al. [96] reviewed HEV sourced by a fuel cell–battery–ultracapacitor. In his review, a PEMFC, Ni-MH battery, and Maxwell ultracapacitor was picked to accomplish a streamlined HEV. The energy control to regulate the power flow between the fuel cell system, battery, or ultracapacitor was basically utilizing ECoS code and traction regulation approach that was simulated in MATLAB/Simulink. The energy control was tested for four driving schedules using pareto front analysis , to be specific, the New European drive Cycle , Urban Dynamometer Driving Schedule, Highway Fuel Economy Test, and Japanese driving cycle (10–15). In light of the outcomes, the framework was obviously ideal for NEDC, and used just 6.75 g/km hydrogen fuel. Be that as it may, the report concentrated more on the correlation of the drive cycle tests and did not explain on the EMS.

Meanwhile, Garcia et al. [97] provided an account of five distinctive control methodologies for pinnacle control HEVs and thoroughly outlined the control procedures for fuel cell–battery–ultracapacitor HEVs. These control strategies include fuzzy logic, operation mode, course type, equivalent fuel consumption minimization, and predictive technique individually. The regulation procedures were inspected by differentiating their presentations on a 400 kW assessed hybrid powertrain. They suggested that equivalent consumption minimization strategy (ECMS) control reduced fuel usage showed the least troublesome control procedure. The author gave an unequivocal commitment to a fuel cell–battery–ultracapacitor HEV. Regardless of this, the survey was quite recently restrictive in real time application. Jennifer et al. [98] investigated the powertrain topologies of fuel cell, battery and ultracapacitor using MATLAB/Simulink. They conducted parametric study to achieve optimal component sizing of power sources. A fuel cell of 40 kW, high power lithium ion battery of nominal voltage 346.5 V and ultracapacitor voltage of 400 V were used in this study. They suggested that the highest fuel economy was achieved with fuel cell-battery-ultracapacitor combination which benefits battery life due to low stress on battery.

2.2 Recovery of regeneration energy

Zhang et al. [99] reported braking energy control of a fuel cell hybrid electric bus (FCHB). Coordinating regeneration braking system (RBS) with pneumatic braking system (PBS) leads to recapture of braking energy and improves fuel economy of FCHB. They concluded that hydrogen consumption was reduced by 16% and fuel economy increased by 9% in coordinated regeneration braking strategy and also hydrogen consumption improved by 11.5% by replacing Ni-MH with Li-ion battery in test results. However, they did not elaborate the state of charge (SOC) variation of the energy storage system. Huang et al. [100] reported a hybrid energy storage system (HESS), which comprises a battery and an ultracapacitor. They proposed a power splitting strategy based on frequency-varying filter method. They found in their prototype electric vehicle tests, that most of the transient demand was supplied by the ultracapacitor and 30% of energy recouped by the ultracapacitor in each driving cycle test. There was little evidence, however, of any study on power and fulfilling the conditions of fuel economy.

Qian et al. [101] reported a simulation model for a fuel cell hybrid vehicle (FCHV). They built the power control technique utilizing logic threshold method by using hybrid power control unit. The control system recuperates braking energy and nourished to the battery. The top threshold value was agreeable in NEDC driving cycle, and top and general threshold values were acceptable in Highway cycle. Kim et al. [102] experimentally studied a fuel cell-battery hybrid system that used a generator as an alternative for motor to recover braking energy. They conducted the experiments using NEXA power module of 1.2 kW fuel cell hybridized with 50 Ah Ni-MH battery and reported that regeneration efficiency using generator was 63.8 % compared with 24.2 % efficiency of regenerative braking using motor. Yanan et al. [103] in their report, discussed braking energy recovery of an electric vehicle designed in ADVISOR. The recovery efficiency was around 60 % using a rectifier filter, and by changing frequency, rectifier output and driving motor generation.

Patil et al. [104] described multiple ultracapacitor banks which assist continuous storing of braking energy and expend on to the load once fully charged. They controlled a NUC140 ARM CORTEX M0 PROCESSOR, and the energy bank in each charging and discharging for efficient utilization of recovered braking energy. The potential effects of regenerative braking system on fuel economy of the hybrid vehicles can be exceptional, they discovered.

The rate of used energy during deceleration procedure in the total expended energy for three different driving cycles (ECE in Europe, UDDS in USA and 10–15 in Japan) can accomplish 60.1 %, 43.3 % and 52.5% individually [42]. Chengqun et al. [105] presented a novel methodology to increase regenerative braking energy efficiency for electric vehicle. The author proposed three types of braking control strategies such as serial 1, serial 2 and parallel control strategies for road tests carried out under city conditions. Among the three control strategies, serial 2 control strategy gives better results.

2.3 Energy Management System

Li et al. [106] applied fuzzy logic control (FLC) to reduce the fuel consumption of a hybrid powertrain with fuel cell-battery-ultracapacitor combination developed in ADVISOR software. The FLC for FC+B+UC has better execution as far as mileage under every single driving cycle is concerned. Castaings et al. [15] reported real-time energy management strategies to minimize the minimization of the battery current RMS esteem empowers to expand battery lifetime. They looked at ג-control and filtering base control strategies and concluded that the ג-control is better suited for high ultracapacitor voltage ranges whereas filtering base control is favorable for low voltage ranges.

Hongwen et al. [107] proposed an energy regulation strategy for a hybrid power system based on fuzzy logic control, which comprises of a battery and an ultracapacitor used in electric vehicle and tested on Hardware in the loop test bench. They concluded that fuzzy logic control strategy can save 4.1 % energy capacity of a hybrid system than conventional rule based control strategy. However, there was no evidence of SOC variation in energy storage systems.

Huang et al. [108] proposed a power allocation technique based on frequency-varying filter method. They found in their prototype electric vehicle tests, that most of the transient demand was supplied by ultracapacitor and 30% of the energy was recouped by ultracapacitor in each driving cycle test. Schaltz et al. [109] proposed a power sharing scheme for the main source and additional sources, to reduce power rating of the batteries. However, they failed to improve the power output efficiency and control strategy has the limitation to analyze the average positive and negative needs.

Odeim et al. [80] described the genetic algorithm and Pareto front investigation to limit the normal battery power and hydrogen utilization in a multi-target work. By implementing these two analysis, both hydrogen consumption and average battery power were minimized. Erdinc et al. [110] proposed an energy management system (EMS) in light of fuzzy logic and wavelet transform to manage power sharing in a hybrid PEMFC-Battery-Ultracapacitor vehicular framework to increase fuel economy and lifetime of FC system. Bernard et al. [111] proposed a real-time control, charge-sustaining, strategy for fuel cell hybrid vehicles based on Pontryagin Minimum Principle (PMP). The control strategy was validated experimentally using a hardware-in-the-loop test bench.

Paganelli et al. [112] exhibited a technique in terms of control system called Equivalent Consumption Minimization Strategy. This procedure is shown to be robust under an extensive variety of working conditions. Rodatz et al. [113] also executed a real time control by utilizing the idea of comparable hydrogen utilization, indicating practical results. Wang et al. [114] proposed a novel co-estimator to evaluate the model parameters and condition of-charge all the while to decrease the estimation exactness altogether. To diminish the meeting time, the recursive minimum square calculation and the disconnected recognizable proof strategy were utilized to give starting esteems little deviation. Trials were executed to investigate the robustness dependability and exactness of the proposed strategy.

Fletcher et al. [115] suggested a model to gauge the impact of the EMS on the power module degradation.They recommended an ideal methodology for a low-speed ground vehicle utilizing Stochastic Dynamic Programming (SDP). The SDP controller endeavors to limit the aggregate running expense of the power device, in terms of both fuel utilization and debasement, each weighted by their individual expenses. Ansarey et al. [116] explored the model-based ideal energy administration of a fuel cell hybrid vehicle outfitted with battery and ultracapacitor by applying multi-dimensional dynamic programming (MDDP) and achieved drastic decrease in fuel utilization by including ultracapacitors.

Martinez et al. [117] investigated the practical control structure (PCS) and energy administration systems in view of lively naturally visible portrayal to assess the execution of power module testbed hybrid electric vehicle. Reproduction of the model has demonstrated that this methodology is performing well and meet the requirements. Song et al. [118] proposed a novel semi-dynamic HESS that uses a converter with minimal rating among semi-dynamic Hybrid Energy Storage System (HESS).

The primary targets were to limit the measurements of battery-ultracapacitor framework to decrease its cost and to limit capacity loss of batteries because of its thermal runaway. Wei et al. [119] concentrated on the coveted execution of the vehicle by lessening the original battery pack by including ultracapacitors in the hybrid system. The hybrid system worked at high voltage, and was associated with inverter without DC/DC converter to avoid energy loss. Their outcomes recommended that the batteries give normal power while the ultracapacitors help peak power demands.

Bassam et al. [120] proposed a Proportional Integral (PI) strategy to improve the energy consumption, fuel cell efficiency and hydrogen consumption for a marine passenger vessel modeled in MATLAB/Simulink environment. The proposed PI strategy is compared with the equivalent consumption minimization strategy (ECMS), original PI and state based energy management strategies. The new proposed PI gives better results compared with ECMS in case of energy consumption and operational cost, but it has higher energy and operational cost with state based energy and original PI strategies.

Bizon et al. [121] proposed four new control strategies for stationary and vehicle applications based on Load Following (LF) and Maximum efficiency Point Tracking (MEPT) in order to control fuel consumption rate and enhance FC net power availability. Results indicate that 12 % FC net power increased by using MEPT control and LF control reduces battery size and it operates in charge sustaining mode.

Allaoua et al. [122] presented a PEMFC and ultracapacitor bank hybrid electric vehicle. This study enables the prediction of hybrid power source dynamic behavior under driving cycles. The hybrid powertrain was simulated in MATLAB/Simulink environment to know the feasibility of energy management between two power sources. Hames et al.[123] presented different control strategies to increase vehicle energy efficiency using batteries and ultracapacitors in order to reduce the slow dynamics of fuel cell. Peak power source, operating mode control, fuzzy logic control and equivalent consumption minimization strategies were used. Equivalent consumption minimization (ECMS) gives better results.

Karaki et al. [124] proposed an energy management using forward dynamic programming (FDP) to reduce hydrogen consumption and to increase battery life by controlling charge sustained (CS) and charge depleted strategies. Payri et al. [125] proposed a new energy management to optimize power management for vehicle using stochasting approach which is done by upgrading ECMS method to predict future driving conditions using existing vehicle driving data. Wilberforce et al. [126] explored current advances in fuel cell electric hybrid vehicles. The author described about latest designs of hybrid vehicles in the market with technical specifications as well as challenges faced by fuel cells.

2.4 Motivation from the literature review

Most of the researchers focused on the energy management techniques in the literature. Following are the gaps identified from the literature review.

- Only some researchers focused on hybridization performance of power sources, which can increase vehicle fuel economy.
- There is no significant literature on downsizing fuel cell power for fuel cell hybrid vehicles, which reduces the powertrain cost and increases fuel economy.
- Most of the researchers estimated the hybrid vehicle performance for standard drive cycles. The recent drive cycle i.e. World Harmonised Light Vehicles Test Cycle (WLTC) *developed by United Nations Economic Commission for Europe (UNECE)* has not been investigated much in the literature.
- Only limited research papers are available on energy consumption analysis.
- Performance comparison of simulation results with real vehicle test data has not been addressed.

Hence there is an adequate scope for further research in the area of downsizing and hybridization of the energy sources. The proposed research focuses on the development of new downsized Fuel Cell Hybrid Electric Vehicle (FCHV) configuration to achieve equivalent fuel economy with Toyota Mirai 2017 Fuel Cell Electric Vehicle (FCEV). In this work, downsizing the fuel cell stack power by 30% with corresponding increase in the battery pack size to achieve equivalent performance in terms of fuel economy and better acceleration performance using Advanced Vehicle Simulator (ADVISOR) in comparison with Toyota Mirai 2017 Fuel Cell Electric Vehicle (FCEV), has been made. Further, new standard drive cycle World Harmonised Light Vehicles Test Cycle (WLTC) is embedded into ADVISOR to estimate the real time driving performance. It aims to estimate fuel economy, acceleration and gradeability performance, energy consumption, cold start performance, optimal hybridization and reduce the powertrain cost. Downsized Fuel cell Hybrid Vehicle is also compared with Toyota Mirai 2017 AVL test data in order to estimate the real time vehicle performance.

2.5 Objectives of the present research work

This research focuses on the development of new downsized Fuel Cell Hybrid Electric Vehicle (FCHV) configuration to achieve equivalent fuel economy with Toyota Mirai 2017 Fuel Cell Electric Vehicle (FCEV).

The research objectives are as follows

1. To determine the degree of hybridization of Fuel cell- ultracapacitor for Hybrid vehicle

2. To analyze the performance comparison of downsized FC-Battery Hybrid Electric Vehicle with Toyota Mirai Fuel Cell Electric Vehicle for urban and hill road driving cycles.

3. To estimate the hybridization performance of downsized Fuel Cell-Battery Hybrid Electric Vehicle for New European Driving Cycle (NEDC) and World Harmonized Light Vehicles Test Cycle driving conditions (WLTC).

    i. Performance comparison of downsized Fuel Cell-Battery HEV with Fuel Cell-Ultracapacitor HEV
    ii. Energy consumption analysis

4. To estimate the performance comparison of downsized Fuel Cell-Battery Hybrid Electric Vehicle with Toyota Mirai 2017 FCEV ANL test data.

CHAPTER - 3

3. ADVISOR Simulation methodology

3.1 Introduction

ADVISOR was made in the MATLAB/Simulink environment. MATLAB provides an easy-to-use matrix-based programming environment for performing calculations while Simulink can be used to represent complex frameworks graphically utilizing block diagrams. ADVISOR utilizes three essential graphical user interface (GUI) screens to control the user through the simulation process. With GUIs, the user can iteratively assess the effects of vehicle parameters and drive cycle prerequisites on vehicle execution, mileage, and emissions. The GUIs ease interaction with raw input data and output data that is available in MATLAB workspace. The vehicle model is portrayed graphically utilizing Simulink block diagrams to characterize the connections between vehicle components. The model at that point peruses the information from MATLAB workspace during the simulation and yields the outcomes to the workspace in the results window. ADVISOR is employed on basis of backward facing approach.

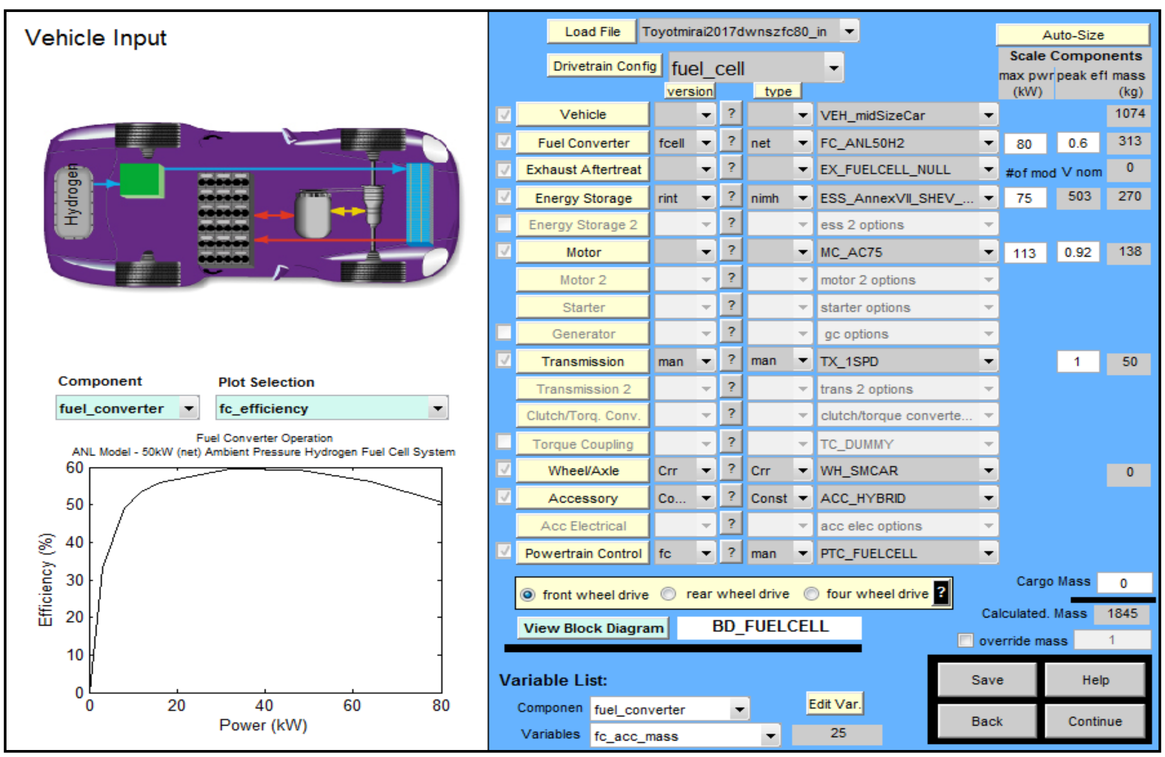


Figure 3.1 ADVISOR vehicle input screen

3.1.1 ADVISOR Vehicle input screen

- In the ADVISOR vehicle input screen, shown in Figure 3.1, the user ‘‘creates’’ the vehicle of interest. Pull-down menus are used to chose a vehicle configuration (i.e. series, parallel, conventional, and fuel cell etc.), and the components that will make the driveline.
- Characteristic performance maps for different components are shown in the lower left of the window and are accessible using the associated pull-down menus. The size of a component (e.g. peak power and the number of modules) can be changed by altering the characteristic value displayed in the boxes on the extreme right portion of the screen.
- Finally, any scalar parameter can be changed by utilizing the edit variable menu in the lower right bit of the window. All vehicle arrangement parameters can be saved for future use. When the user is satisfied with the vehicle input characteristics, the ‘continue’ button takes them to the simulation setup window.

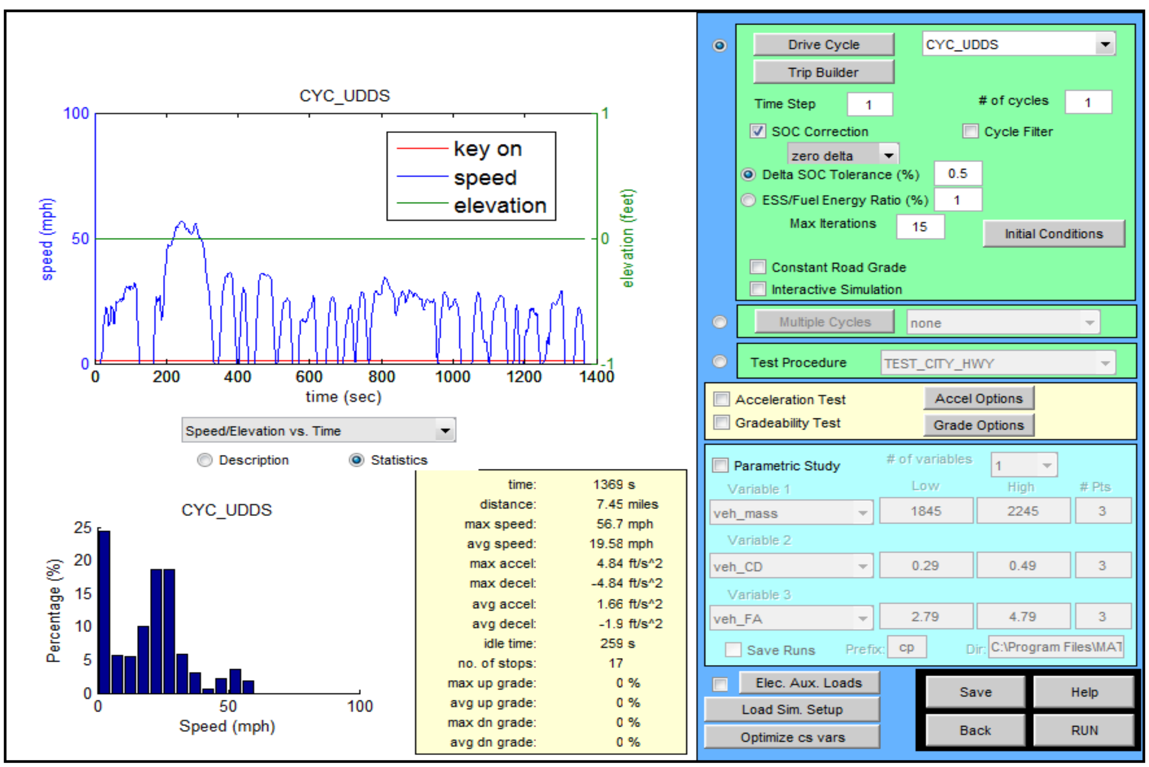


Figure 3.2 ADVISOR simulation setup screen

3.1.2 ADVISOR simulation setup

- In the ADVISOR simulation setup window (Figure 3.2), the user characterizes the event over which the vehicle is to be simulated. Some of the events that may be simulated include a single drive cycle, various cycles, and other available test procedures.
- In the right portion of the window, the user chooses drive cycles and characterizes the simulation parameters. For instance, when a single drive cycle is chosen, the user can see the speed trace in the upper left portion and statistical analysis of the cycle in the lower left part.
- After the drive cycle selection, user need to enable SOC correction button, which facilitates the simulation results at zero change in SOC.
- The user also can use the initial conditions button to customize the boundary conditions for powertrain simulation.
- After the simulation parameters are configured, clicking on ‘run’ will execute the simulation process and provide results screen at finish.

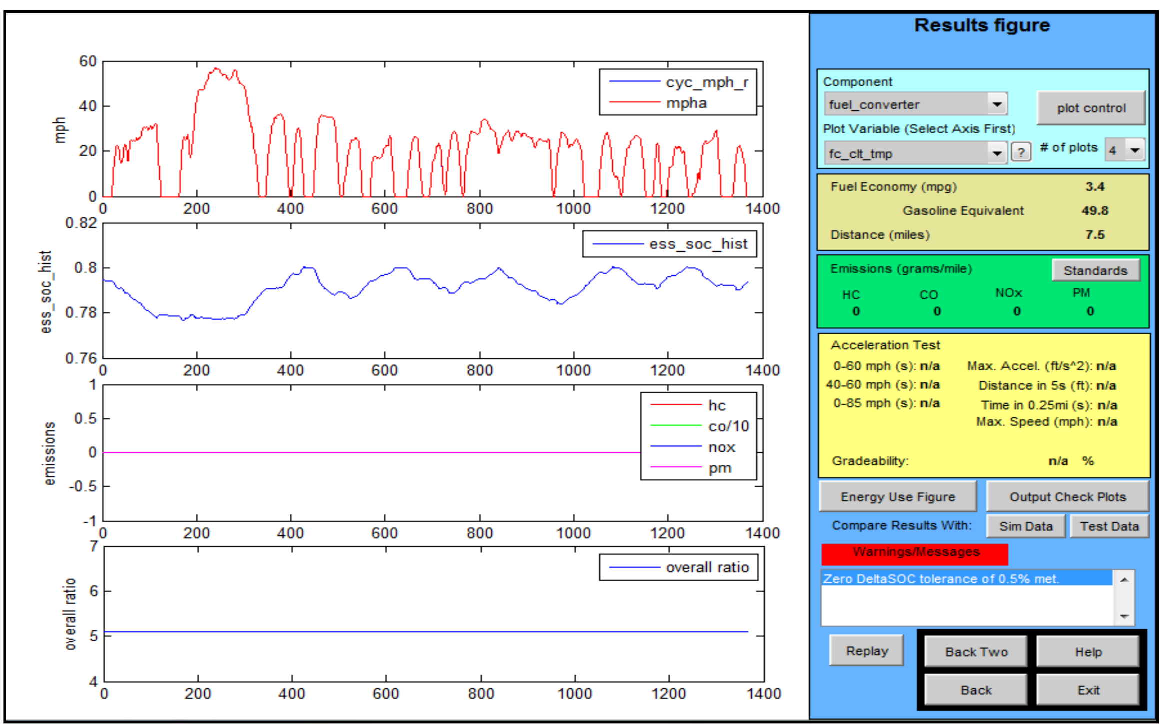


Figure 3.3 ADVISOR results screen

3.1.3 ADVISOR results screen

- The ADVISOR results screen (Figure 3.3), provides the ability to review the vehicle performance, both integrated over a cycle and instantaneously at any point in the cycle.
- On the right side of the screen, a summary of the results such as fuel economy in terms of miles per gallon gasoline equivalent (mpgge), acceleration and gradeability results is provided. In the left portion, the detailed time-dependent results are plotted.
- The results displayed on the left can be dynamically changed to show other details (e.g. fuel cell power, engine speed, engine torque, battery current, etc.) using the pull-down menus in the upper right portion of the screen. ADVISOR GUI is used to interface with the data in MATLAB workspace.

3.1.4 ADVISOR Characteristics

Easy-to-use graphical user interface (GUI).
Fast simulation solutions.
Available as open source code software.
Customizable.
Scalable component models.
Good customer support, software maintenance, and documentation.
Free and publicly available.
Highly parameterized models.
Provides accurate solutions.
Modular structure.

3.2 Standard drive cycles available in ADVISOR

A drive cycle comprises vehicle speeds as a function of time. There are more than 40 different drive cycles to choose from in the ADVISOR software. The following are some of the standard drive cycles.

UDDS (Urban Dynamometer Driving schedule) - used for city driving conditions.

HWFET (Highway Fuel Economy Test) - used for highway driving conditions.

USO6 - also called as Supplemental Federal Test Procedure (SFTP). It is used for aggressive speed and acceleration condition of the vehicle.

NEDC (New Europian Driving Cycle) - used to estimate the emissions and fuel consumption of light duty vehicles.

Japanese 1015 - used to estimate the emissions and fuel economy of light duty vehicles.

NREL2VAIL - used to estimate the gradeability performance of the vehicle.

WLTC (Worldwide Harmonized Light Duty Vehicle Test Cycle) - to estimate the emissions and fuel economy of light duty vehicles on chassis dynamometer.

IDC Urban (Indian Driving Cycle Urban) - used for city driving conditions of Indian roads.

IDC Highway (Indian Driving Cycle Highway)- used for city driving conditions of Indian roads.

3.3 Governing equations

The ADVISOR component blocks are modeled based on the following equations.

Fuel cell model:

$V_{cell} = E_{cell} - (V_{activation} + V_{ohmic} + V_{concentration})$ (3.1)

$V_{activation} = a_c + b_c \ln j$ (3.2)

$V_{ohmic} = jR_{ohmic}$ (3.3)

$V concentration = C \times \ln\left(\frac{jL}{jL-j}\right)$ (3.4)

Where, Ecell is the reversible voltage of single cell, j is the current density, a_c and b_c are two constants, R_{ohmic} is the total ohmic resistance, j_L is the limiting current density and C is constant.

The overall cell reaction for the fuel cell is as follows

$H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$ (3.5)

Fuel cell stack voltage = $E = N\left(\left(E_0 + \frac{RT}{2F}\right)\ln\left[\frac{PH_2\sqrt{\frac{PO_2}{P_{std}}}}{P_{H2O}}\right] - L\right)$ (3.6)

Where,

E = Nernst potential

E_0 = Open circuit voltage

R= Universal gas constant =

F = Faraday's constant

P_{H2}, P_{O2} and P_{H2} are the partial pressures of hydrogen, oxygen and water vapour

$$\dot{m}_{H2} = M_{H2} \times \int \frac{N_{cell} \times I_{FC}}{2F} dt \qquad (3.7)$$

Where, M_{H2}=Molar mass of hydrogen

F = faraday constant

N_{cell} = number of cells

I_{FC} = Fuel cell current

$$\eta_{FC} = \frac{P_{FC}}{\dot{m}_{H2} \times LHV_{H2}} \qquad (3.8)$$

Where, P_{FC} = Fuel cell power

$\dot{m}_{H2}$ = Hydrogen consumption

LHV = Lower heating value

<u>Battery</u>

Battery voltage ,$V_{battery} = V_{ocv} - R_{battery} \times I_{battery}$ (3.9)

Battery current, $$I_{out} = \frac{(V_{ocv} - \sqrt{V_{ocv}^{2} - 4R_{battery}P_{battery}}}{2R_{battery}} \qquad (3.10)$$

Where, V_{ocv} = pen circuit voltage of single battery cell, volts

$R_{battery}$ = internal resistance of battery, ohms

$I_{battery}$ = battery current, amperes

<u>Ultracapacitor</u>

Ultracapacitor current= $$I_{uc} = \frac{(V_{uc} - \sqrt{V_{uc}^{2} - 4R_{uc}P_{uc}}}{2R_{uc}} \qquad (3.11)$$

Ultracapacitor voltage, $V_{uc} = V_{uc} - R_{uc} \times I_{uc}$ (3.12)

Where, V_{uc} = open circuit voltage of single ultracapacitor cell, volts

R_{uc} = internal resistance of ultracapacitor, ohms

I_{uc} = ultracapacitor current, amperes

State of charge, $SOC(t) = SOC(t_0) - \int_0^t \frac{i}{C}(i)dt$ (3.13)

C= ESS capacity

i = ESS current

Vehicle dynamics

Vehicle power required for cruising, $P_e = \frac{\left(m.g.f_r + \frac{1}{2}\rho_a C_d A_f V^2 + m.g.i\right)V}{1000 \times \eta_t \times \eta_{em}}$ (3.14)

Where, m = vehicle mass, kg

f_r = rolling resistance constant

ρ_a = air density. kg/m^3

C_d = drag coefficient

A_f = vehicle frontal area, m^2

i = road grade

η_t = transmission efficiency

η_{em} = motor average efficiency

Fuel economy

$$MPGe = \left\langle \frac{(Total\ miles\ driven) \times (Energy\ of\ one\ gallon\ gasoline)}{(Total\ energy\ of\ all\ fuels\ consumed)} \right\rangle \quad (3.15)$$

Where, mpgge = miles per gallon gasoline equivalent, kW-hr/100 miles.

= total energy of all fuels consumed

3.4 Boundary conditions

The following boundary conditions are considered for ADVISOR vehicle simulations.

<u>Simulation conditions</u>

Time step = 1 sec

SOC correction = zero delta

Delta SOC tolerance = 5%

Maximum iterations = 15

<u>Initial conditions</u>

Ambient temperature = 20^0 C

Air specific heat, Cp = 1009

ESS module initial temperature = 20^0 C

Motor controller initial temperature = 20^0 C

ESS initial SOC = 0.8

<u>Acceleration test conditions</u>

Shift delay = 0.2 sec

Fuel cell system - enabled

Energy storage system - enabled

Initial SOC = 0.8

Vehicle mass => 1845 kg

Acceleration 1 => 0 to 60 mph

Acceleration 2 => 40 to 60 mph

Acceleration 3 => 0 to 85 mph

<u>Gradeability test conditions</u>

Speed = 55 mph

Duration = 10 seconds

Fuel cell system - enabled

Energy storage system - enabled

Initial SOC = 0.8

Minimum SOC = 0.4

Grade lower bound = 0

Grade upper bound = 10

Grade step size = 1

Speed tolerance = 0.05 %

Maximum iterations = 25

Vehicle dynamics

Coefficient of drag (Cd) = 0.29

Frontal area (FA) = 2.79 m^2

Air density = 1.2 kg/m^3

Centre of gravity height (CG) = 0.5 m

Glider mass = 1074 kg

Wheel base = 2.71 m

Fuel converter

Fuel lower heating value (LHV) = 120 MJ

Maximum power = 80 kW

Wheel

Wheel rolling resistance constant = 0.009

3.5 Parameter definitions

Hybrid ratio: Hybrid ratio is defined as the ratio of energy storage system (ESS) power to the total hybrid power.

Hybrid power = Fuel cell power + ESS power

Drive cycle: A drive cycle is a standard speed trace. Drive cycles are sometimes, but not always, based on real-world driving. They are generally used for either fuel consumption or emissions testing to provide a common test procedure.
Mpgge: It is a measure of the average distance traveled per unit of energy consumed to compare energy consumption different alternative vehicles. The units are kW-hr/100 miles

Acceleration performance: The time required to accelerate a vehicle between two speeds.

Gradeability performance: The maximum grade a vehicle can ascend maintaining a particular speed.

MPGe: The distance travelled by the vehicle in miles per gallon gasoline equivalent of energy consumed.

(1 gallon gasoline = 33.7 kW-hr)(reference?)

Fuel Economy: Fuel economy, or mileage, is the relationship between distance traveled and the amount of fuel consumed for a specific vehicle and speed trace. Fuel economy is most commonly expressed as miles per gallon (MPG).

State of charge (SOC): State of charge is the level of electric battery relative to its capacity. The unit of SOC is percentage

Driving range: The maximum distance travelled by the vehicle per full tank of fuel filled

3.6 MODELING OF DEGREE OF HYBRIDIZATION OF FUEL CELL-ULTRACAPACITOR FOR HYBRID SPORT UTILITY VEHICLE

3.6.1 Introduction

Hybridization of energy component control source with other two secondary energy sources, for example, batteries and ultracapacitors will assist the fuel cell (FC) for a long time. In hybrid power source, the FC power module provides the main power consistently during the acceleration phase, while secondary power source gives supplementary power, increasing speed and peak load operation and capturing the regeneration braking energy during vehicle deceleration. Hence, the stress on FC power module and cost will be diminished. The transient performance of the powertrain and the energy storage efficiency will be improved. Ultracapacitor has the nature of more power density and moderately less energy density. It can permit many years of cycle life and overall increased performance of the batteries. This chapter illustrates an ADVISOR model depending on approved individual segment models that are exhibited to research the effect of hybridization to enhance the mileage of a large SUV in various drive cycles. The aims of this examination are to comprehend the effective cooperation of FC energy units and ultracapacitors, and to decide an ideal framework.

A sport-utility vehicle is demonstrated in Advanced Vehicle Simulator (ADVISOR) with a power device fuel cell (FC)/ultracapacitor hybrid electric drivetrain utilizing approved part models. The net power developed from the FC stack and ultracapacitor, electric traction drive and vehicle mass is fixed. High power density quality of ultracapacitor is a major preferred standpoint for FC hybrid power train to improve the mileage and acceleration of the vehicle. The simulations were carried out in two different drive cycles: city driving cycle (urban dynamometer driving schedule; UDDS) and highway driving cycle (highway fuel economy test). From the simulation results, it was observed that fuel economy and regeneration efficiency increase for an urban driving cycle (UDDS). Simulation results with respect to fuel economy show that the degree of hybridization is beneficial and it varies for different drive cycles. The simulation plots demonstrate that ultracapacitor basically helps the energy component stack to take care of vehicle power requirement and to accomplish superior execution and a higher mileage.

3.6.2 Vehicle Description

The SUV selected for this simulation study depends on all-wheel drivetrain of Chevrolet 2000 model that was changed over to an FC hybrid power vehicle. For this demonstration, the external shape of the vehicle remains unchanged, and the existing engine power train is supplanted by FC/ultracapacitor arrangement for hybrid electric power train. The key technical specifications for this vehicle are mentioned in Table 3.1.

Table 3.1 Vehicle Parameters.

Fuel cell net power (kW)	170
Motor power (kW)	166
Drag Coefficient	0.45
Frontal Area, m^2	3.17
Rolling Resistance Coefficient	0.008
Mass, kg	2700

3.6.3 Vehicle component Models

Electric Drivetrain

Vehicle all-wheel traction drive comprises a pair of induction motors of each 83 kW AC power to deliver tractive power of 166 kW. This power rating is sufficient for acceleration and gradeability performances coordinating with conventional vehicle (5.3 l V8 motor 210 kW). The engines were integrated with sun and planet gear arrangement, replacing the traditional four-speed self-shifting transmission to achieve a maximum speed of 80 mph. Inverter and motor models depend on the approved ADVISOR models [127].

Fuel cell model

The FC stack module operates at 1.7 bar at maximum power level using a double-rotating screw-type compressor and it depends on estimations from 110-cell 20 kW gross power modules [128]. A validated model of hybrid power source vehicle data in [129,130] using ADVISOR.

Ultracapacitor model

The simple ultracapacitor resistor–capacitor (RC) model includes a resistor R, which gives the ultracapacitor's ohmic deficiency, additionally called equivalent series resistor (ESR) with capacitor C, which recreates the capacitance of ultracapacitor during the state of charge (SOC) variation impacts. The specifications of the ultracapacitor are mentioned in Table.3.2

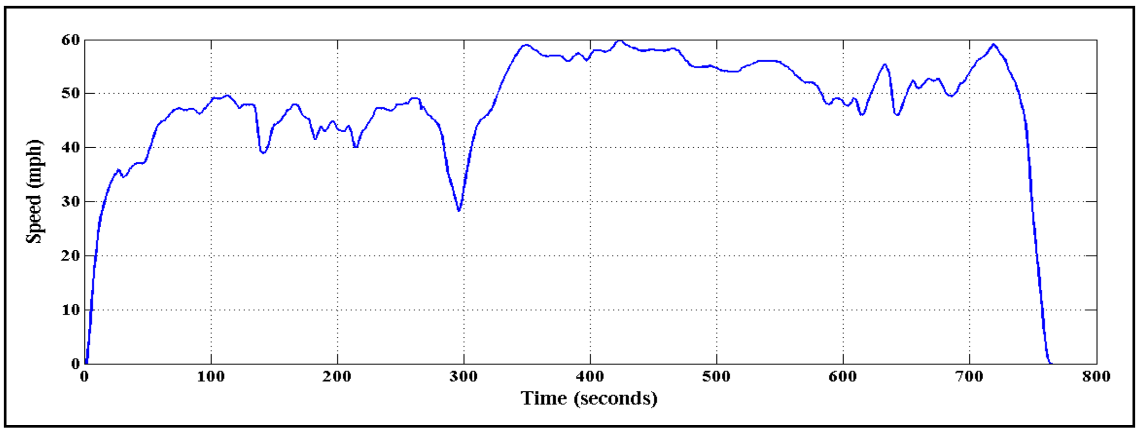
Table 3.2 Ultracapacitor specifications [131]

Ultracapacitor parameters	**Value**
Capacitance	2700 ± 20% (F)
Internal resistance (de)	0.001 ± 25% (fi)
Leakage current	0.006 (A), 72 h, 25°C
Operating temperature	− 40 to 65°C
Rated current	100 (A)
Voltage	2.5 (V)
Volume	0.6 (I)
Weight	0.725 (kg)

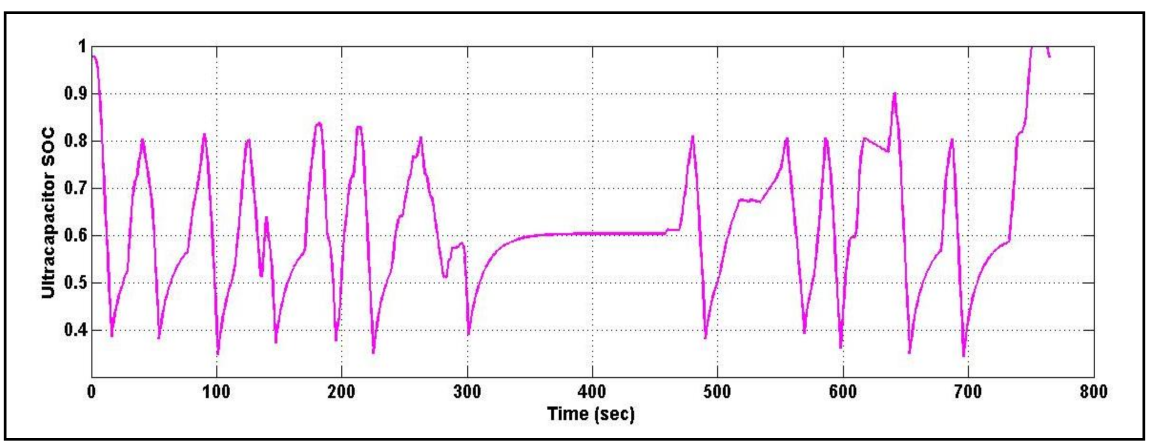
Vehicle ADVISOR model

Table.3.1 represents the electric drivetrain, which is fixed, and FC power module (variable size) and ultracapacitor packs which are included for fuel cell hybrid electric vehicle in ADVISOR model. Varying vehicle setups using FC energy component segment sizes from zero (a pure ultracapacitor-powered vehicle) to pure FC power source (without ultracapacitor) are chosen to examine the range of hybrid ratio with same vehicle mass, and hence, performance. For every setup, the desired power is regulated through drivetrain control and extra auxiliary loads. For the present vehicle model, a supply of around 166 kW and auxiliary loads (steering control, power brakes, 12 V loads) are around 1500 W. For the abovementioned power demands, around 170 kW of power-delivered FC stack and ultracapacitors are required. The potential to deliver supply 170 kW of energy for high-voltage drive system of the vehicle assures the vehicle performance.

Figure.3.1 demonstrates the case study results with respect to time for highway fuel economy test (HWFET) driving cycle for hybrid vehicle. Speed variation over the driving cycle is shown in Figure3.1 (a). There is no variation in ultracapacitor state of charge (SOC) during the drive cycle to give repeated SOC-corrected hydrogen economy results shown in Figure 3.1 (b). Fuel cell energy unit requires a base power during control system operation. The ADVISOR model is utilized to predict the mileage and hybrid power train proportions for various drive cycles. Motor controller power, fuel cell power and ultracapacitor power are shown in Figures.3.1(c), 3.1(d) and 3.1 (e) respectively.



(a)



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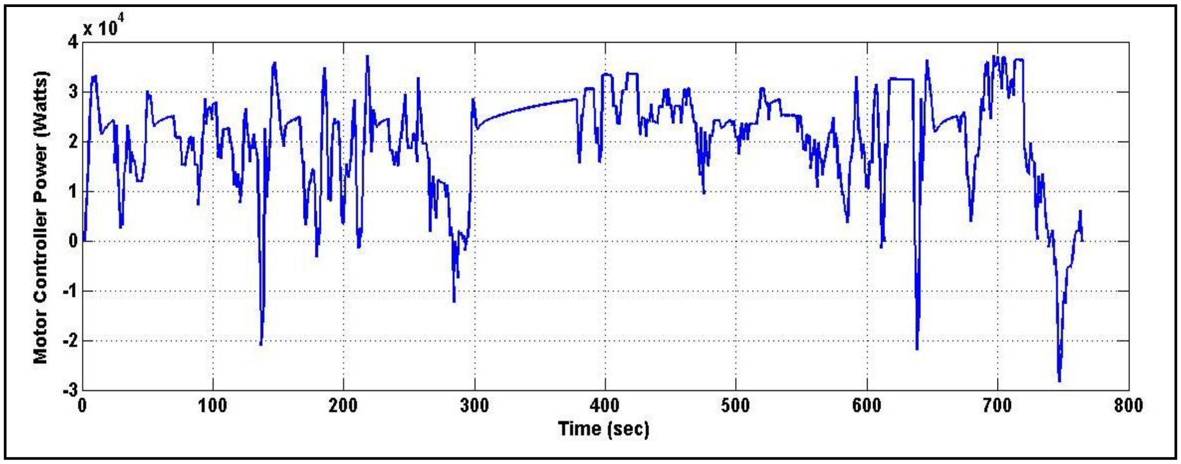

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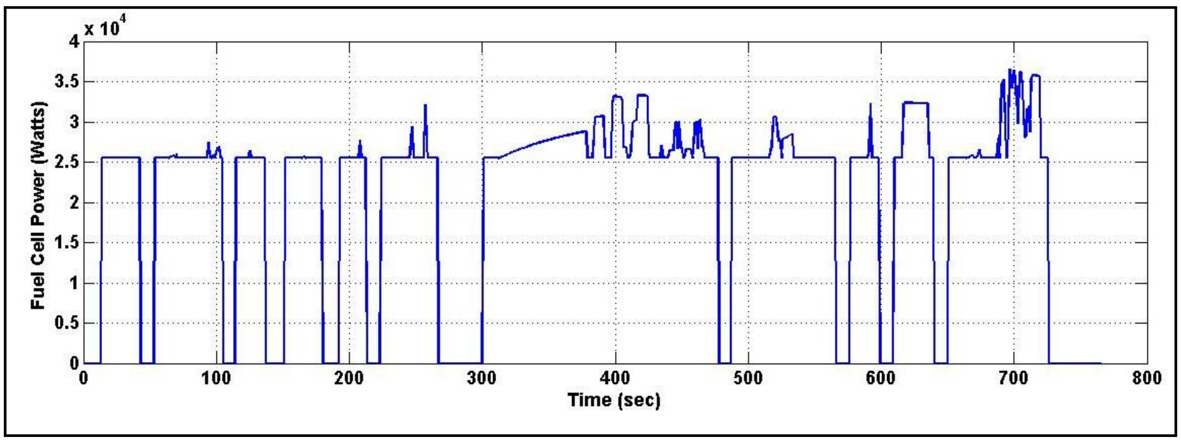

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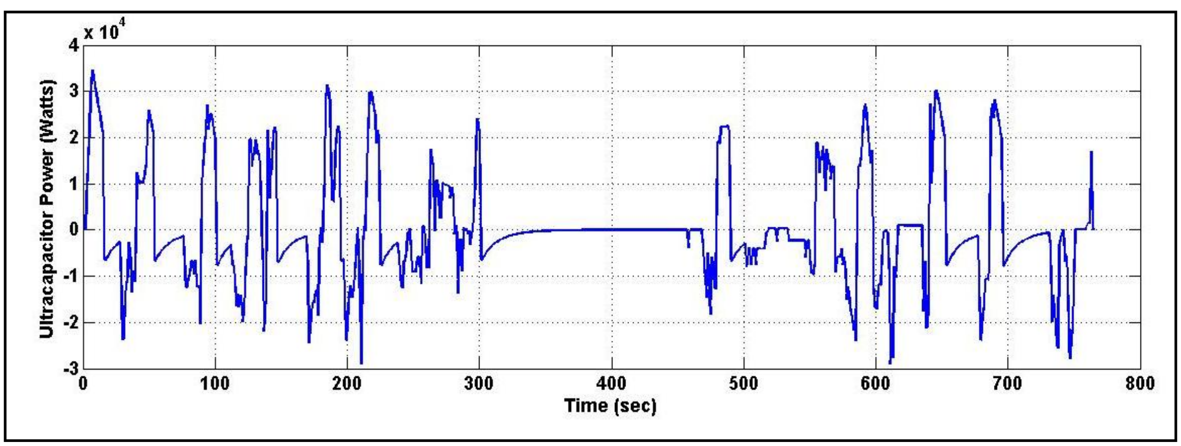


(e)

Figure 3.4 (a)-(e) ADVISOR simulation results for highway driving cycle

3.7 Hybridization results and discussions

A step incremental power of 10 kW for FC module and ultracapacitor module are considered for this model. The lower limit of FC power is set so as to ensure that the vehicle maintains a steady speed of 103 kph (65 mph) on straight roads. A power demand of 30 kW supplied by the FC stack decides the minimum tractive power designs at 40 kW as total FC power. The SUV model vehicle can cover the power range from this minimum power level to the most extreme net power of 170 kW for the only FC source. The rest of the power which is not provided by the FC unit decides the volume of ultracapacitor required for a dual-power framework. The level of hybrid ratio is determined by the volume of gross FC stack power in a hybrid component to gross stack power for the only FC power module design (225 kW). This component is likewise near the proportion of FC power to hybrid FC power in addition to ultracapacitor power (170 kW). Table.3.3 records the scope of module sizes used to provide roughly steady accessible power.

Table 3.3 Component size ratio

Hybrid Ratio	Fuel Cell net Power (kW)	Ultracapacitor Power (kW)
0	170	0
0.14	145	25
0.21	134	36
0.27	123	47
0.33	113	57
0.39	103	67
0.44	94	76
0.5	85	85
0.55	75	95
0.6	67	103
0.65	59	111
0.7	50	120
0.74	43	127
0.77	38	132
0.82	30	140
1	0	170

Hybridization empowers the size of FC to be reduced using an energy storage system, i.e., during peak loads, it permits the FC and the system operates more competently. When the power request is low, the FC provides the desired power. The use of stored energy permits speedy beginning of the power device and favors the recognition of braking energy. The degree of hybridization is indicated by the ratio of ultracapacitor power to net fuel cell plus ultracapacitor power. Table 2 lists the range of component capacity used to provide approximately constant available power. The lower limit of fuel cell power (30 kW) is chosen to ensure that the vehicle maintains a constant speed of 103 kph (65 mph) on a level road. Thus, the minimum net power required from the fuel cell system is 30 kW. The hybridization ratio is related as

$$\text{Hybrid ratio} = \frac{P_{ess}}{P_{ess} + P_{fc}} \tag{4.1}$$

P_{fc} = Fuel cell power; P_{ess} = Energy storage system power

3.8 Hybrid fuel economy results

Fuel economy plots shown in Figures 3.5 and 3.6 rely on the drive cycle dynamics. The primary increment is because of the expansion in FC stack size and productivity. The consistent power request is constantly over the FC least power criteria. The efficiency rises to some degree with energy component measure, then remains moderately consistent or diminishes before rising and dropping off once more. The FC power device estimate keeps on expanding and the ultracapacitor limit diminishes. The fuel economy rises up to 70% hybridization and decreases significantly at higher hybridization ratios due to low power assistance from fuel cell for HWFET, US06 and C65 drive cycles shown in Figure 3.5. As the fuel cell power continues to decrease and the ultracapacitor capacity increases, the interaction between the power spectrum of the drive cycle, the minimum fuel cell power and the energy processed through the ultracapacitor produces peaks in fuel economy around the degree of hybridization of 0.9 – 1.0. A large majority of the energy conversion is obtained at the minimum fuel cell power level. The peak in highway fuel economy is achieved where the fuel cell efficiency is highest as shown in Figure 3.6. The decrease in fuel economy for higher hybrid ratio is due to lower ability to trap regeneration brake energy as the ultracapacitor capacity diminishes.

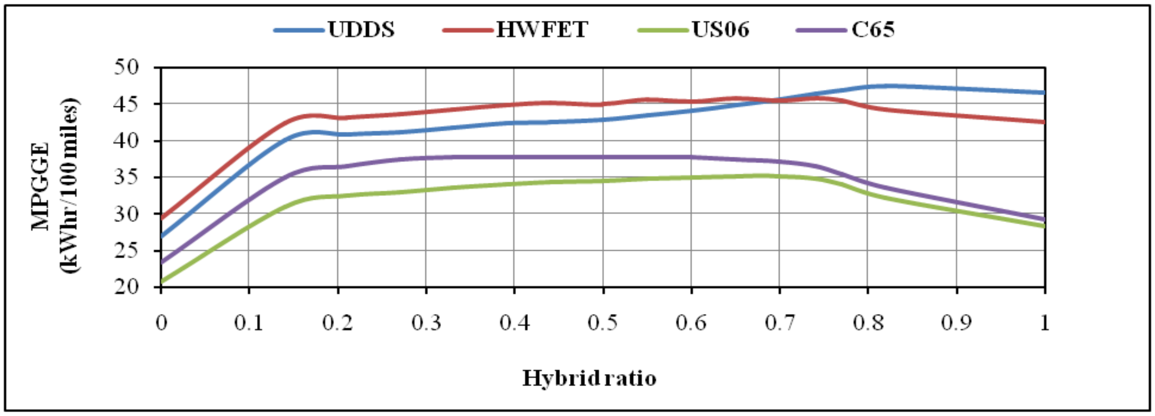


Figure 3.5 Fuel economy variation with hybrid ratio

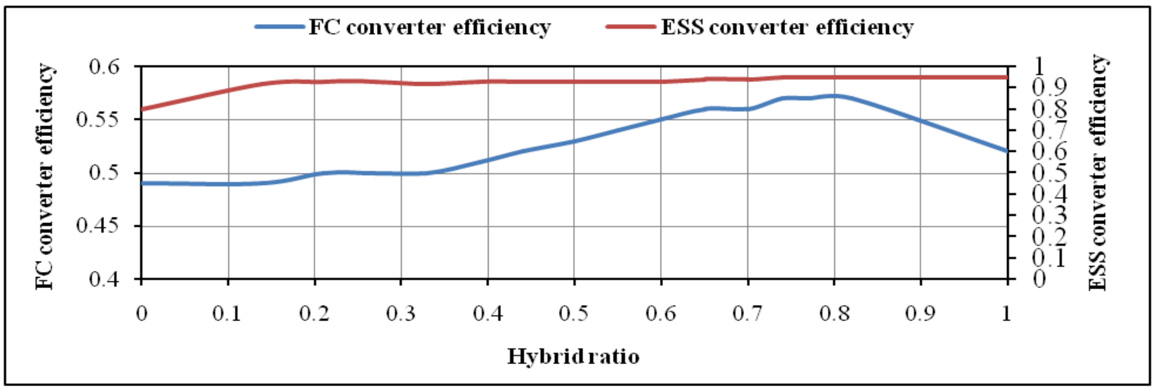


Figure 3.6 Component efficiency variation with hybrid ratio

A substantial dominant part of the energy conversion is achieved at the base energy component control level. The majority of highway hydrogen economy is accomplished at the peak fuel efficiency. With an increase in the FC stack size, the minimum power level as well as the hybrid ratio increase. The drop in hydrogen economy for the higher hybrid ratio is due to lower ability to trap regeneration braking energy as the ultracapacitor capacity is diminished. FC energy unit may be profitable by diminishing its size to maintain a strategic extreme execution at minimum load or on/off operation because of least power request. For the same hybrid ratio (0.60), FC–ultracapacitor power train fuel economy is higher by 35.46% when compared with FC battery in urban dynamometer driving schedule (UDDS).Ultracapacitor has the nature of peak power density allowing sufficient energy storage for acceleration power requirements and fuel economy. The benefit of ultracapacitor is that it can withstand broad range of SOC and hence has increased durability. Its higher specific power characteristic to provide peak power surge is beneficial for hybrid power applications. The large storage capacitance of the ultracapacitor is utilized to meet the power shortfall during start-up and transient operation. By increasing the modules of ultracapacitor, there will be an increase in the vehicle fuel economy, whereas increasing the modules of battery reduces fuel economy because of incremental mass of battery and small specific power with respect to an increase in hybrid ratio.

3.9 Results and discussions

- The degree of hybridization for fuel economy depends on the dynamics of the drive cycle. For the highway drive cycle, the initial increase is due to the increase in ultracapacitor power. The fuel economy is relatively constant.

- As the fuel cell power continues to decrease and the ultracapacitor capacity increases, the interaction between the power spectrum of the drive cycle, the minimum fuel cell power and the energy processed through the ultracapacitor produces the peaks in fuel economy around degree of hybridization of 0.9 – 1.0.

- The fuel economy rises up to 70% hybridization and decreases significantly at higher hybridization ratios due to low power assistance from fuel cell for HWFET, US06 and C65 drive cycles.

- Large amount of energy conversion occurs at the minimum fuel cell power level enforced by the control strategy, which results in increase of fuel cell efficiency.

- Fuel cell system may benefit by downsizing to avoid excessive operation at light load or on/off operation due to minimum power demand.

Chapter 4

PERFORMANCE COMPARISON OF DOWNSIZED FUEL CELL-BATTERY HEV WITH TOYOTA MIRAI FCEV FOR URBAN AND HILL ROAD DRIVING CYCLES

4.1 Introduction

In general, hybridization of FC hybrid vehicle with energy storage system enhances the performance and improves the fuel economy of the vehicle. The hybrid ratio is specified by the ratio of energy storage system (ESS) power to the total power. The significance of hybridization results in increase of fuel economy for urban and rural driving conditions. The aim of this analysis is to understand the energy interactions of the fuel cell and battery and to identify an optimal energy management. This chapter presents a fuel cell hybrid (FCH) mid-size car modeled and simulated in ADVISOR. In order to model the vehicle, the parameters were adopted from 2017 Toyota Mirai FCEV and investigated for Urban Dynamometer Driving Schedule (UDDS) and NREL2VAIL driving cycles to verify the performance. The Urban Dynamometer Driving Schedule (UDDS) and mountain driving cycle (NREL2VAIL) were considered to estimate the fuel economy for urban and hill road driving conditions.

4.2 Vehicle description

For the present powertrain, the vehicle parameters are considered from 2017 Toyota Mirai FCEV [132] to evaluate the performance of the proposed FC hybrid mid-size car. The fundamental vehicle parameters for this type of vehicle are vehicle mass, fuel cell (FC) power, battery modules, motor power, drag coefficient, rolling resistance coefficient and frontal area are included in Table 4.1. ADVISOR vehicle input screen, and vehicle block diagram are shown in Figures 4.1 and 4.2 respectively.

Miles per gallon equivalent (MPGe) is a measure of the average distance covered by the vehicle per unit of energy consumed. The energy content of one gallon gasoline is equivalent to 33.7 kilowatt-hours, which is equivalent to 1 kg of hydrogen consumed.

Table 4.1 Vehicle specifications [132]

Parameter	2017 Toyota FCEV	Proposed FCHV
Vehicle total mass, kg	1850	1845
Fuel Cell Power, kW	114	80
Battery Nominal voltage, V	248 .5	503
Battery pack , kWh	1.6	3.27
Battery modules	37	75
Electric motor power, kW	113	113
Vehicle glider mass, kg	1074	1074
Rolling resistance coefficient, f_r	0.009	0.009
Motor efficiency	0.90	0.90
Air density, kg/m^3	1.202	1.202
Aerodynamic drag coefficient, C_d	0.29	0.29
Frontal Area, A_f, m^2	2.79	2.79

Table 4.2 Fuel cell power sizing criteria for UDDS cycle

Parameter	Component specification	mpgge/MPGe	Vehicle mass	Reduction of FC power (%)
Toyota Mirai 2017 -Specifications				
Fuel cell power (kW)	**114**	**67**	**1850**	**-**
Battery modules	**37**			
Motor power(kW)	**113**			
Proposed Fuel Cell Hybrid Vehicle (FCHV) sizing criteria				
Fuel cell power (kW)	103	47.2/71.39	1954	10 ↓
Battery modules	75			
Motor power (kW)	113			
Fuel cell power (kW)	92	48.5/69.48	1921	20
Battery modules	75			
Motor power	113			
Fuel cell power(kW)	**80**	**49.8/67.67**	**1845**	**30**
Battery modules	**75**			
Motor power(kW)	**113**			
Fuel cell power(kW)	68	50.2/67.13	1849	40
Battery modules	75			
Motor power(kW)	113			
Fuel cell power(kW)	57	52/64.8	1816	50
Battery modules	75			
Motor power(kW)	113			

Table 4.2 shows the MPGe and fuel cell power sizing criteria for the proposed Fuel Cell Hybrid Vehicle (FCHV) over the Urban Dynamometer Driving Schedule (UDDS) drive cycle. The fuel economy parameter (MPGe) of FCHV is calculated with the help of equation 3.15 by varying the Fuel Cell and Battery power to achieve optimal hybrid energy for the same motor power demand. Fuel cell power is reduced from 114 kW to 57 kW with 10 % step value while the battery capacity is doubled for the same motor power demand of 113 kW. It is observed that, at 30 % reduction in fuel cell (FC) power, i.e. at 80 kW, the proposed hybrid powertrain configuration achieved fuel economy of 67.67 MPGe, which is equivalent to the fuel economy performance of 2017 Toyota Mirai Fuel Cell Electric Vehicle (FCEV). Hence, FC power is downsized from 114 kW to 80 kW (30 % reduction in FC power), while the battery capacity was increased from 1.6 to 3.2 kW-hr to estimate the fuel economy and acceleration performance of FCH downsized vehicle with the benchmark vehicle.

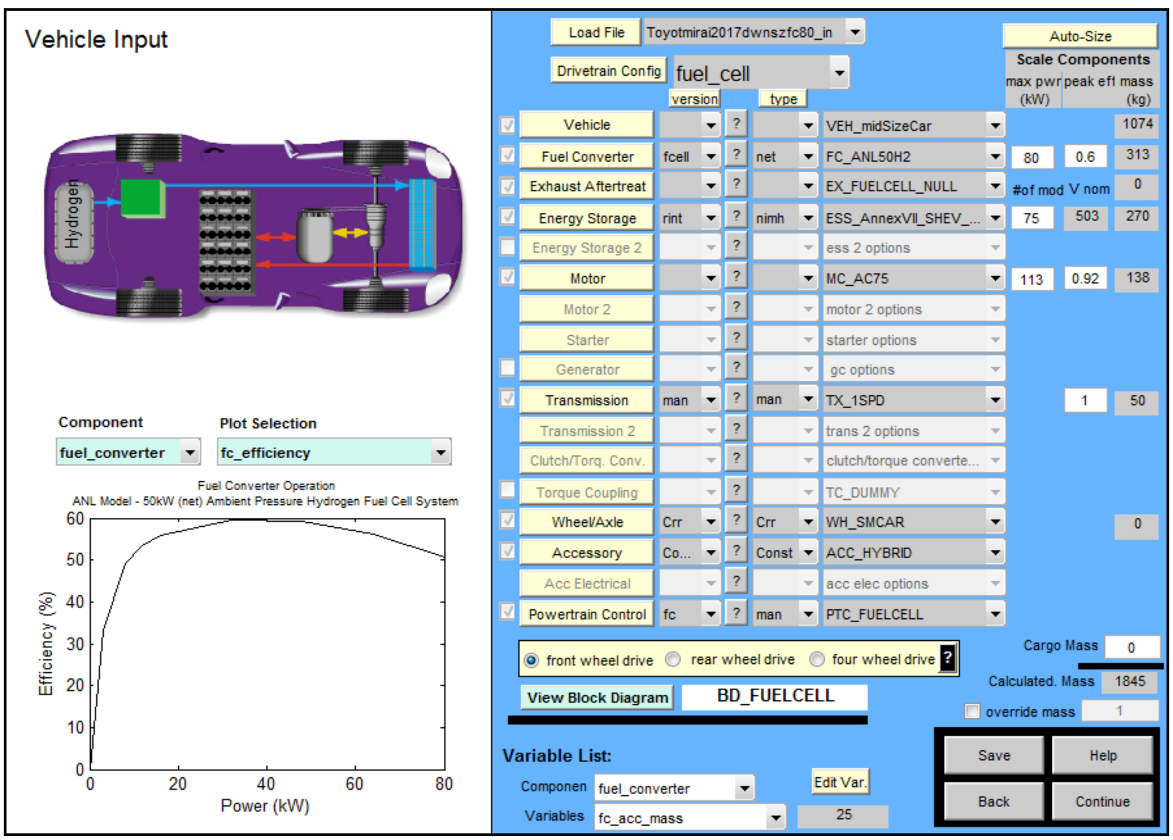


Figure 4.1 ADVISOR Vehicle Input screen

MPGe is a measure of the average distance traveled per unit of energy consumed. It is determined with the help of equation 3.15 by converting the vehicle consumption per unit distance.

$$\text{MPGe} = \left\langle \frac{(Total\ \ miles\ \ driven\ )\times(Energy\ \ of\ \ one\ \ gallon\ \ gasoline\ )}{(Total\ \ energy\ \ of\ \ all\ fuels\ \ consumed\ \ )} \right\rangle$$

Here, energy of one gallon gasoline = 33.7 kW-hour = 1 kg of hydrogen [133]

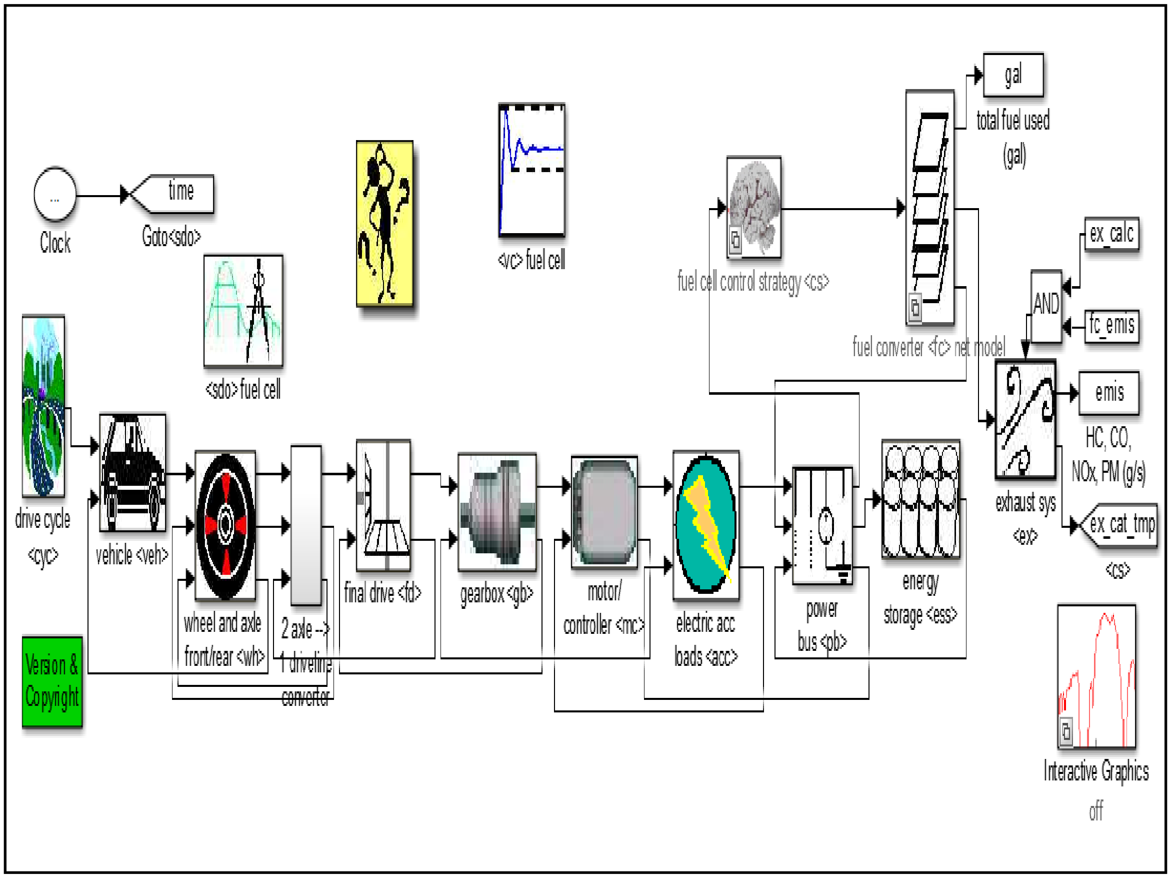


Figure 4.2 - ADVISOR block diagram

Fuel cell delivers the main power for steady speed driving conditions while the battery provides the boosting power during acceleration surge, peak load conditions and recuperates the kinetic energy by employing regenerative braking. Battery has more energy density and its equivalent internal resistance is a vital constraint for hybrid power management. UDDS stands for Urban Dynamometer Driving Schedule; this cycle runs on a city route of 7.5 miles (12.07 km) with regular stops (17 stops). This cycle achieves a maximum speed of 56.7 mph (91.25 km/h) and a mean speed of 19.6 mph (31.5 km/h) with an idle time of 259 seconds. The mountain drive cycle NREL2VAIL (I-70) runs for 86.8 miles in a time period of 5692 seconds from the city of NREL Golden, CO to the city of VAIL, CO. The typical speed ranges between 45-60 mph for this drive cycle.

The 10-15 is a Japanese driving cycle for emissions and mileage testing of passenger vehicles. The Japanese 10-15 cycle runs for a distance of 4.16 km at an average speed of 22.7 km/h, with 660 seconds of cycle duration time. The US06 cycle describes 8.01 mile (12.8 km) route with a maximum speed of 80.3 miles/h (129.2 km/h) ,mean speed of 48.4 miles/h (77.9 km/h for a duration of 596 seconds. It is an aggressive acceleration and high speed driving condition associated with rapid speed fluctuations and the driving behavior following startup. The New European Drive Cycle (NEDC) cycle is a combination of ECE, also known as Urban Driving Cycle (UDC) and Extra Urban Driving Cycle (EUDC) cycles. The entire cycle includes four ECE phases and one EUDC phase with driving distance of 1180 seconds [134].

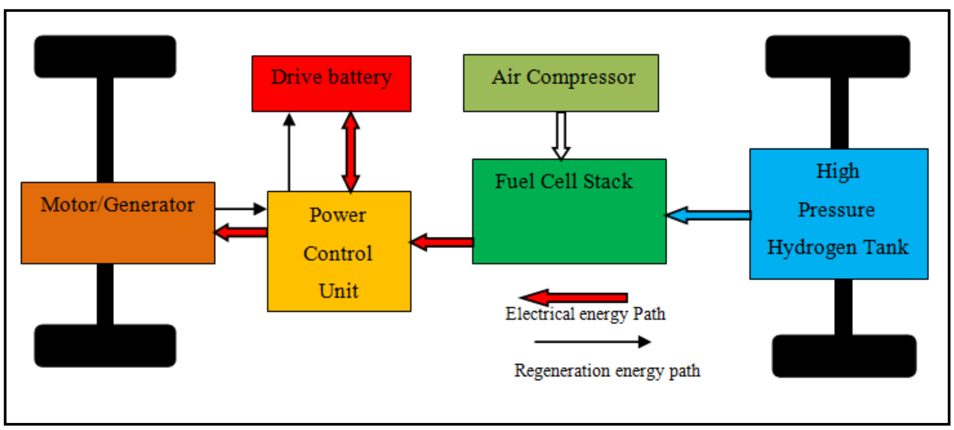
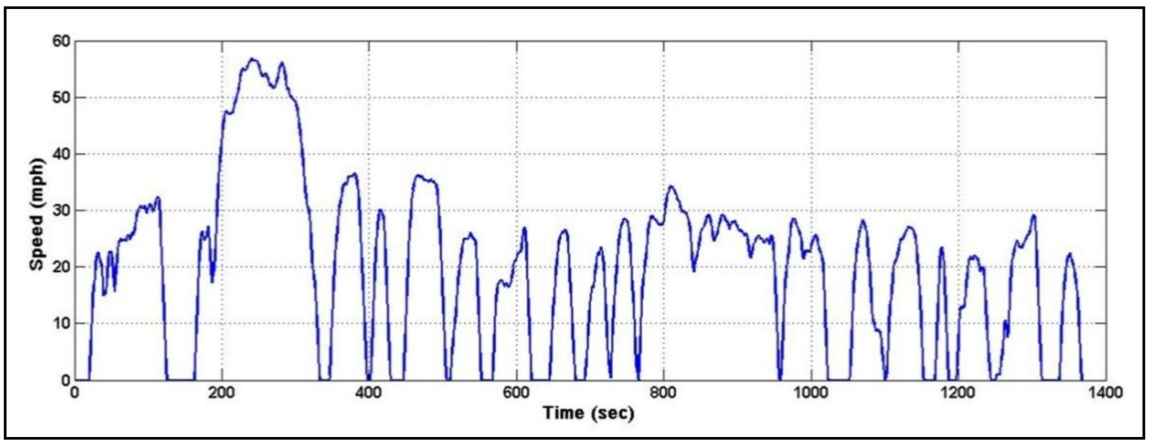


Figure 4.3 Toyota Mirai FCHV Hybrid Powertrain

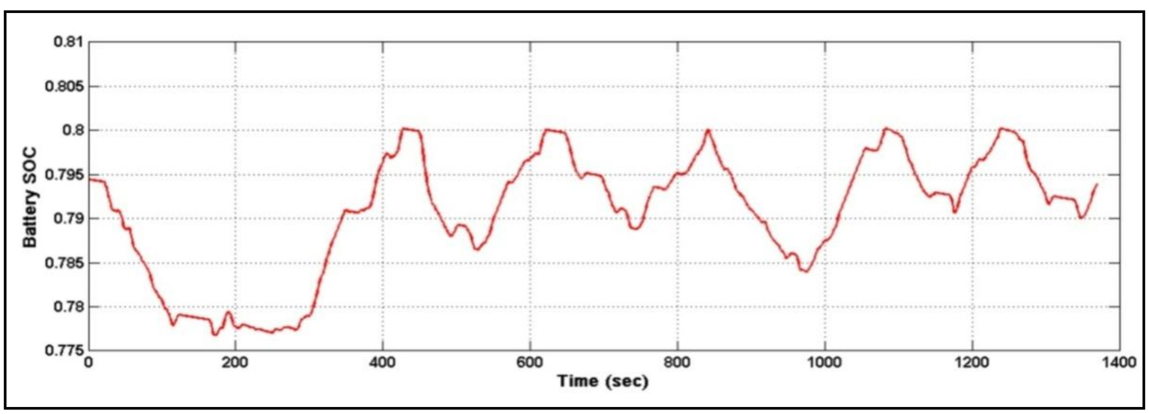
Figure 4.3 represents the structure of Toyota Mirai FCEV powered by PEM fuel cell-battery hybrid system. The hybrid powertrain structure consists of the motor, power control unit, drive battery, air compressor, fuel cell stack and high pressure hydrogen tank. Pure hydrogen gas is stored in the tank at a pressure of 70 Mpa and is supplied to the fuel cell stack which generates desired the electrical power to the hybrid powertrain via power control unit. Both motoring and regenerative power flows are controlled by power control unit of the hybrid powertrain.

4.2.1 Simulation results of FCH downsized Vehicle for UDDS Cycle

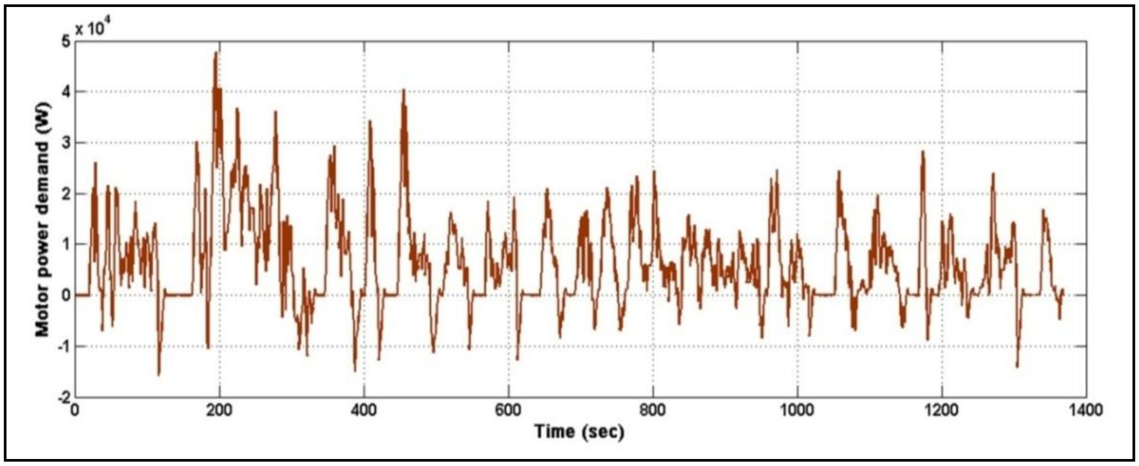
Figure. 4.4 (a)-(d) depict ADVISOR Simulation results of vehicle speed, state of charge (SOC) of battery, motor power demand, fuel cell power and battery power with respect to UDDS drive cycle. From the results, it can be observed that the battery SOC drops from 79.4 % to 78 % ; during the vehicle start up period of 100 seconds and finally regains its initial SOC at the end of the drive cycle. The fuel cell and battery generates 31.2 kW and 17.2 kW respectively in order to achieve the motor peak power demand of 47.71 kW. During the startup and low speed conditions of the vehicle, only the battery assists the motor tractive power demand without utilizing the fuel cell power. In UDDS drive cycle, the fuel cell is turned off frequently. The power demand is initially taken care of by the battery while the fuel cell is in idle condition. Both fuel cell and battery assists the motor power demand only during the maximum speed conditions of the vehicle.



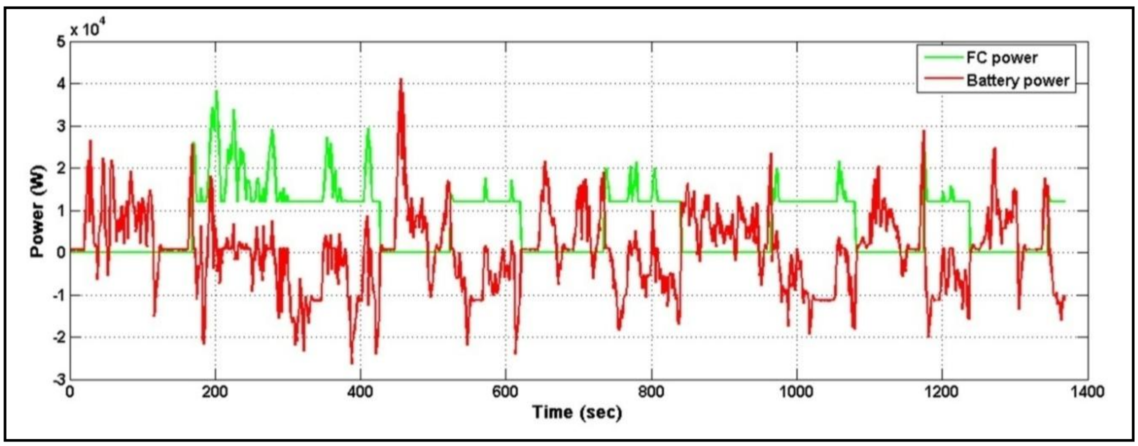
(a)



(b)



(c)

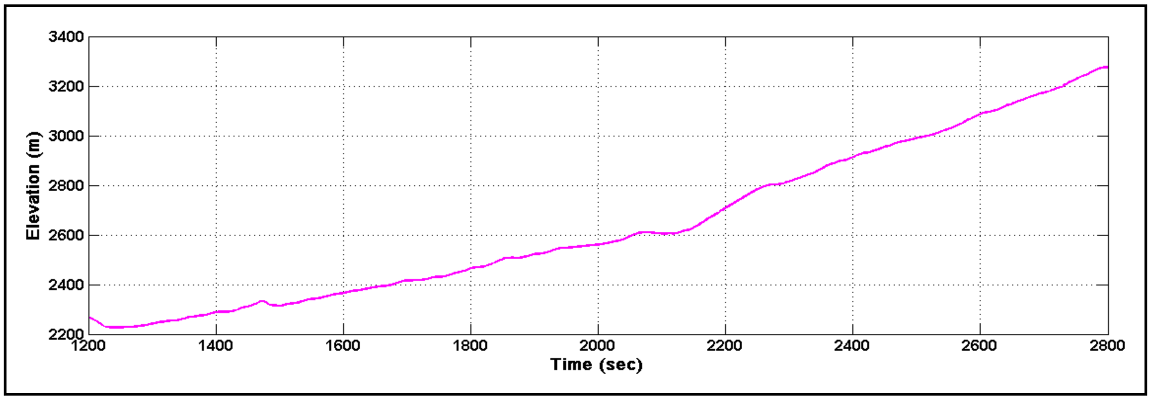


(d)

Figure 4.4 (a)-(d) Simulation results for urban drive cycle

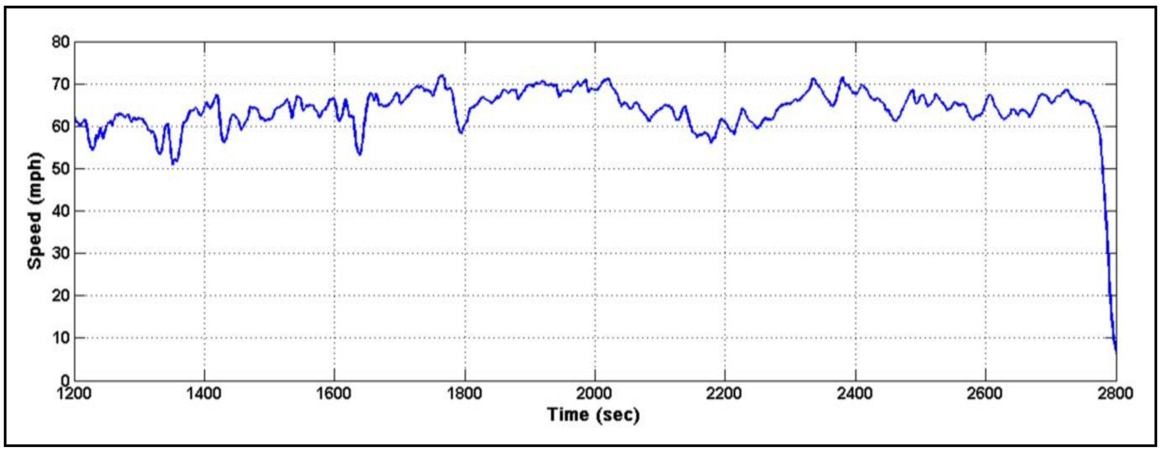
4.2.2 Simulation results of FCH downsized Vehicle for NREL2VAIL Cycle (uphill region)

Figures 4.5 (a)-(e) show the mountain driving performance for uphill region. For this analysis, the performance is considered for a period of 1600 seconds i.e. during 1200 sec to 2800 sec and for an elevation of 1004 meters (2271m -3275m) shown in Figure 4.5 (a). Speed, battery SOC and motor power demand according to road elevation is presented in Figures 4.5 (b), 4.5 (c) and 4.5 (d) respectively. It is evident that, during the uphill driving condition, both fuel cell and battery power assist the motor peak power demand as shown in Figure.4.5 (e).



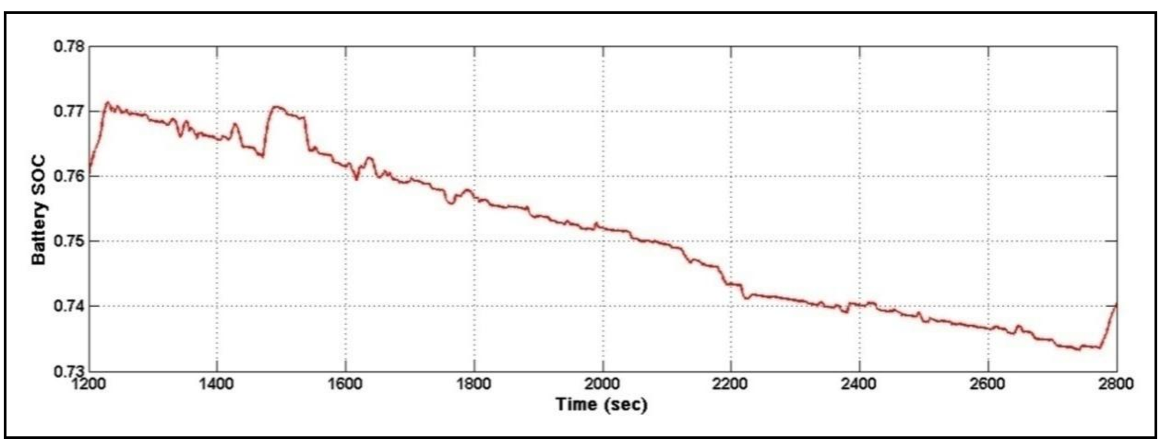
Elevation (m)
Time (sec)
3400
3200
3000
2800
2600
2400
2200
1200
1400
1600
1800
2000
2200
2400
2600
2800

(a)



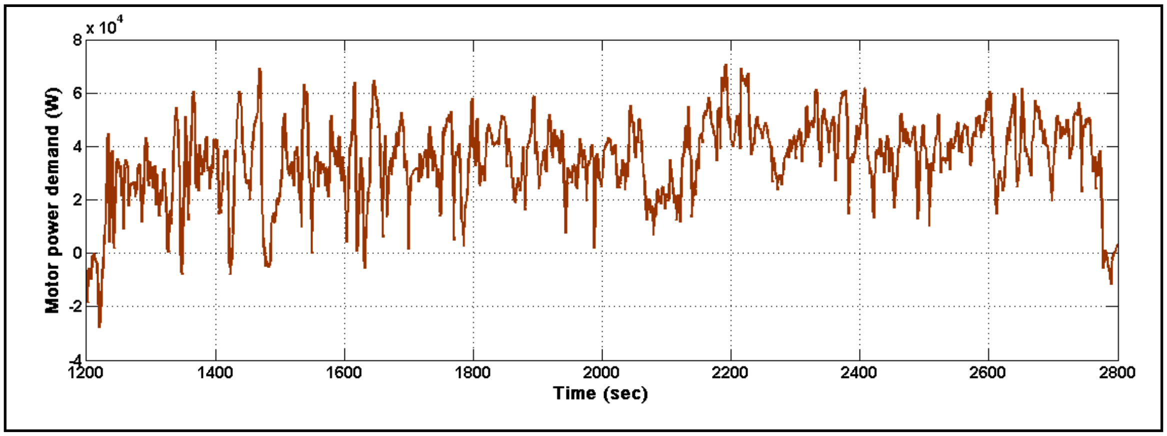
Speed (mph)
Time (sec)
80
70
60
50
40
30
20
10
0
1200
1400
1600
1800
2000
2200
2400
2600
2800

(b)

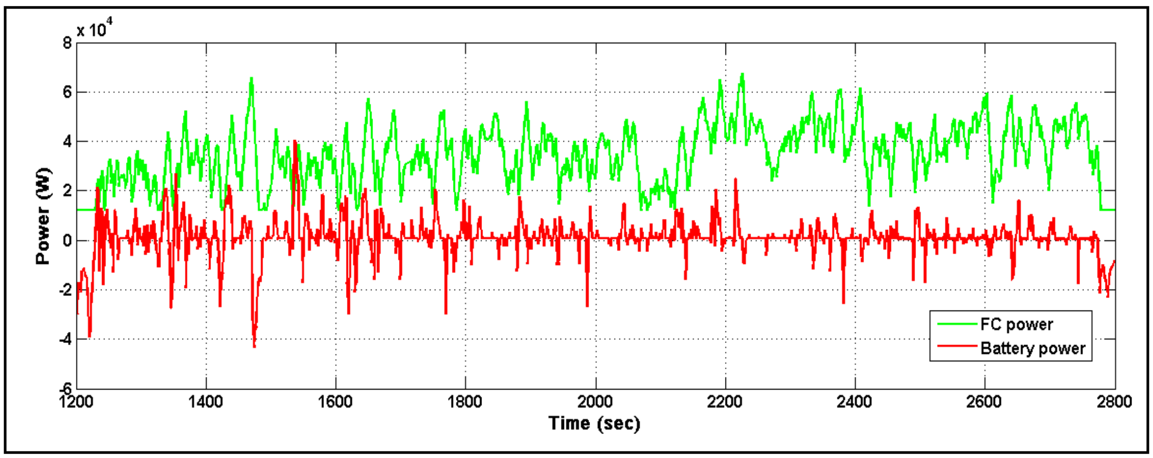


Battery SOC
Time (sec)
0.78
0.77
0.76
0.75
0.74
0.73
1200
1400
1600
1800
2000
2200
2400
2600
2800

(c)



(d)

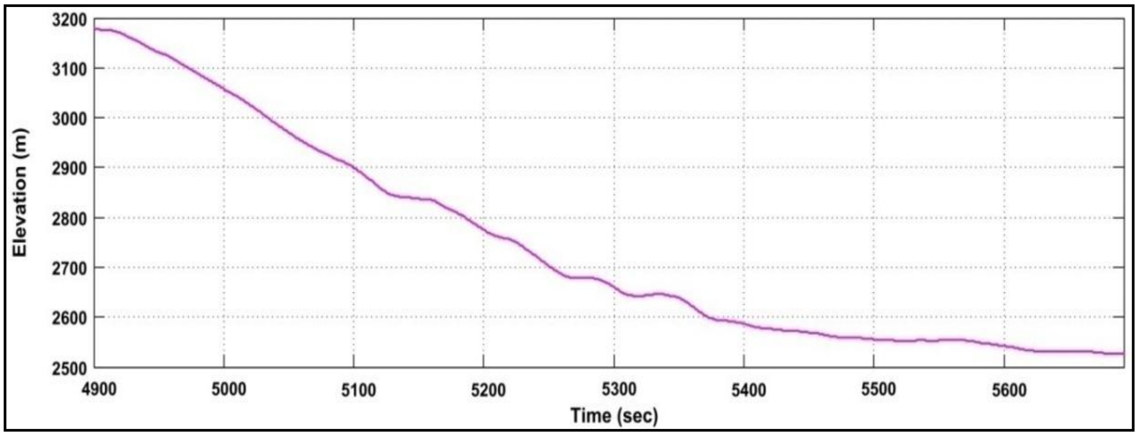


(e)

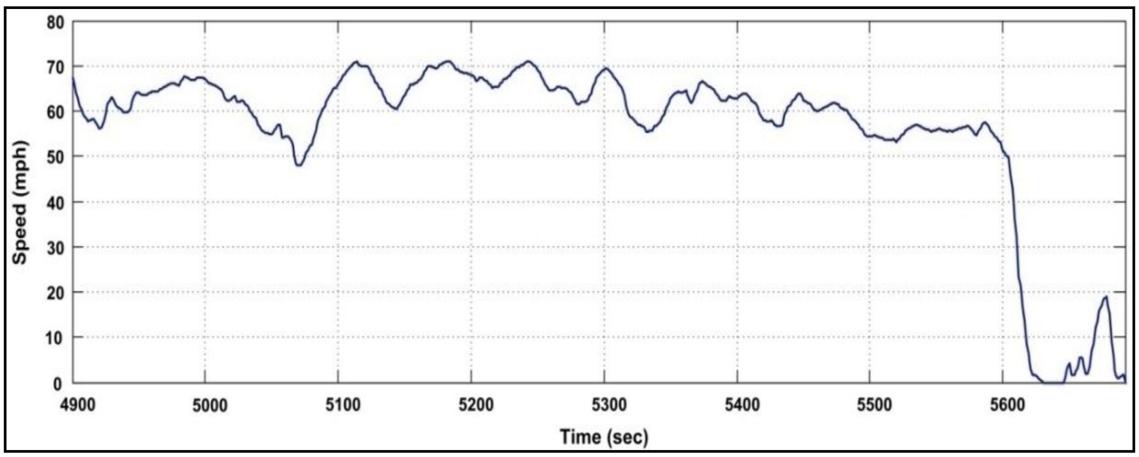
Figure 4.5 (a)-(e) Simulation results for mountain uphill region (NREL2VAIL) driving cycle

4.2.3 Simulation results of FCH downsized Vehicle for NREL2VAIL Cycle (downhill region)

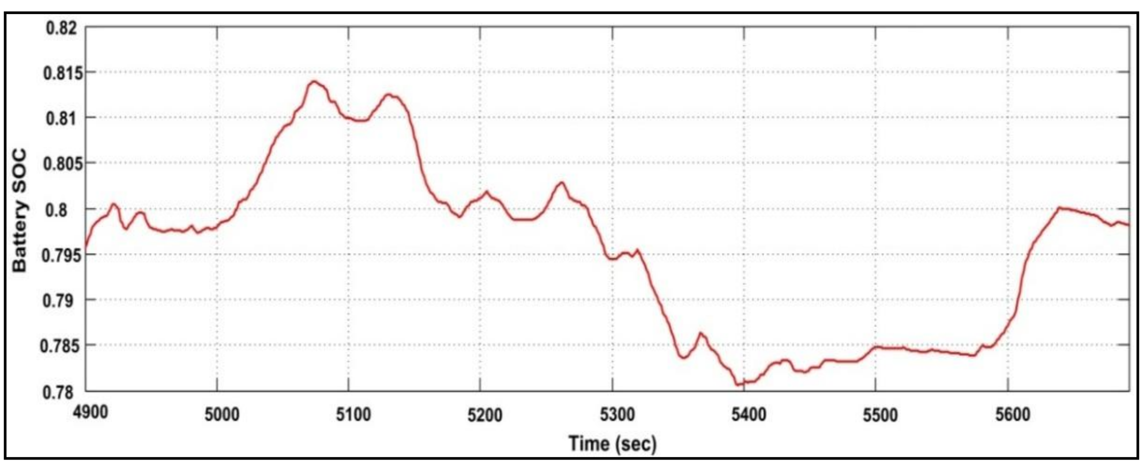
For downhill driving region, the road elevation, speed variation, battery SOC and motor power demand are shown in Figure 4.6 (a),4.6 (b), 4.6 (c) and 4.6 (d) respectively. It is found that, most of the tractive power supplied by battery pack only is shown in Figure 4.6 (e). At this juncture the fuel cell is switched to idle condition, so that the battery can work in two unique states: releasing to give extra energy to take care of the vehicle power demand or charging to spare the abundant energy generated by the fuel cell.


3200
3100
3000
2900
2800
2700
2600
2500
Elevation (m)
4900
5000
5100
5200
5300
5400
5500
5600
Time (sec)

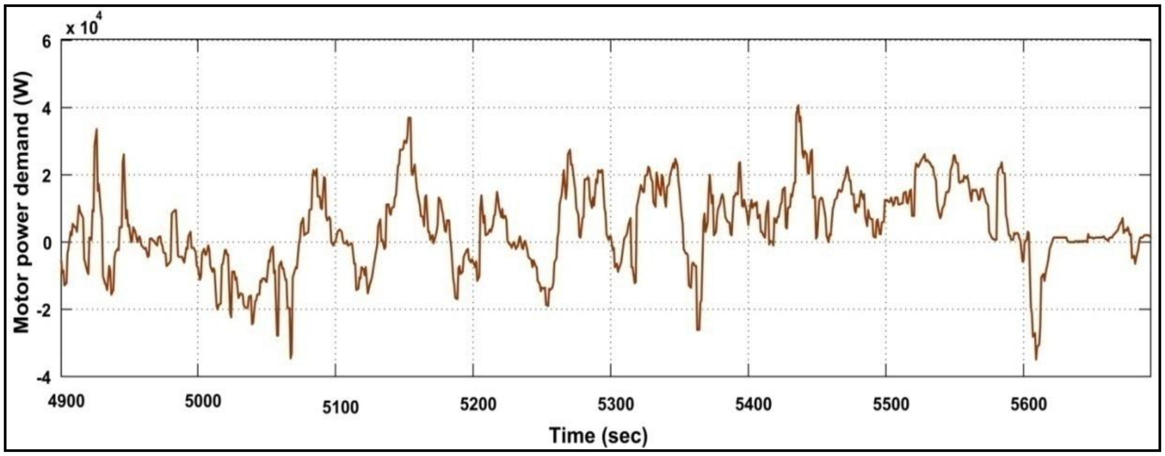
(a)


80
70
60
50
40
30
20
10
0
Speed (mph)
4900
5000
5100
5200
5300
5400
5500
5600
Time (sec)

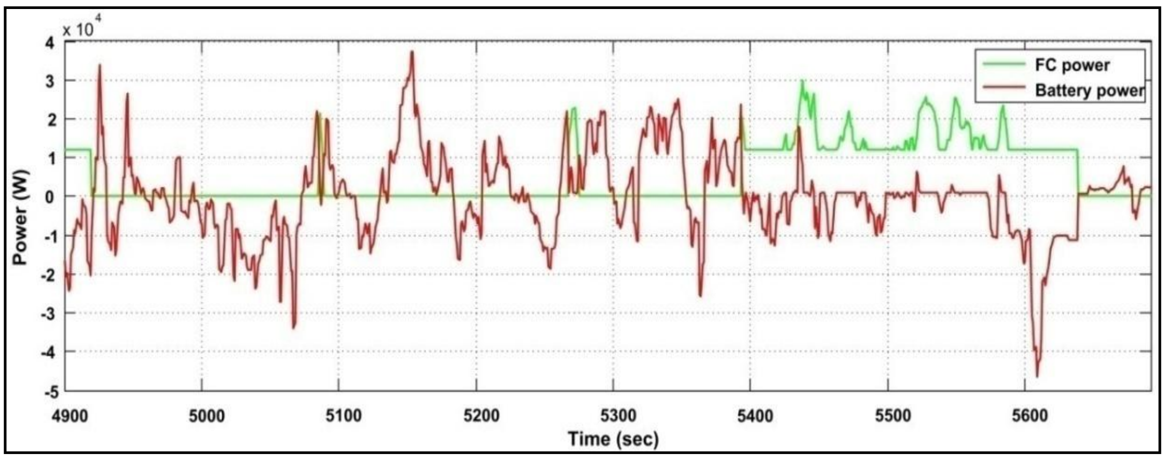
(b)


0.82
0.815
0.81
0.805
0.8
0.795
0.79
0.785
0.78
Battery SOC
4900
5000
5100
5200
5300
5400
5500
5600
Time (sec)

(c)



(d)



(e)

Figure 4.6 (a)-(e) Simulation results for mountain downhill region (NREL2VAIL) driving cycle

4.2.4 Acceleration and gradeability performance of FCH downsized vehicle

Table.4.3 represents the acceleration of the FCH downsized vehicle with respect to benchmark Toyota FCHV. The acceleration performance is shown in Table.4.3, it is observed that the acceleration times ranges between 0-62 m/h, 40-60 m/h and 0-85 m/h and it is minimized for FCH downsized vehicle, which validates the dynamic performance of the vehicle. Table 4.4 shows the gradeability performance which involves the maximum speeds achieved by the vehicle with respect to the percentage of grade. From the simulation results, it can be observed that the vehicle achieves 21.8 % grade foran FCH downsized vehicle in contrast to 19.1 % grade for a Toyota FCHV with a maximum speed of 55 mph. Table 4.5 and 4.6 show the energy usage (in kJ) of major components for FCH downsized vehicle in motoring and regenerative modes. The efficiencies and energy losses of major components of the vehicle are shown in the tables.

Table 4.3 Acceleration performance

Parameter	**Toyota FCEV**	**FCH Downsized**	**Change (%)**
Speed Range	Time (seconds)	Time (seconds)	
0-60 mph	9.0	7.5	- 16.67 %
40-60 mph	5.9	3.6	-38.9 %
0-85 mph	23	14.4	-37.3%
Max speed, mph	97.7	97.9	-

Table 4.4 Gradeability Performance

Maximum speed (mph)	**Toyota FCEV (%)**	**FCH Downsized(%)**	**Maximum Grade at 20 mph for Toyota FCHV (%)**	**Maximum Grade at 20 mph (FCH Downsized) (%)**
90	7.0	9.3	50.6	50.6
60	16.7	19.4		
55	19.1	21.8		

Table 4.5 Energy of major components in power mode (UDDS)

	Fuel in (kJ)	**Fuel out (kJ)**	**Fuel loss (kJ)**	**Efficiency**
Fuel		18053		0.51
Fuel converter	18053	9251	8802	
Energy storage	4826	4596	249	0.95
Energy stored	-20			
Motor	9014	7056	1957	0.78
Wheel	6579	6043	536	0.92
Aero			1275	
Rolling			1953	
Aux loads	958		958	

Table 4.6 Energy of major components in regenerative mode (UDDS)

	Fuel in (kJ)	**Fuel out (kJ)**	**Fuel loss (kJ)**	**Efficiency**
Motor	1384	950	433	0.69
Wheel	2815	2777	38	0.99
Braking			1270	

Table. 4.7 depicts the fuel cell power, motor power demand, battery pack energy capacity, voltage and average fuel economy of fuel cell hybrid (FCH) mid size car in comparison with benchmark Toyota FCEV for UDDS cycle. The Fuel cell power is reduced from 114 kW to 80 kW while the motor power demand remains same as 113 kW. Miles per gallon equivalent (MPGe) performance of FCH downsized vehicle achieves equivalent fuel economy with standard 2017 Toyota Mirai FCEV. The acceleration performance is improved for FCH downsized vehicle. The powertrain achieves an equivalent fuel economy of 67.67 MPGe (miles travelled per one gallon gasoline equivalent energy) for a FCH downsized vehicle in comparison with 2017 Toyota FCEV on mileage basis. Moreover, the driving range is also in compliance with benchmark vehicle.

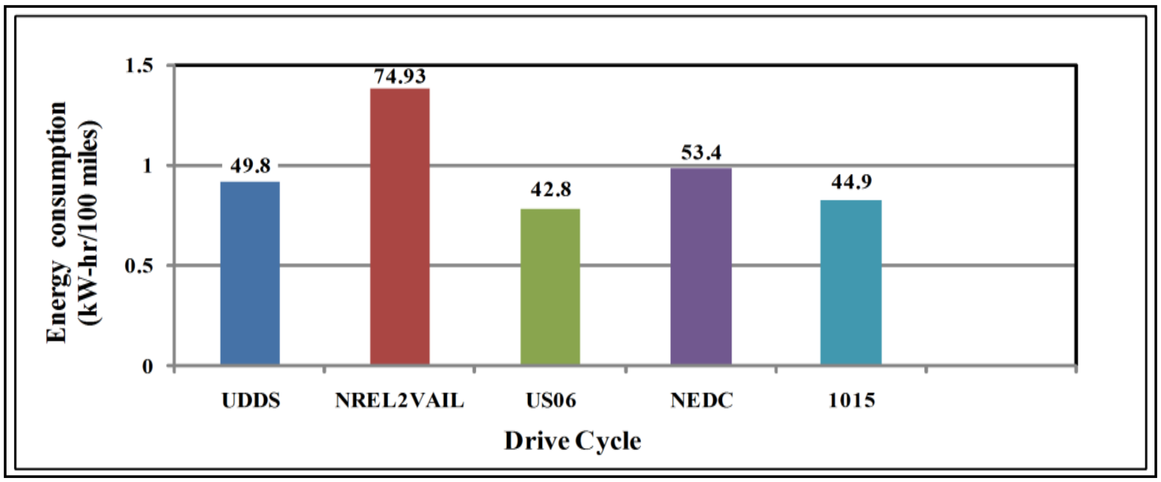
Table 4.7 Performance Comparison of FCH Downsized Vehicle with 2017 Toyota Mirai FCEV

Parameter	**2017 Toyota Mirai FCEV**	**FCH Downsized Vehicle**
Fuel cell power, kW	114	80
Motor power, kW	113	113
Battery pack, kWh	1.6	3.27
Battery pack voltage, V	244.8	503
Average fuel economy, MPG_e	67	67.67
Acceleration performance (0-60 miles), sec	9	7.5
Driving Range, miles	312	312

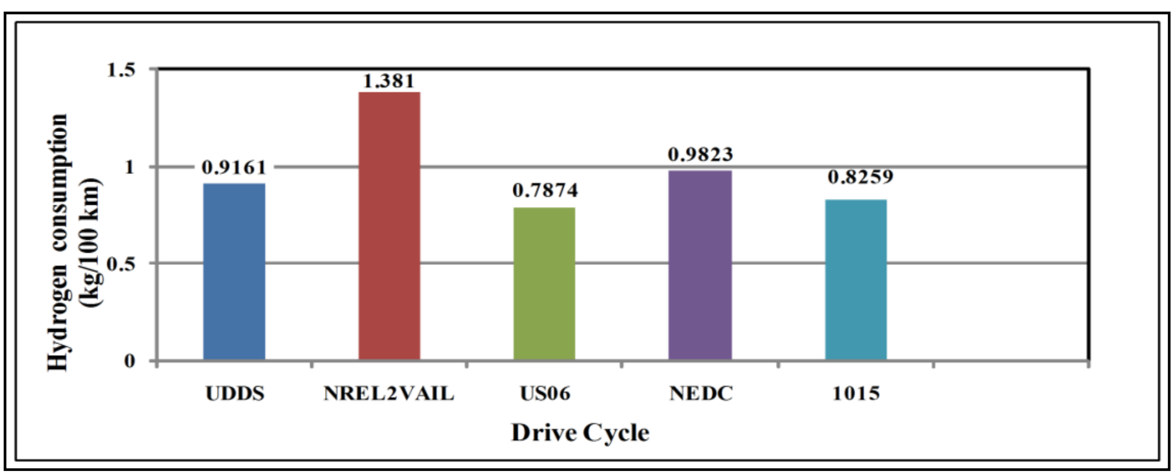
4.2.5 Fuel economy results of FCH downsized Vehicle for different drive cycles

Figure 4.7(a) shows an estimated energy consumption of FCHV for different drive cycles on the basis of kW-hr per 100 miles. NREL2VAIL (uphill region) drive cycle consumes more energy ie 74.93 kW-hr because the powertrain requires peak power during the uphill region, whereas UDDS consumes 49.8 kW-hr for city driving conditions. US06, NEDC and 1015 cycles consume 42.8, 53.4 and 54.9 kW-hr/100 miles respectively. Figure 4.7(b) depicts the prediction of hydrogen consumption of FCHV on the basis of kg of hydrogen per 100 kilometers. The estimated amounts of hydrogen consumption for

NREL2VAIL and NEDC drive cycles are 1.381 kg and 0.9823 kg respectively. (0.9161, 0.7874 and 0.8259). The estimated fuel economy of FCHV on MPGe basis is shown in Figure 4.7(c). The US06 cycle achieves 78.7 MPGe better fuel economy compared with other drive cycles. The UDDS cycle achieves 67.67 MPGe, which is equivalent to 2017 TOYOTA Mirai fuel economy ie 67 MPGe by downsizing the 30% fuel cell power for FCHV. Figure 4.7(d) illustrates the estimated driving range of FCHV for various driving cycles. The UDDS cycle achieves the equivalent driving range of 312 miles with benchmarked Toyota FCEV. The estimated ranges of NREL2VAIL, US06, NEDC and Japanese 1015 drive cycles are 207, 363, 291 and 346 miles respectively.



(a)



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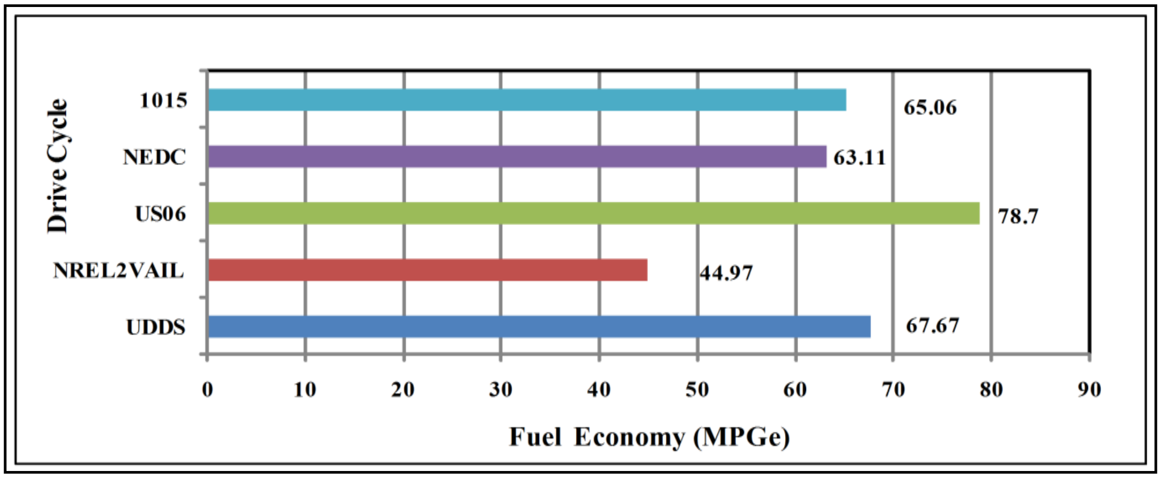

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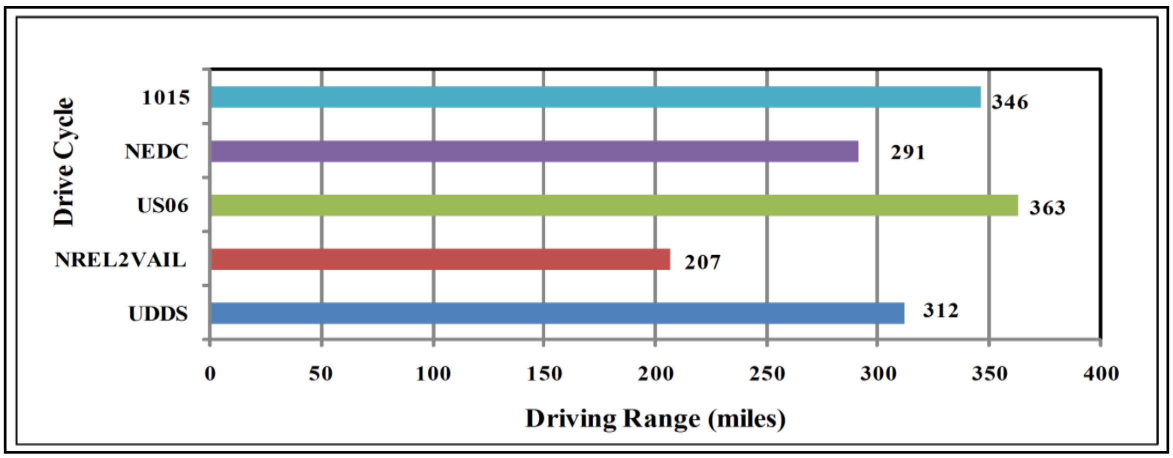


(d)

Figure 4.7 Fuel economy results (a) Energy Consumption (b) Fuel Consumption based on hydrogen usage (c) Fuel economy on miles per gallon equivalent (MPGe) basis (d) Driving range for various cycles.

The estimated cost reduction achieved for the downsized FCHV (estimated cost of Toyota Mirai Fuel Cell System (FCS) is $233/kW-net power at 1,000 systems per year production) is $7122 which is equivalent to approximately 26 % as shown in Figure 4.8.

It can be emphasized that 30 % downsizing in fuel cell power is compensated through equivalent battery storage capacity, while the estimated increase in battery cost is $800 for an additional battery pack of 1.6 kW-hr capacity ($500/kW-hr for Ni-MH batteries). The total power train cost is $20240, which is equivalent to 26% cost reduction in comparison with bench mark vehicle.

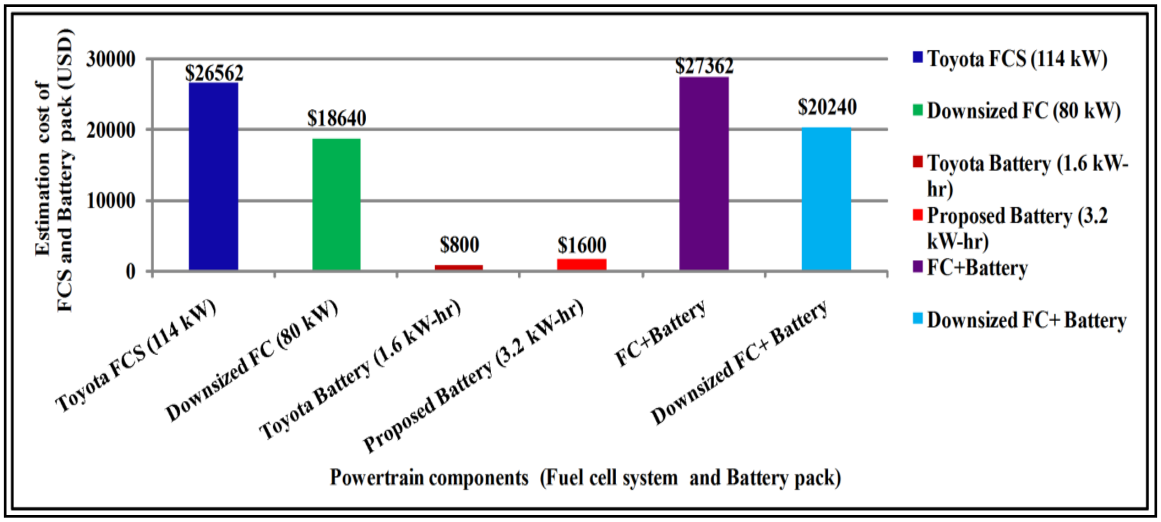


Figure 4.8 Cost estimation of proposed downsized Fuel cell system and battery pack

4.2.6 Estimation of battery Hybrid Pulse Power Characterization (HPPC) Test results

The HPPC (Hybrid Pulse Power Characterization) test is basically used to determine the dynamic performance of a energy storage system based on the power capability ,state of charge (SOC) and depth of discharge (DOD) characteristics and voltage utilization capability for a test profile that involves both discharge and recovery pulses. These characteristics are utilized to demonstrate the regeneration pulse and discharge pulse power capabilities at various SOC levels for both Power Assist goals (18-s discharge, 2-s regeneration) and Dual Mode goals (12-s discharge, 10-s regeneration). Both Power and energy capabilities are assessed using the battery pulse power test.

The HPPC test starts with a completely charged device after a 1-hour idle period and ends before it reaches 90% DOD, discharge of the cell at a C/1 rate to 100% DOD, and a final 1-hour rest. The voltages amid at each idle period are recorded to build the cell's OCV (open-circuit voltage) performance.

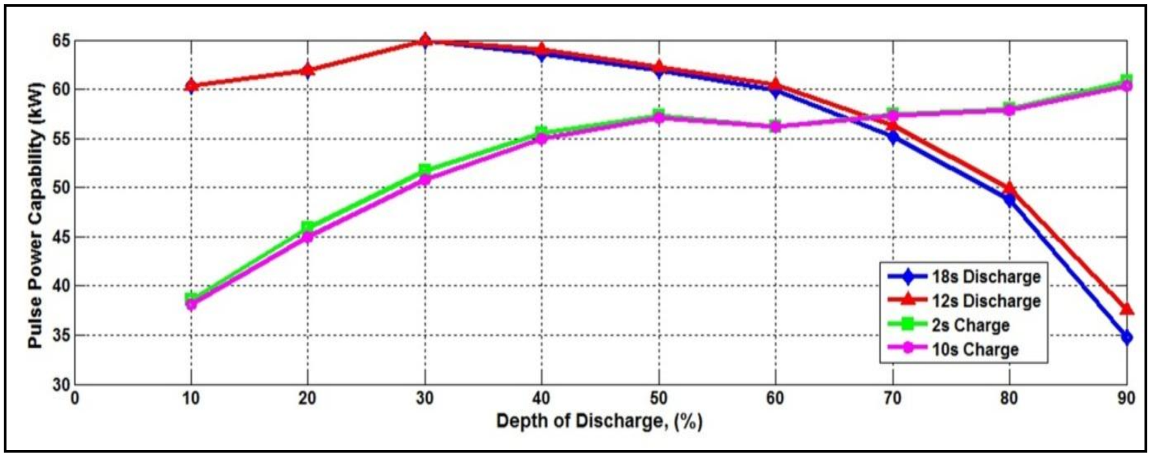


Figure 4.9 (a) Toyota FCEV

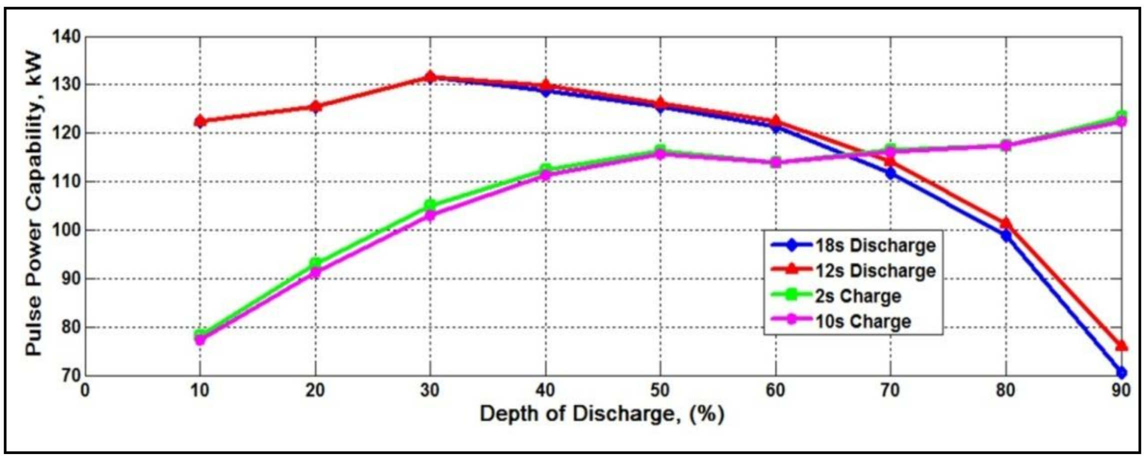


Figure 4.9 (b) Fuel cell downsized vehicle

Figures 4.9 (a) and 4.9. (b) depict the simulation results of battery charge and discharge peak powers for Toyota FCEV and downsized FCHV respectively. The peak pulse discharge power is 62 kW for a duration of 18 seconds and the peak pulse charge power is 57 kW for a duration of 10 seconds at 50 % DOD for Toyota FCHV while the peak pulse discharge power is 124 kW for a duration of 18 seconds and the peak pulse charge power is 113 kW for a duration of 10 seconds for FCH downsized vehicle at 50 % DOD. Thus, it indicates as increase in both discharge and charge peak pulse powers by 50 %. Therefore, downsizing the fuel cell power and increasing the battery modules will increase the battery pulse power capability and reduce the fuel cell stack size, cost and increases the vehicle performance.

4.2.7 Fuel cell power downsizing results

In the present work, FC power is downsized from 114 kW to 80 kW (30 % downsized) for the unchanged motor peak power demand of 113 kW, while the battery size is increased to 75 modules to compensate base power from the fuel cell. This configuration gives better performance for the hybrid powertrain. The acceleration times (Table.2) decrease by 16.67 %, 39.9% and 37.3 % for vehicle speed ranges of 0-60 mph, 40-60 mph and 0-85 mph respectively. By comparing all the results here, the conclusion is that downsized model has benefited in terms of dynamic and equivalent mileage performance of the vehicle.

4.2.8 Results and discussions

This chapter outlines the modeling, downsizing and performance of an FCH mid size car. The hybrid powertrain is modeled in ADVISOR which is basically developed in MATLAB/Simulink environment. The fuel economy result confirms that hybridization effectively improves the vehicle performance powertrain.

- The proposed downsized Fuel Cell Hybrid Vehicle (FCHV) is achieved an equivalent fuel economy of 67.67 MPGe with benchmark vehicle Toyota Fuel Cell Electric Vehicle (FCEV).
- Moreover, the acceleration performance also increased by 16.67 % from 0 to 60 mph speed range. It is concluded that the downsized vehicle attained good performance in terms of fuel economy and dynamic performance.

- By increasing the battery modules, the pulse power capability of battery pack was enhanced. From the cost analysis, (i.e. Figure 4.8) it can be emphasized that the estimated cost reduction was achieved for downsized FCHV is 26 % approximately.

CHAPTER - 5

HYBRIDIZATION PERFORMANCE OF FUEL CELL-BATTERY HYBRID ELECTRIC VEHICLE FOR NEDC, WLTC, IDC URBAN AND IDC HIGHWAY DRIVING CONDITIONS

5.1 Introduction

This chapter presents a new real time advanced drive cycle World harmonized Light Vehicle Test cycle (WLTC) is embedded into the ADVISOR and used for estimating the driving performance of downsized Fuel cell Hybrid Electric Vehicle. The development of WLTC was carried out under a program launched by the World Forum for the Harmonization of Vehicle Regulations (WP.29) of the United Nations Economic Commission for Europe (UN-ECE) through the Groupe de Rapporteurs on Pollution and Energy (GRPE). The aim of this project was to develop a World-wide harmonized Light duty driving Test Cycle (WLTC), to represent typical driving characteristics around the world, to have the basis of a legislative worldwide harmonized type certification test from 2014 onwards. In this work the performance of hybridization, cold start ability, maximum speed conditions of downsized FCHV for WLTC, NEDC, and Indian driving conditions are estimated. WLTC procedures include several WLTC test cycles applicable to vehicle categories of different power-to-mass (PMR) ratio. The PMR parameter is defined as the ratio of rated power (W) / curb mass (kg).

5.2 World-Wide Harmonized Light duty Test Cycle (WLTC)

World-wide harmonized Light duty Test Cycle (WLTC), a new legislative driving cycle is used to predict more accurately the exhaust emissions and fuel consumption under real-world driving conditions. It is developed under the Groupe de Rapporteurs on Pollution and Energy (GRPE) also called as Working Party on Pollution and Energy (GRPE) and sponsored by the European Union with Switzerland and Japan as members. India, Korea and USA have also actively contributed. The objective was to design harmonized driving cycle from ‘‘real world’’ driving data in different regions around the world, combined with suitable weighting factors. To this aim, driving data and traffic statistics of light duty vehicles use were collected and analyzed as basic elements to develop harmonized cycle.

The regional driving data and weighting factors were then combined in order to develop a unified database representing worldwide light duty vehicle driving behavior. From the unified database, short trips were selected and combined to develop a driving cycle that was as representative as possible of the unified database. Approximately 765,000 km of data were collected, covering a wide range of vehicle categories, road types and driving conditions. The resulting WLTC is an ensemble of three driving cycles adapted to three vehicle categories with different power-to-mass ratio (PMR). It has been designed as a harmonized cycle for the certification of light duty vehicles around the world.

Table. 5.1 Details of drive cycle

Parameter	NEDC	WLTC	IDC _urban	IDC_highway
Cycle time, sec	1184	1800	2689	881
Distance, miles	6.79	14.45	10.87	7.24
Max Speed, mph	74.56	81.6	38.87	47.22
Average Speed, mph	20.64	28.89	14.57	29.55
idle time, sec	298	235	267	3
No of stops	13	8	52	1

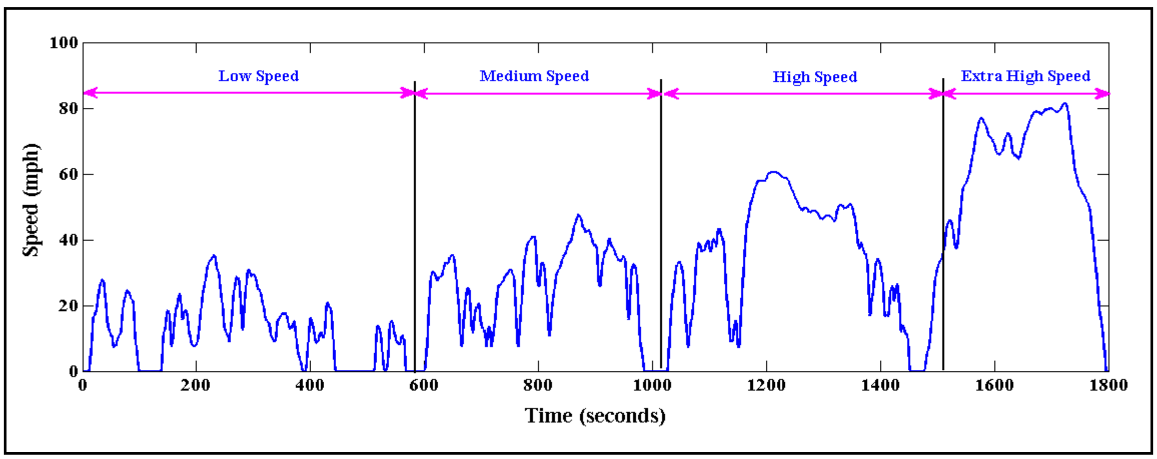


Figure 5.1 WLTC cycle for Class 3b vehicles

The real time advanced drive cycle World harmonized Light Vehicle Test cycle (WLTC) is embedded into the ADVISOR [135] and this estimates the driving performance of downsized Fuel cell Hybrid Electric Vehicle.

In this work, the performance of hybridization, cold start ability, maximum speed conditions of downsized FCHV for WLTC, NEDC, and Indian driving conditions are estimated. The main aim is to develop a gearshift procedure which simulates representative gearshift operation for light duty vehicle. The drive cycle information is shown in Table 5.1. With the maximum power-to-mass ratio, Class 3 is indicative of vehicles driven in Europe and Japan. Class 3 vehicles are classified into 2 sub categories according to their maximum speed: Class 3a with $v_{max} < 120$ km/h and Class 3b with $v_{max} \geq 120$ km/h. Selected parameters of the Class 3 cycles are given in Table. 5.2, and the different vehicle speeds for Class 3b are shown in Figure 5.1

Table.5.2 Categories WLTC Test cycle [136]

Category	**PMR, W/kg**	**V_max, km/h**
Class 3b	PMR>34	$V_{max} \geq 120$
Class 3a		$V_{max} \leq 120$
Class 2	34 ≥PMR > 22	
Class 1	PMR≤ 22	

PMR for present analysis is= (80000 W/1845 kg)= 43.36 (> 34); WLTC Class 3b cycle is considered.

Key features of WLTC Drive cycle

- More realistic driving behavior and Longer test distances.
- A greater range of driving situations (urban, suburban, main road, motorway).
- Higher average and speed maximum drive power.
- More dynamic and representative accelerations and decelerations.

5.3 New European Driving Cycle (NEDC)

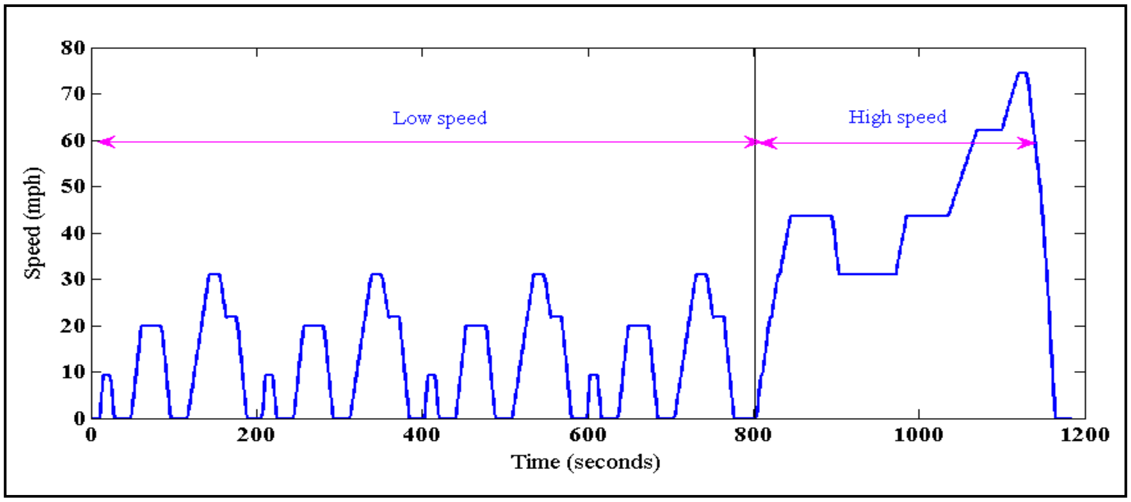


Figure 5.2 Speed profile of NEDC driving cycle

Figure 5.2 depicts the NEDC cycle which includes four urban driving cycles (UDC) characterized by low vehicle speed, low engine load, and low exhaust gas temperature, followed by one extra- urban driving cycle (EUDC) to account for more aggressive and higher speed driving.

5.4 Fuel cell system efficiencies for NEDC and WLTC drive cycles

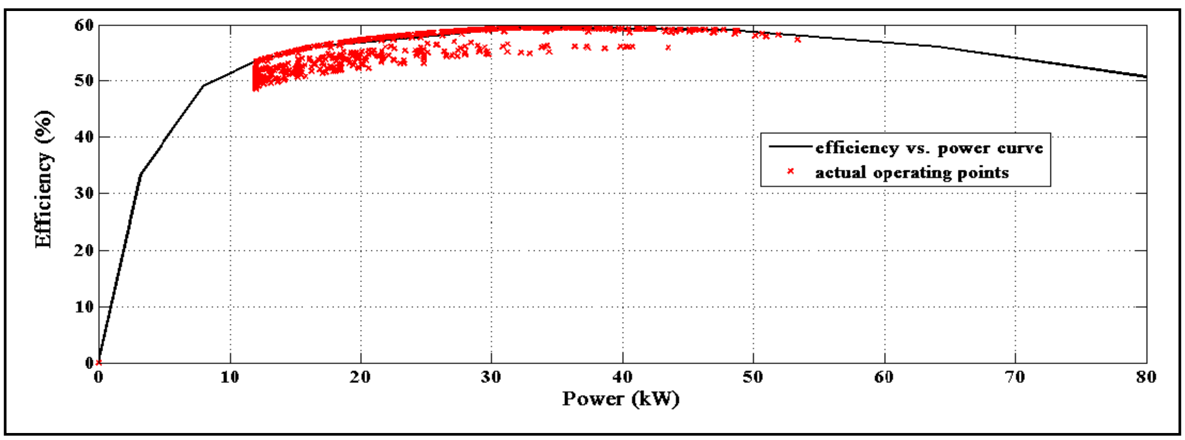


Figure 5.3 (a) Efficiency curve for NEDC drive cycle

Figure 5.3 (a) shows the fuel cell stack efficiency variation with operating power condition of fuel cell power of hybrid vehicle for NEDC driving condition. It can clearly be seen that the fuel cell operates at peak efficiency in 10 to 60 kW region. The maximum efficiency achieved at maximum power region due to low engine speed and low load is followed by aggressive and higher speed driving for NEDC driving cycle. Whereas, for the WLTC driving cycle, the maximum fuel cell efficiency (i.e. 10 to 40 kW region) is attained at low vehicle power demand is followed by steady speed condition. Figure 5.3 (b) depicts the efficiency variation with respect to vehicle power demand. The maximum efficiency of the operating region is lower for WLTC driving cycle, because the driving speed profile comprises of different low, medium and maximum speed conditions. Most of the time it is accelerating and decelerating over the whole cycle.

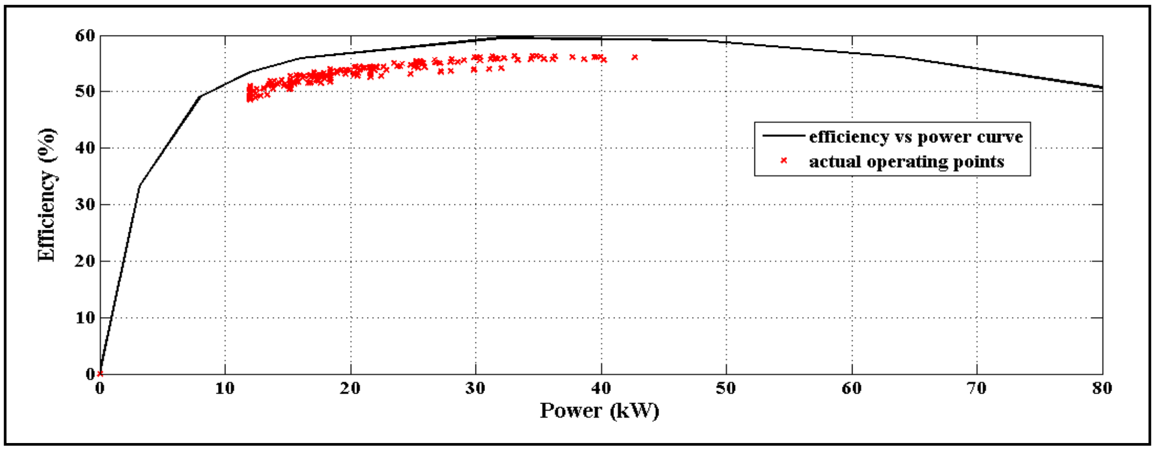


Figure 5.3 (b) Efficiency curve for WLTC drive cycle

5.5 Hybridization results for NEDC and WLTC driving cycles

$$\text{Hybrid ratio} = \frac{Pess}{Pess + Pfc} \qquad \text{(From the equation 4.1)}$$

Figure 5.4 (a) shows fuel economy in terms of miles per gallon gasoline equivalent (MPGGE) results for both NEDC and WLTC driving cycles. The initial increase in fuel economy is due to increase in battery size and remains relatively constant upto 60% hybridization, then it decreases towards hybrid ratio=1 (EV mode) due to lack of fuel cell power assistance. Figure 5.4 (b) depicts how the fuel converter efficiency is relatively better for WLTC driving cycle than NEDC cycle. Table 5.3 shows the fuel economy results at different hybrid ratio levels for various drive cycles on energy generation basis per 100 miles. The new WLTC drive cycle achieved about 50% more energy content compared with NEDC drive cycle at 60 % hybridization level.

Table 5.3 Fuel economy results for different drive cycles

			MPGGE (kWhr/100 miles)					
Hybrid ratio	**FC power**	**ESS power**	**US06**	**UDDS**	**NEDC**	**WLTC**	**IDC_urban**	**IDC_high way**
0	80	0	39.2	29.3	36.2	50.4	22.8	44.2
0.1	72	8	54.2	51.9	54	102	44	59.8
0.2	64	16	45.9	52.4	49.2	97	46.2	60
0.3	56	27	44.4	52.1	48.4	97.6	48.8	61.6
0.4	48	34	43.1	54.8	49	99.9	50.1	63.3
0.5	40	40	43.1	55.8	49.6	102	51.4	65.7
0.6	32	49	42.7	57.6	50	105.2	53.6	68
0.7	24	56	44.1	59	48.7	106.8	54.1	69.4
0.8	16	64	47.4	60.5	53.6	109	56.5	71.6
0.9	8	72	65.1	59.8	63.7	121.7	58.5	69
1	0	81	36.9	36.9	36.9	36.9	36.9	36.9

The energy storage system (ESS) converter efficiency is initially better for WLTC drive cycle and increases gradually towards higher hybridization values but, it is lower than the NEDC efficiency. Better converter efficiency is achieved for NEDC drive cycle from 0.2 to 0.8 hybrid ratio in Figure 5.4 (c); then it falls down at higher hybridization values, which is due to the low speed and low load condition of the drive cycle and frequent stops in urban drive conditions. The lower efficiency for WLTC is due to higher speed driving nature. The energy converter efficiency gradually increases for Indian urban driving cycle and decreases for US06 cycle in Figure 5.4 (d), this is due to the city driving behavior of IDC urban cycle and an aggressive acceleration demand from US06 cycle.

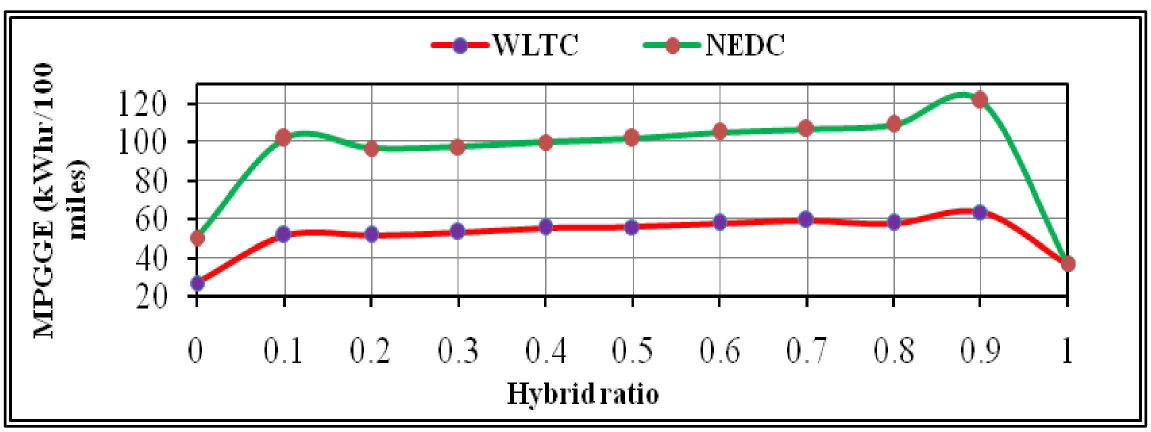


Figure 5.4 (a) Energy consumption over NEDC and WLTC cycles

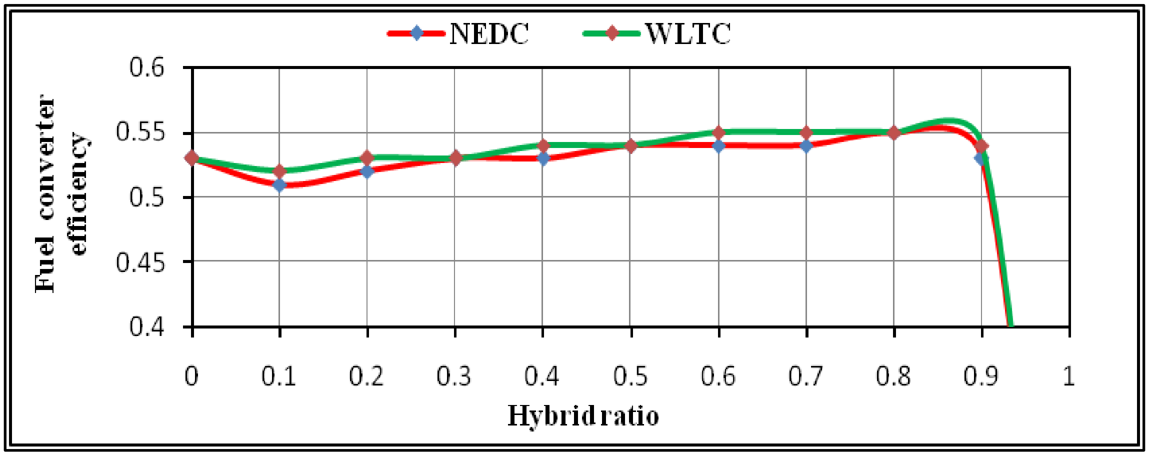


Figure 5.4 (b) Fuel converter efficiency over NEDC and WLTC cycles

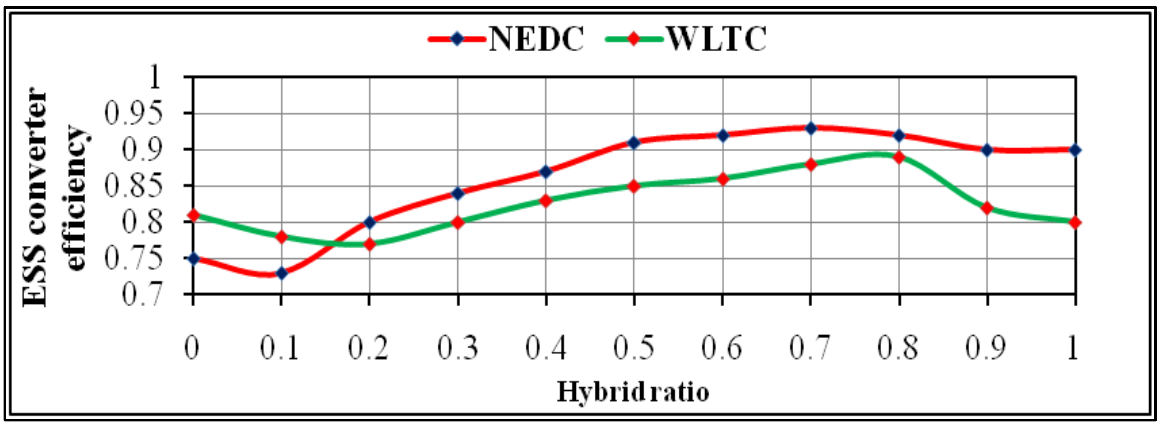


Figure 5.4 (c) ESS converter efficiency over NEDC and WLTC cycles

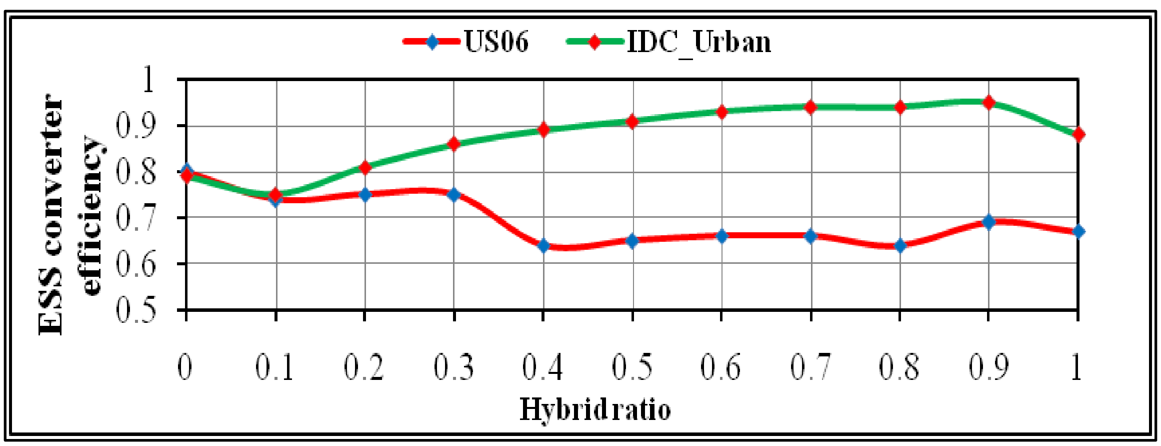


Figure 5.4 (d) ESS converter efficiency over US06 and IDC urban cycles

5.5.1 Component powers at cold start and maximum speed conditions for NEDC driving cycle

The component powers like motor power demand, fuel cell power and battery power over the driving cycle are shown in Figure 5.5 (a). The fuel cell is on and off frequently in low speed urban driving condition of NEDC cycle. Fuel cell produces power for low speed and average motor power demand of the hybrid powertrain. During high speed and accelerating conditions both fuel cell and battery assist the vehicle demand power.

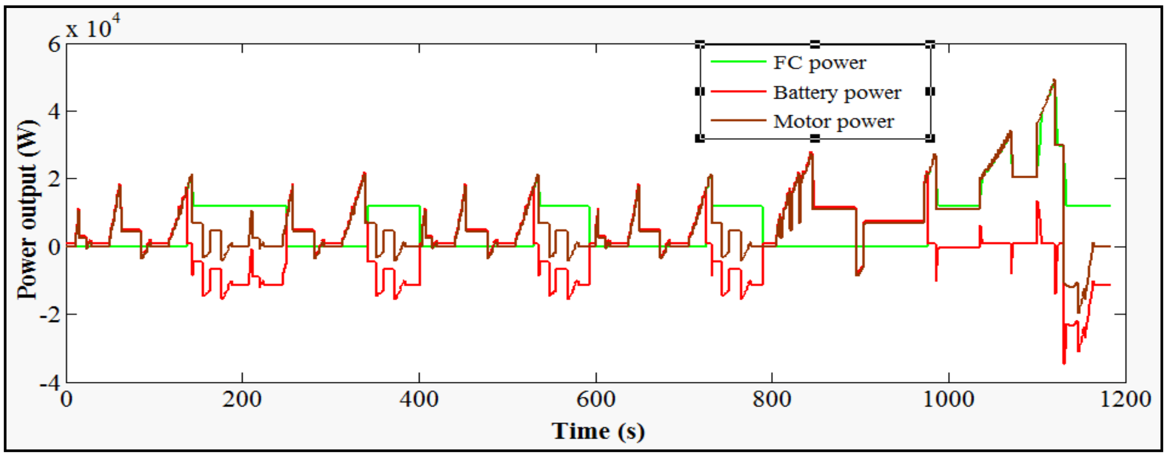


Figure 5.5 (a) Power output over NEDC driving cycle

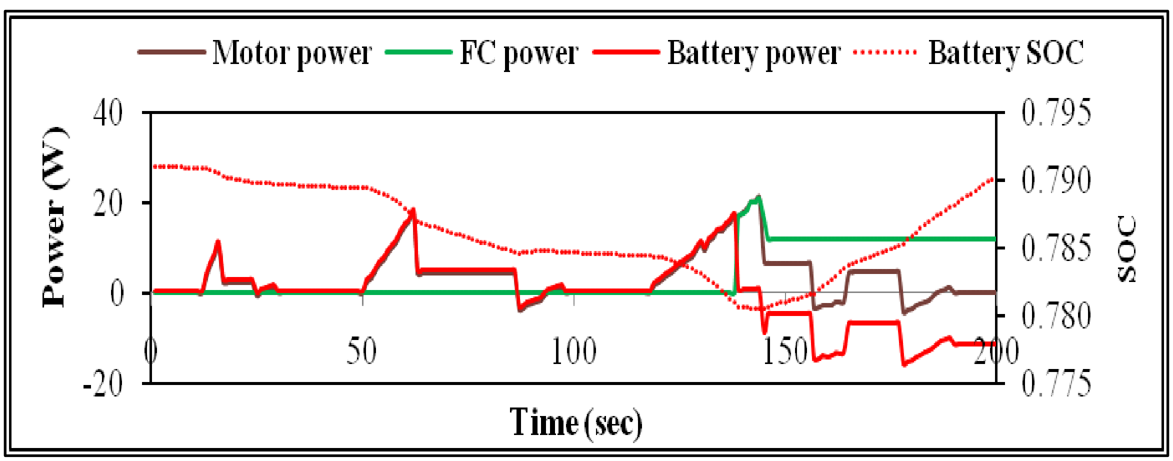


Figure 5.5 (b) Power at cold start condition over NEDC driving cycle

Cold start condition: For the cold start condition of up to 200 seconds, shown in Figure 5.5 (b), the low motor power demand is assisted by battery power only. At 140th second the power demand from motor is more, which both fuel cell and battery produce required power for vehicle. When demand from the motor power reduces, fuel cell supllies the vehicle average power demand of vehicle; in the interim battery unit gets charged.

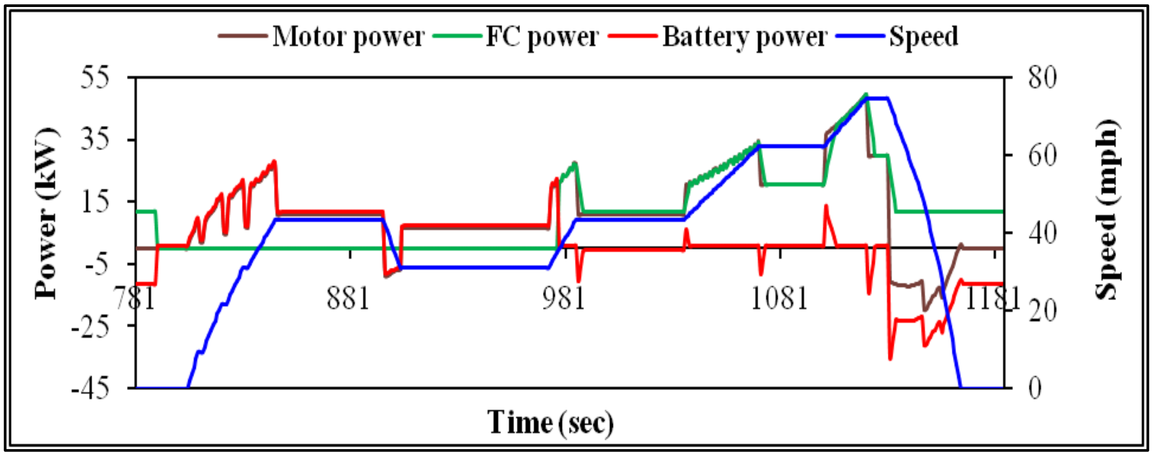


Figure 5.5 (c) Power at maximum speed condition over NEDC driving cycle

High speed condition: The high speed condition considered for this analysis is from 781 to 1181 seconds of the total NEDC driving cycle. In high speed condition, most of the power demand by motor is supplied by both fuel cell and battery. Meanwhile, the low power demand of the vehicle is assisted by the battery only. In the interim the fuel cell is inactive. The fuel cell supplies power for the vehicle acceleration and average power demand is shown in Figure 5.5 (c).

5.5.2 Component powers at cold start and extra high speed conditions for WLTC driving cycle

The component powers like motor power demand, fuel cell power and battery power over the WLTC driving cycle for different speed conditions are shown in Figure 5.6 (a).The fuel cell is on and off frequently in low and medium speed driving condition of WLTC cycle. For high speed and extra high speed conditions of drive cycle, fuel cell assisted the power demand along with battery pack. WLTC cycle gives real world performance compared with NEDC cycle due to different speed profiles.

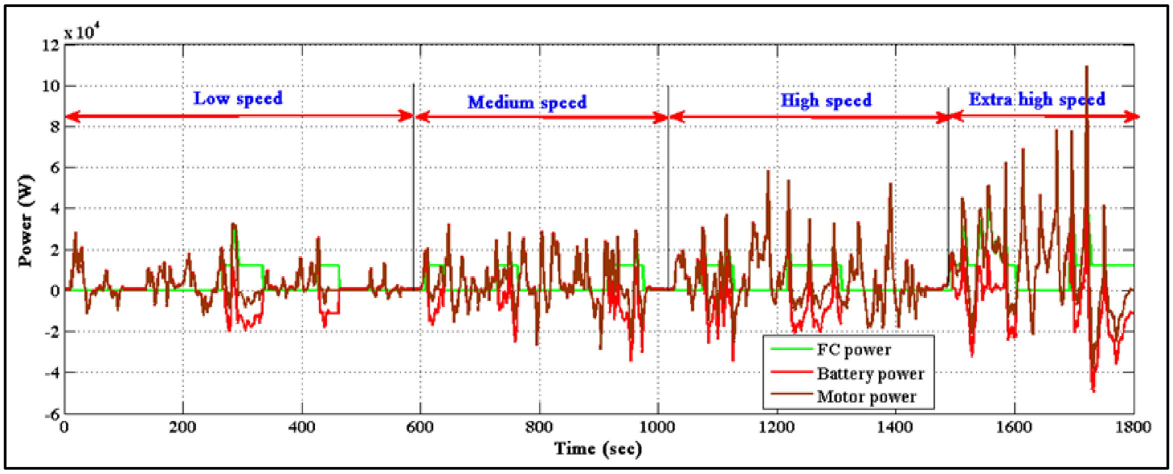


Figure 5.6 (a) Power at different speeds over WLTC driving cycle

Cold start condition: For the cold start condition of up to 300 seconds, shown in Figure 5.6 (b), about 90% of the power demand in cold start condition is supplemented by battery only.When the required power increases, then both fuel cell and battery assist the vehicle. Meanwhile, if the vehicle demand power decreases during the braking, the average power demand is supplied by the fuel cell only in interim battery charged by regenerative braking energy.

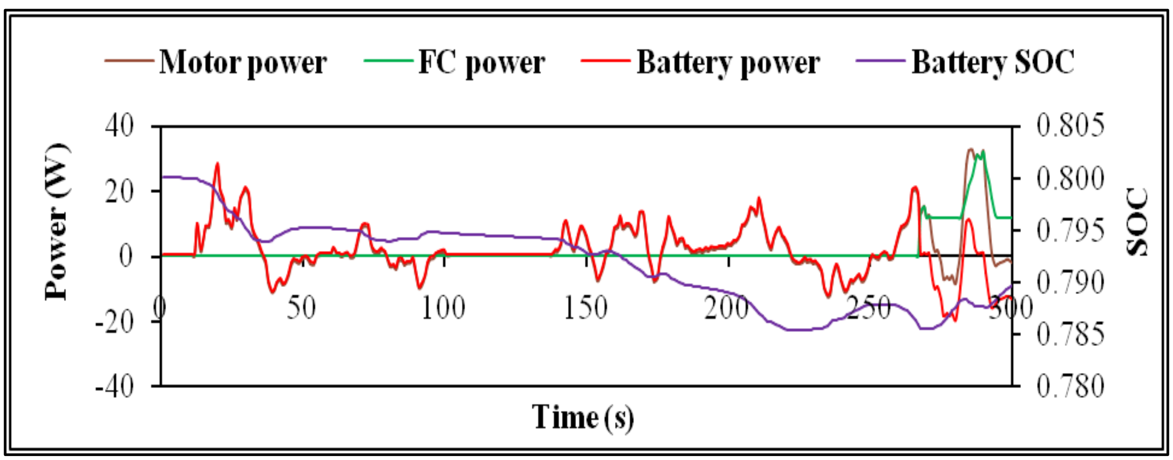


Figure 5.6 (b) Power at cold start condition over WLTC driving cycle

Extra high speed condition: The extra high speed condition considered for this analysis is from 1478 to 1778 seconds of the total WLTC driving cycle. In extra high speed condition, most of the power is supplied by the both fuel cell and battery. Meanwhile, low power and average power demand of vehicle is assisted by fuel cell only, while in the interim, battery gets charged by the fuel cell as shown in Figure 5.6 (c). When the vehicle is in braking condition, the battery gets charged by the regenerative energy. At this moment the fuel cell supplies power for the vehicle.

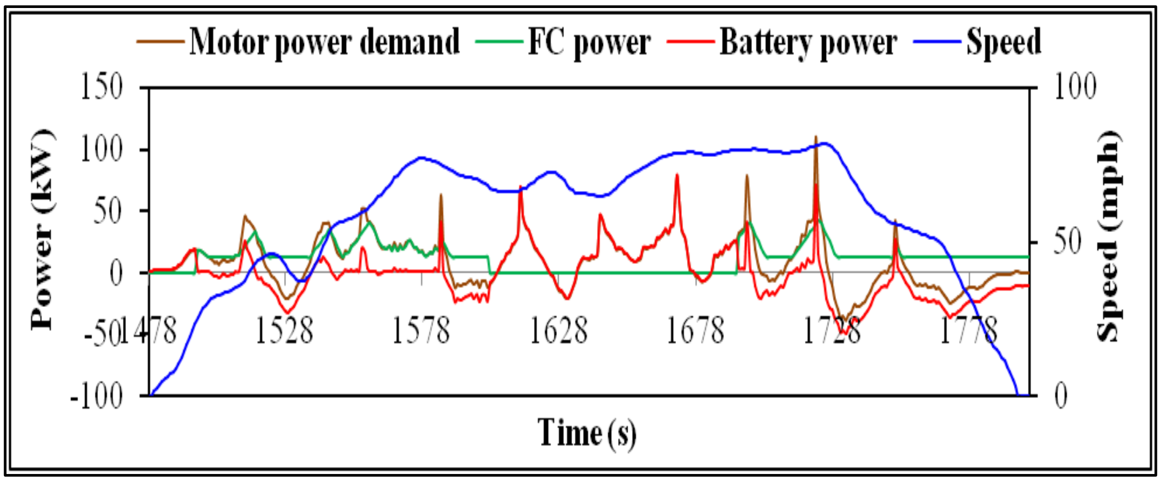


Figure 5.6 (c) Power at Extra high speed condition over WLTC driving cycle

5.6 Performance of Fuel cell -Ultracapacitor Hybrid Electric Vehicle

5.6.1 Speed, SOC and component powers variation over the WLTC cycle

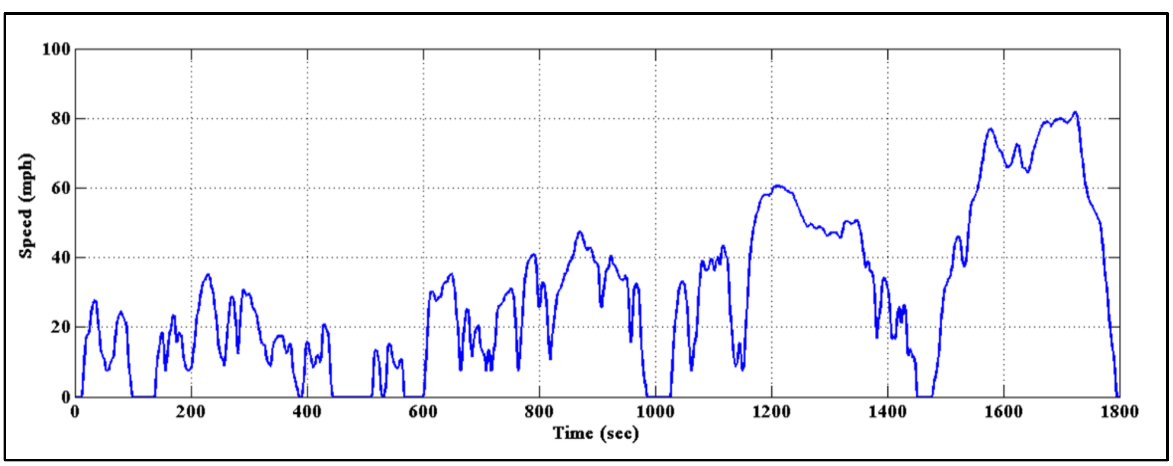


Figure 5.7 (a) Speed profile of WLTC driving cycle

The fuel cell hybrid powertrain is equipped with ultracapacitor pack instead of battery pack to estimate fuel economy, cold start, acceleration, gradeability and energy consumption on watt-hour/ mile basis. Ultracapacitor pack can supply assisted power for surge acceleration driving conditions. State of charge (SOC) variation of ultracapacitor is very low compared with battery energy storage system. The speed profile, SOC variation and component powers like motor power, fuel cell power and ultracapacitor power are depicted in Figures 5.7 (a), 5.7 (b) and 5.7 (c) respectively.

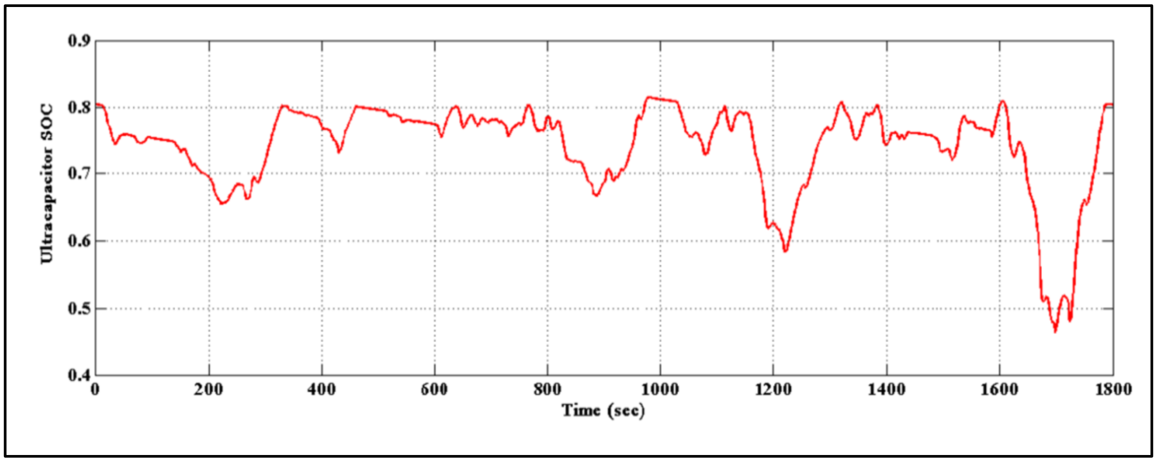


Figure 5.7 (b) Ultracapacitor SOC variation over the WLTC driving cycle

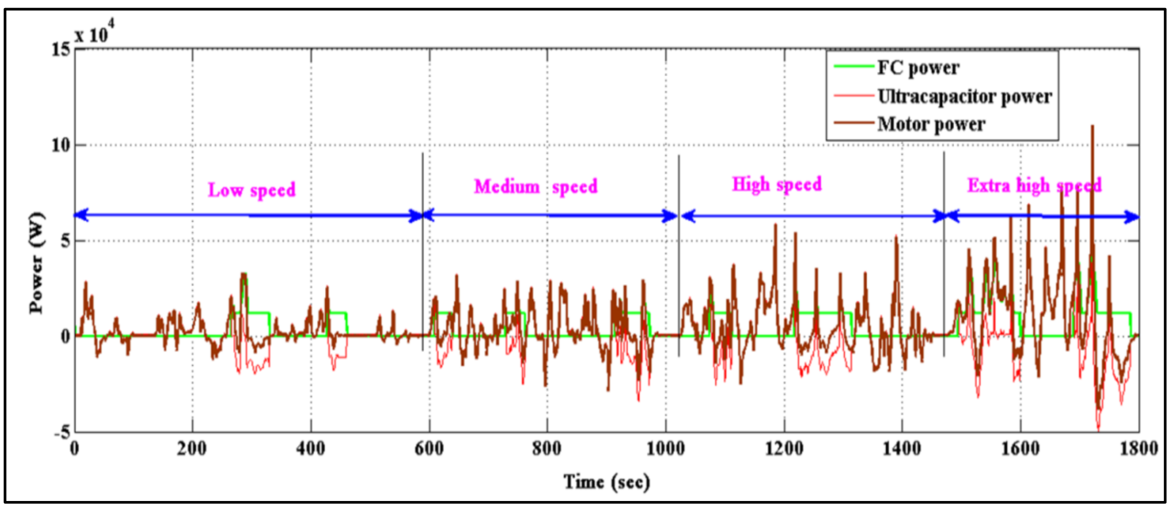


Figure 5.7 (c) Cycle power at different speed conditions over the WLTC driving cycle

5.6.2 Cold start, surge power and extra high speed conditions of WLTC and NEDC drive cycles for downsized Fuel Cell -Ultracapacitor HEV

Cold start condition: For the cold start condition of up to 300 seconds, shown in Figure. 5.8 (a), about 90% of the power demand is supplemented by ultracapacitor only. But, for intial startup condition, ultracapacitor can not assist the vehicle alone, because it has low energy density compared with battery. Both fuel cell and ultracapacitor supply power for cold start condition. When the required power increases, both fuel cell and ultracapacitor assist the vehicle. When the power demand decreases during the braking, the average power demand is supplied by the fuel cell only in interim ultracapacitor charged by regenerative braking energy.

WLTC Drive Cycle:

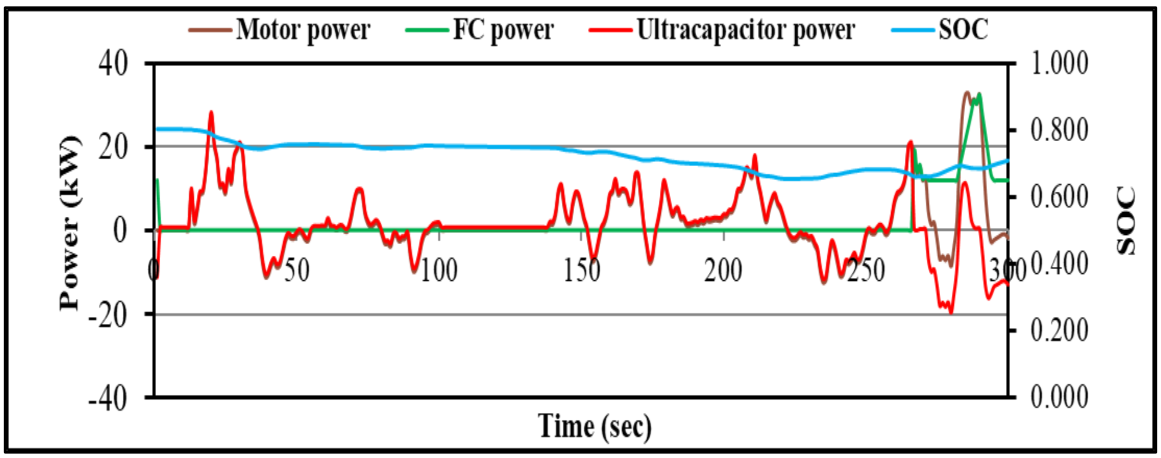


Figure 5.8 (a) Power at cold start condition over WLTC driving cycle

Surge power condition: Figure 5.8 (b) shows the surge power demand for a specific time period over the driving cycle. When the vehicle requires sudden power demand for the surge acceleration condition, it is supplied by the ultracapacitor only correspondingly and then it gets discharged and again recharged according to driving behavior.

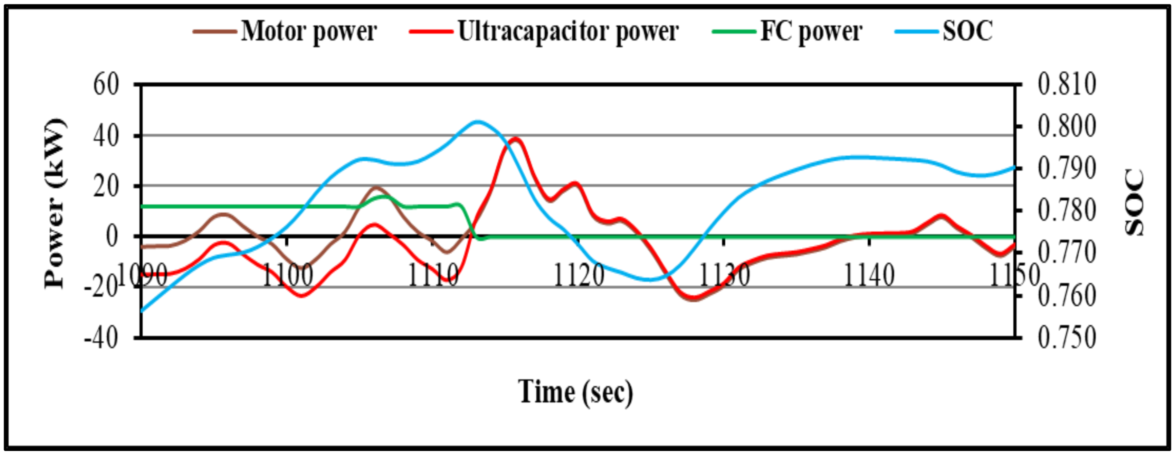


Figure 5.8 (b) Surge power demand over WLTC driving cycle

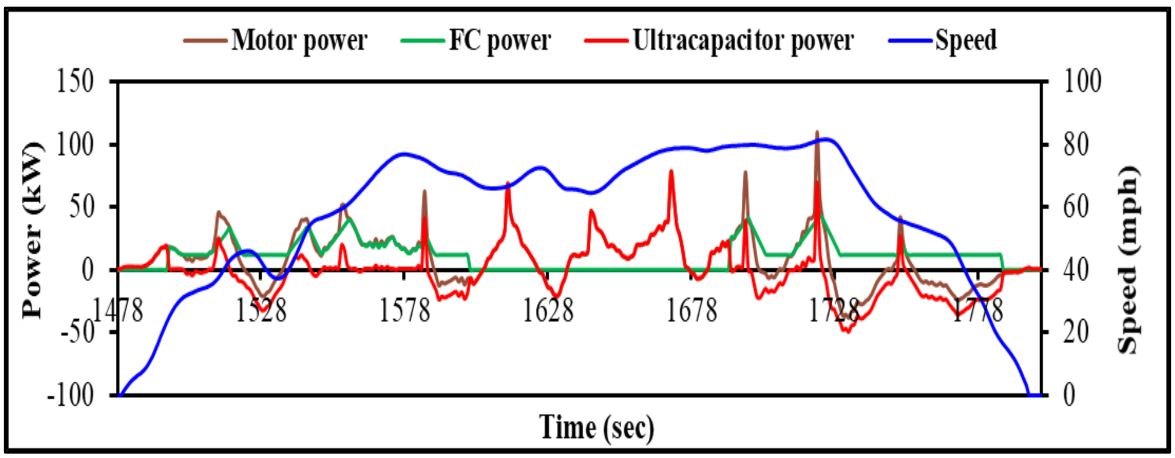


Figure 5.8 (c) Power at extra speed condition over WLTC driving cycle

Extra high speed condition: The extra high speed condition considered for this analysis is from 1478 to 1778 seconds of the total WLTC driving cycle shown in Figure 5.8 (c). In extra high speed condition, most of the motor demand power is supplied by both fuel cell and ultracapacitor. Meanwhile, the vehicle's low power and average power demand is assisted by the fuel cell only in the interim ultracapacitor that gets charged by the fuel cell. When the vehicle is in braking condition, ultracapacitor gets charged by the regenerative energy. At this moment the fuel cell supplies power for the vehicle's average power demand.

NEDC drive cycle:

Cold start condition: For the cold start condition up to 200 seconds is shown in Figure 5.9 (a). For the startup condition, fuel cell generates power before the wheel spins; once the vehicle moves at low speed the fuel cell can assist the motor low in power demand. Meanwhile, the ultracapacitor is charged by the fuel cell. After initial startup, the vehicle is in idle condition for 20 seconds during which time, both fuel cell and ultracapacitor are in inactive mode. At 120 seconds, after idle condition, the sudden vehicle power demand is supplied by the ultracapacitor only due its power density nature. It can be clearly seen that the, ultracapacitor SOC varies according to the motor power demand.

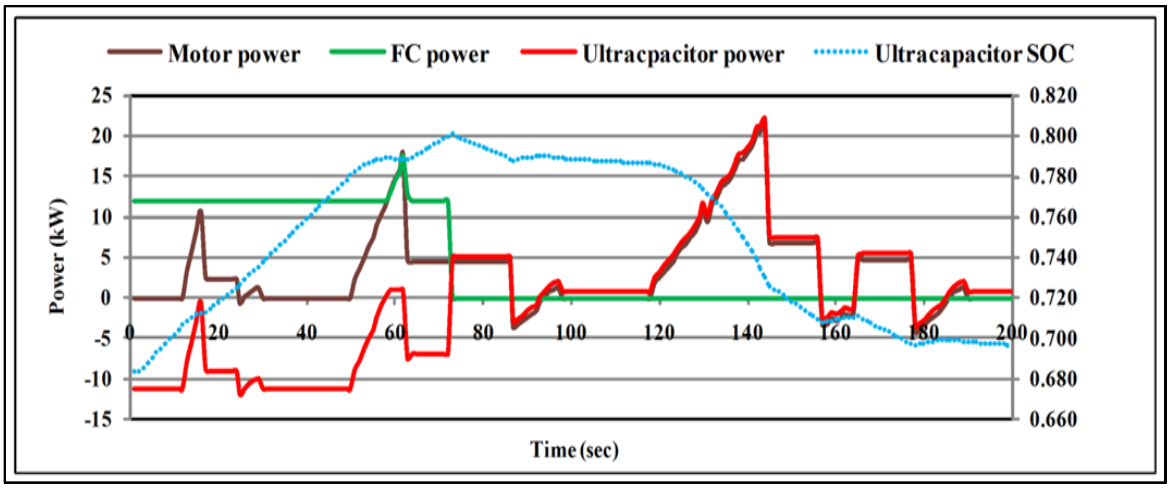


Figure 5.9 (a) Power at cold start condition over NEDC driving cycle

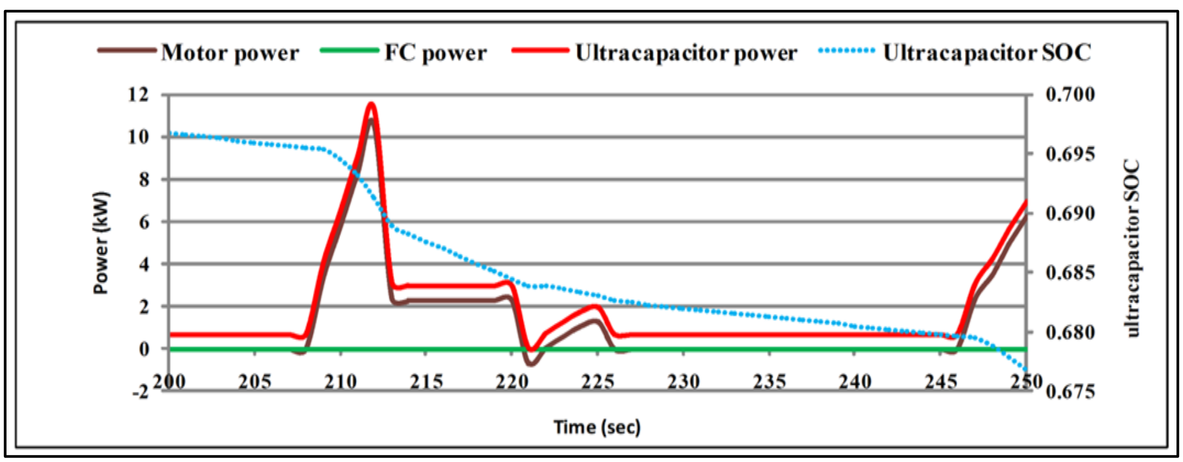


Figure 5.9 (b) Surge power demand over NEDC driving cycle

Surge power condition: Figure 5.9 (b) shows the surge power demand for a specific time instant after 210 seconds over the driving cycle. When the vehicle requires quick surge of power for sudden acceleration, the ultracapacitor alone delivers instantaneous power correspondingly and hence the ultracapacitor is discharged and again recharged according to driving behavior.

Extra high speed condition: The extra high speed condition considered for this analysis is from 781 to 1181 seconds of the total WLTC driving cycle shown in Figure 5.9 (c). In extra high speed condition, most of the motor demand power is supplied by both fuel cell and ultracapacitor. Meanwhile, the low power and average power demand is assisted by the fuel cell only when the interim ultracapacitor gets charged by the fuel cell. When the vehicle is in braking condition, ultracapacitor gets charged by regenerative energy. At this moment, the fuel cell supplies required power to vehicle.

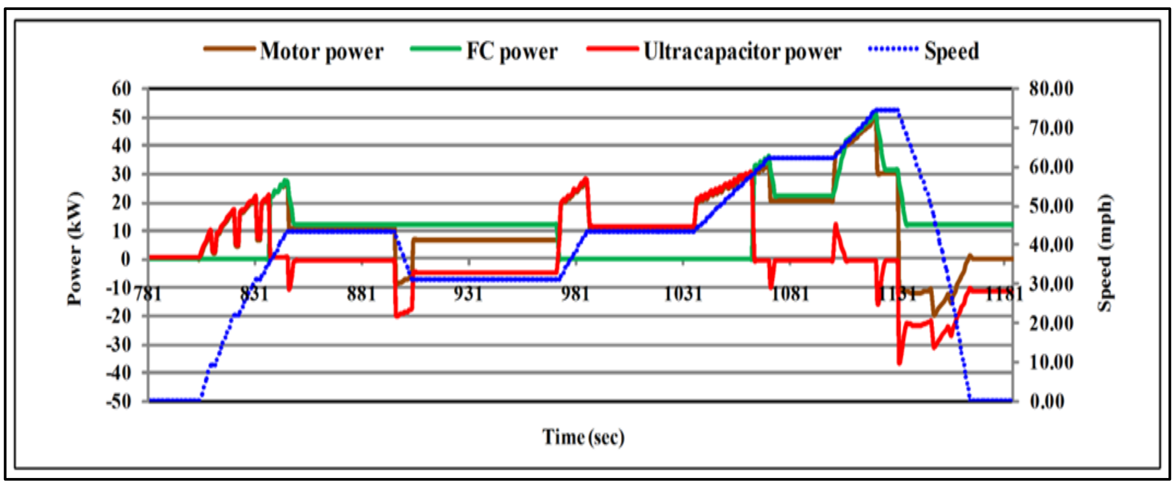


Figure 5.9 (c) Power at extra speed condition over NEDC driving cycle

5.7 Fuel economy (MPGGE), acceleration and gradeability performance

Fuel economy is measured in terms of miles per gallon gasoline equivalent (MPGGE), which indicates the amount of energy consumed in kW-hour/100 miles. MPGGE is decreases gradually with increase in road grade as shown in Figure 5.10 (a). About 50% of fuel economy decreases when road grade increases from 1% to 6%. Hence, the vehicle achieved better fuel economy at lower road grades in comparison with higher road grades. Figure 5.10 (b) shows the acceleration performance for three different powertrain configurations at 80%, 70%, 60% and 50% of the storage system state of charge (SOC) respectively. Downsized fuel cell-ultracapacitor hybrid power train gives better acceleration performance at higher (80% and 70%) ultracapacitor state of charge (SOC). Ultracapacitor cannot assist the vehicle during acceleration demand at its lower SOC values. On the other hand, the downsized fuel cell-battery configuration achieved equivalent acceleration performance in the battery SOC range of 80% to 40%. Pure battery configuration does not give better acceleration performance in comparison with earlier hybrid powertrains.

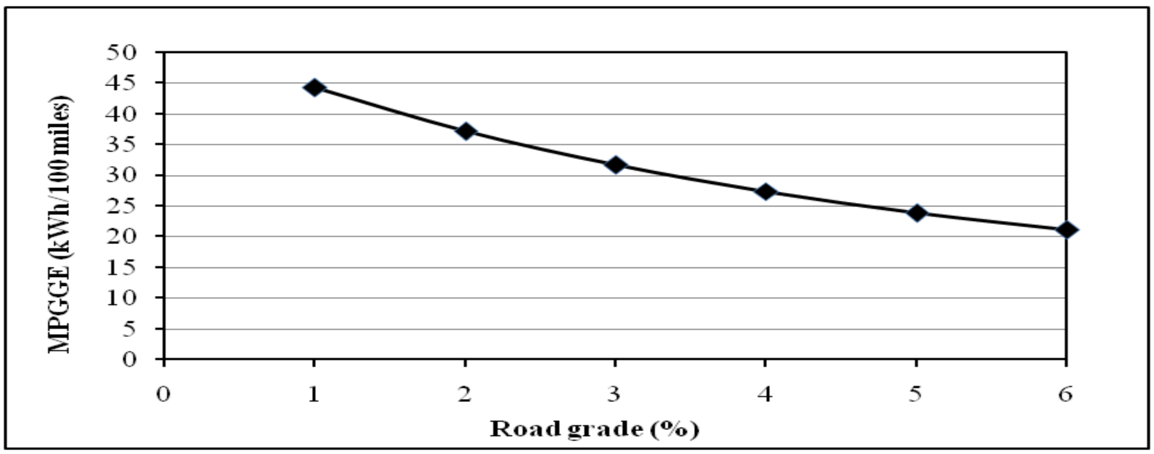


Figure 5.10. (a) MPGGE vs. Road grade

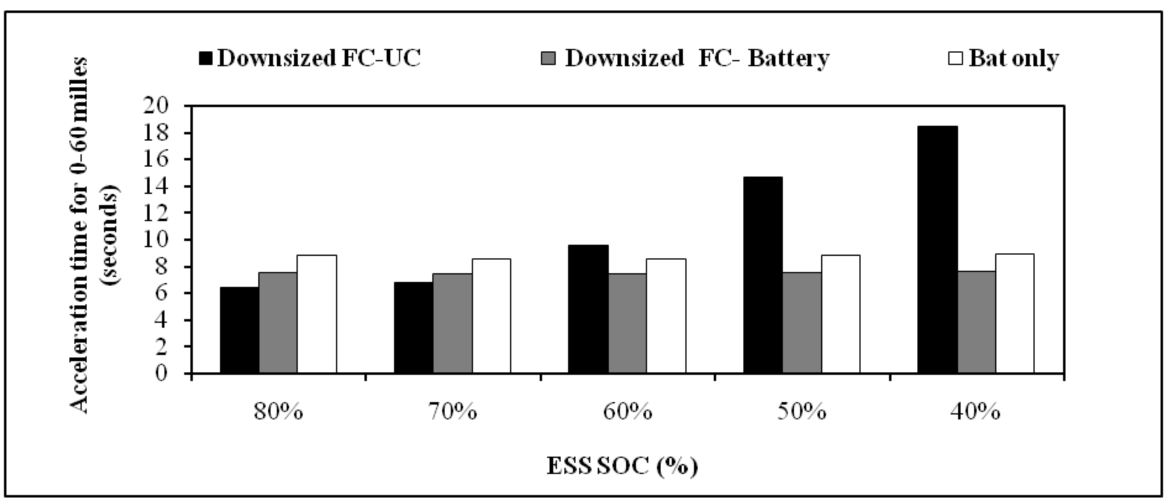


Figure 5.10 (b) 0-60 mph acceleration time vs. SOC

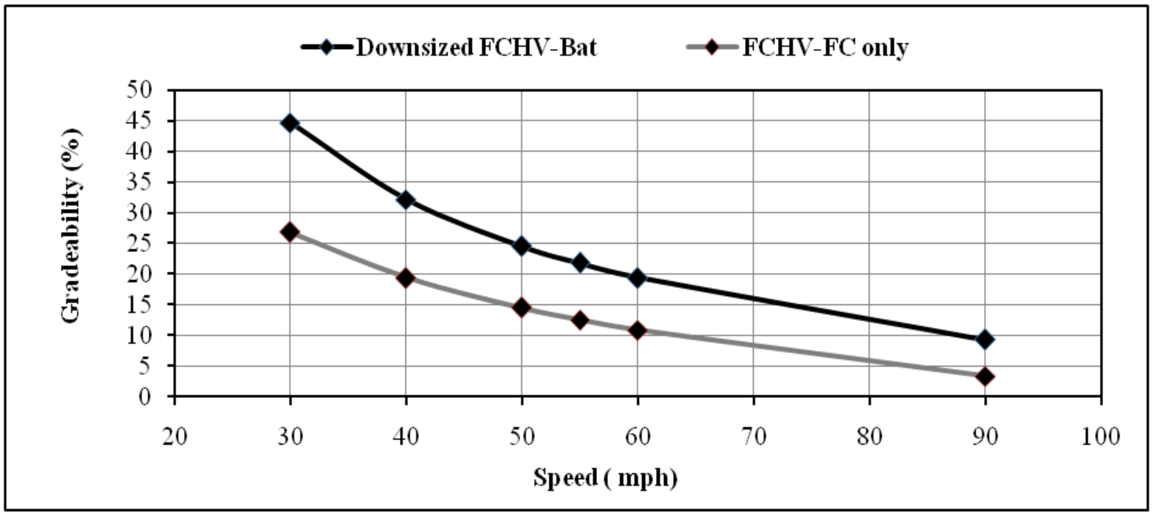


Figure 5.10 (c) Gradeability vs. Speed

Vehicle speed and gradeability are inversely proportional to each other. The maximum possible gradeability is achieved at low speed condition, and it gradually decreases with respect to increase in speed as shown in Figure 5.10 (c). It can be seen that 40% gradeability performance is achieved for fuel cell-battery configuration in comparison with pure fuel cell vehicle. The maximum tractive effort is available at maximum torque level condition, where the vehicle achieves maximum gradeability performance.

5.8 FCHV cold start performance at -30^0 C for different drive cycles

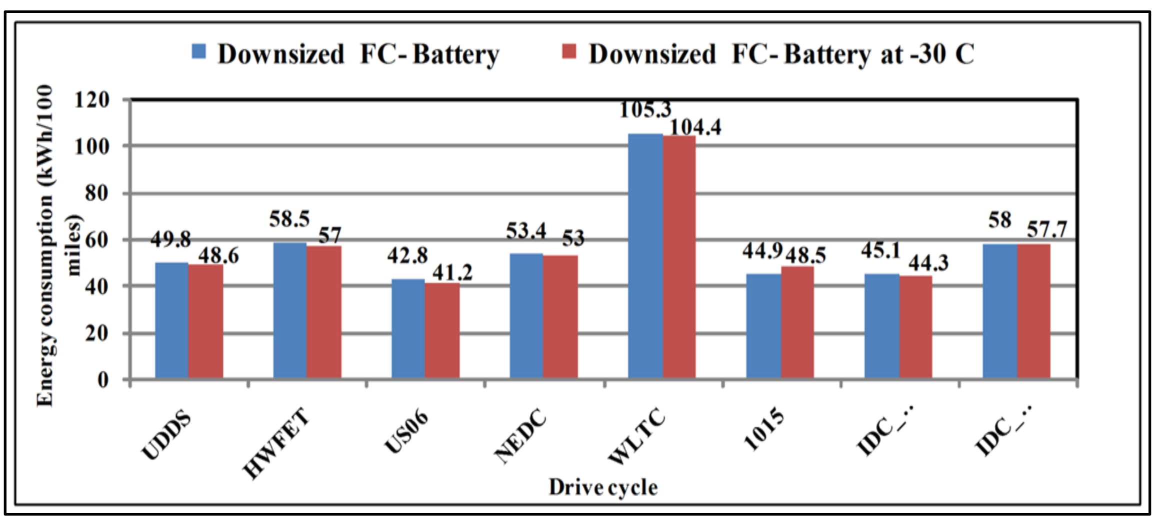


Figure 5.11 (a) Fuel cell - battery cold start performance at -30^{0}C

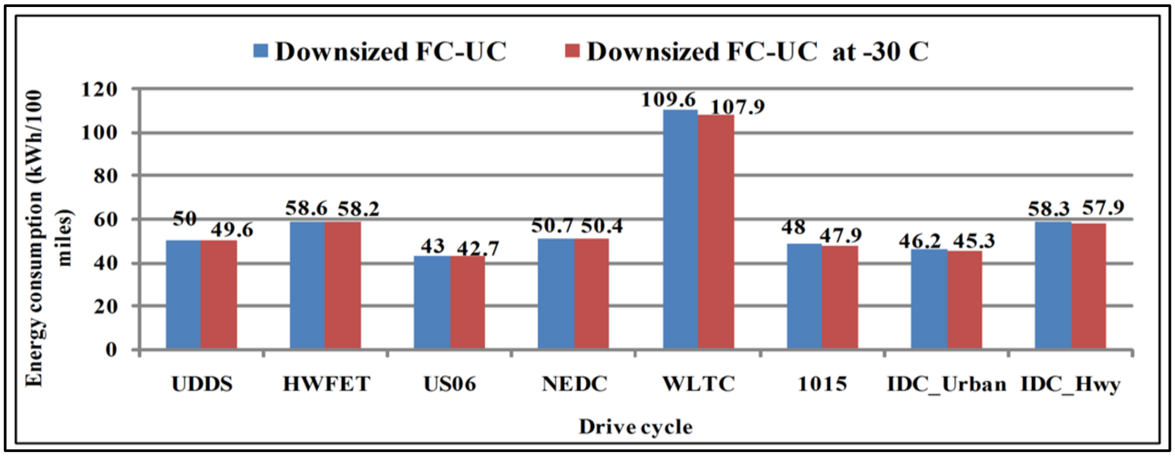


Figure 5.11 (b) Fuel cell - ultracapacitor cold start performance at -30^0 C

The cold start fuel economy performance of both fuel cell-battery and fuel cell-ultracapacitor hybrid powertrains for different drive cycles are shown in Figure 5.11(a) and Figure 5.11 (b) respectively. For both hybrid energy storage powertrains. WLTC drive cycle achieved better fuel economy among other drive cycles. The fuel cell - ultracapacitor hybrid powertrain claims relatively better cold start performance (i.e. at -30^0 C) in comparison with fuel cell- battery configuration due its higher cold start capability nature. Ultracapacitors can assist the vehicle even at -40^0 C ambient condition.

5.9 Fuel economy performance of FCHV- battery and FCHV-ultracapacitor HEV's for different drive cycles

Figure 5.12 (a) shows an estimated fuel economy in terms of energy consumption of FCHV for different drive cycles on the basis of kW-hour per 100 miles for both fuel cell-battery and fuel-ultracapacitor powertrains. The downsized fuel cell-ultracapacitor powertrain delivers approximately 4% more energy than fuel cell-battery combination powertrain for WLTC driving cycle. NEDC delivers 53.4 kW-hour better fuel economy with battery hybrid powertrain in comparison with ultracapacitor hybrid powertrain which delivers 50 kW-hour. The other driving cycles such as, UDDS,HWFET, US06, Japanese 1015 and Indian driving cycles achieved relatively equivalent fuel economy for both hybrid energy storage powertrains. The WLTC cycle consumes relatively more hydrogen than NEDC cycle for fuel cell- ultracapacitor hybrid powertrain. This is because the WLTC cycle has high speed driving patterns. Meanwhile, the fuel cell-battery combination consumes comparatively less hydrogen a kg per 100 km basis. Hydrogen consumption for different driving cycles are shown in Figure 5.12 (b).

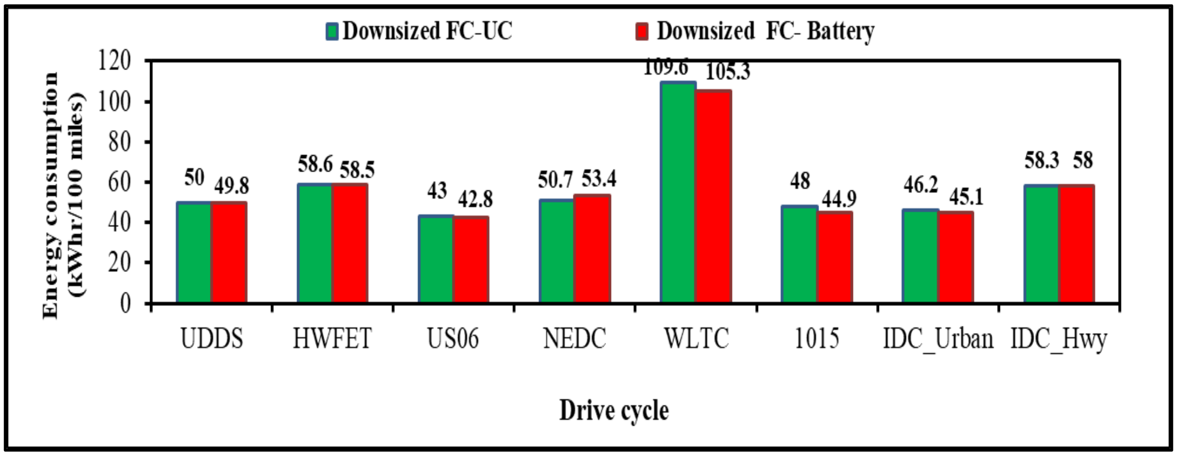


Figure 5.12 (a) Energy consumption vs. drive cycles

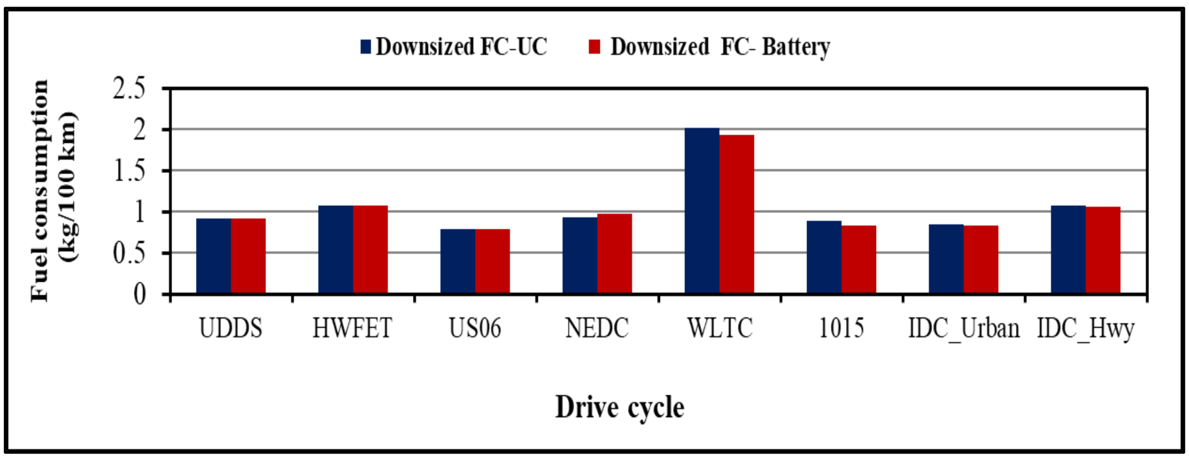


Figure 5.12 (b) Hydrogen consumption vs. drive cycles

The US06, UDDS, NEDC, Japanese 1015 and Indian urban driving cycles achieved better fuel economy with fuel cell-battery hybrid powertrain on miles per gallon equivalent (MPGe) basis depicted in Figure 5.12 (c). WLTC cycle exhibits low MPGe fuel economy due its diverse speed driving behavior.

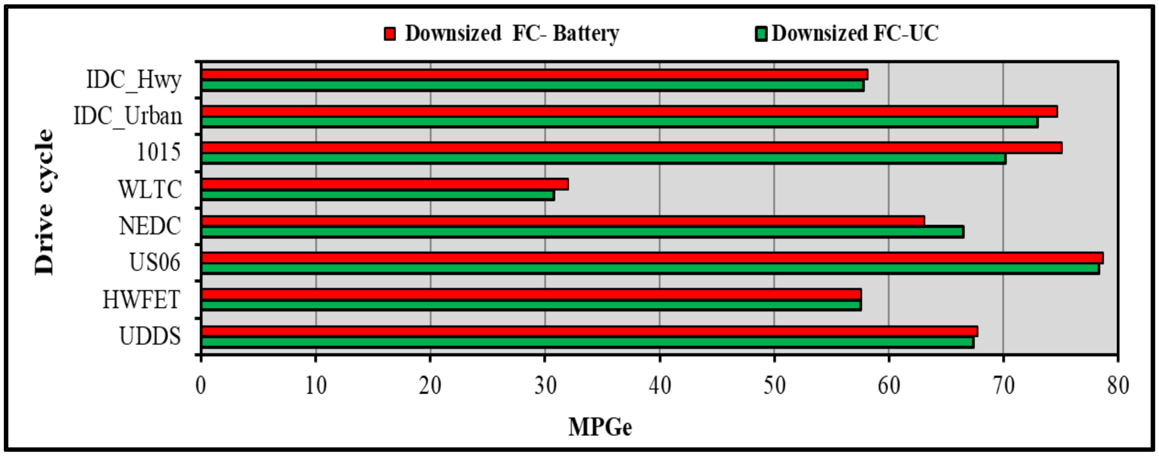


Figure 5.12 (c) Miles per gallon equivalent (MPGe) vs. drive cycles

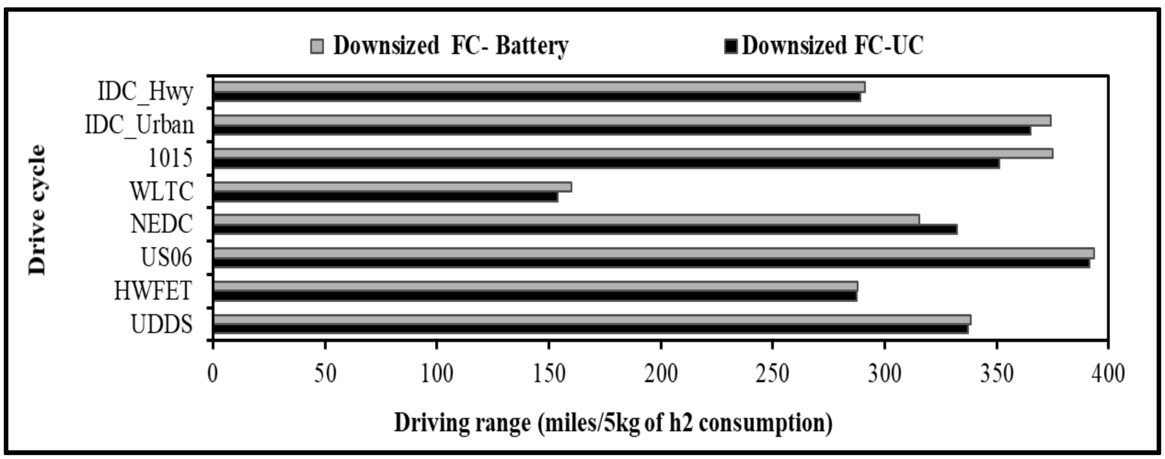


Figure 5.12 (d) Driving range vs. drive cycles

The driving ranges achieved for different driving cycles are shown in Figure 5.12 (d). US06, Japanese 1015, Indian urban and UDDS driving cycles exhibit better driving ranges per 5 kg of hydrogen consumption in comparison with WLTC and HWFET driving conditions. Both WLTC and HWFET cycles consume more hydrogen per mile due to high speed driving behavior. Fuel cell-ultracapacitor powertrain achieved better driving ranges in contrast with fuel cell-battery configuration.

5.10 Energy consumption over different driving cycles

Table 5.4 Fuel cell- Battery powertrain component energy consumption

Fuel Cell - Battery								
Component energy consumption (Wh/mile)	**Drive Cycle**							
	UDDS	**HWFET**	**NEDC**	**US06**	**1015**	**WLTC**	**IDC Urban**	**IDC highway**
FC fuel converter	342.6	302.4	394.4	428.4	369.6	163	380.6	296.5
Energy storage	170.2	43	136.7	141.7	213.2	148.3	212.5	114
Wheel power	223.8	207	295.2	345.1	215.5	142.7	203	207.2
Overall Efficiency	0.179	0.321	0.282	0.306	0.15	0.576	0.131	0.212
Regeneration Efficiency	0.69	0.71	0.73	0.82	0.55	0.73	0.58	0.63
Power Train efficiency	0.4364	0.3897	0.5558	0.6053	0.3697	0.4584	0.3422	0.504

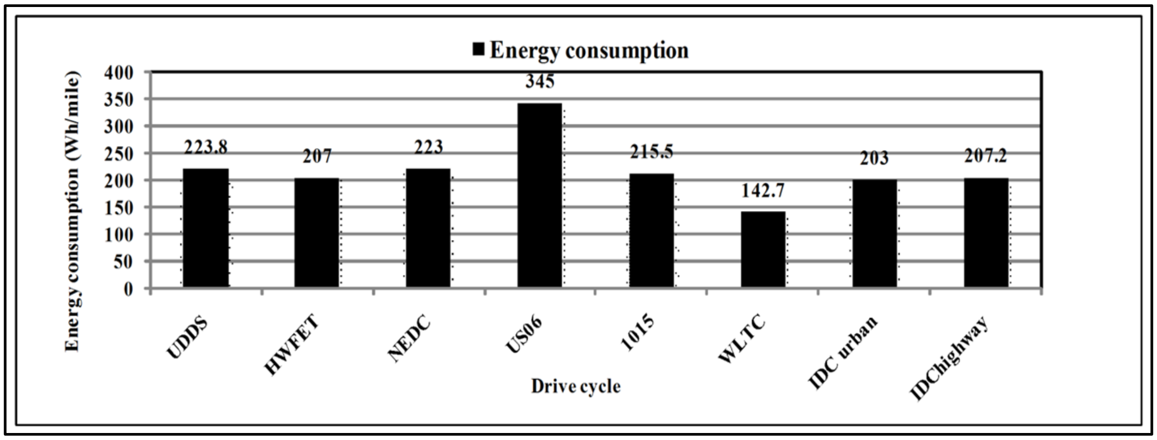
Table 5.5 Fuel cell-Ultracapacitor powertrain component energy consumption

Fuel Cell -Ultracapacitor								
Component energy consumption (Wh/mile)	**Drive Cycle**							
	UDDS	**HWFET**	**NEDC**	**US06**	**1015**	**WLTC**	**IDC Urban**	**IDC highway**
FC fuel converter	340.4	301.2	390.7	426	345	156.5	371	293.7
Energy storage	185	41.3	130.5	148.5	219.3	148.8	219.6	131
Wheel power	223.8	207	295.2	345	215.5	142.7	203	207.2
Overall Efficiency	0.18	0.322	0.287	0.306	0.156	0.598	0.33	0.213
Regeneration Efficiency	0.69	0.71	0.73	0.82	0.55	0.73	0.58	0.63
Power Train efficiency	0.4259	0.2898	0.5663	0.6005	0.3818	0.4674	0.3437	0.4878

Table. 5.4 and Table.5.5 represents the component energy consumption for fuel cell-battery and fuel cell-ultracapacitor powertrains over different drive cycles. For the vehicle, same Watt-hour energy demand fuel cell-ultracapacitor configuration consumes relatively less energy compared with fuel cell-battery combination. Better overall efficiency is achieved by fuel cell-ultracapacitor powertrain in contrast with fuel cell-battery configuration. The fuel cell component energy consumption for UDDS, HWFET, US06, Japanese 1015, WLTC, Indian urban and Indian highway in Wh/mile is relatively less for fuel cell-ultracapacitor configuration compared with fuel cell-battery configuration. Thus, it indicates better assistance from ultracapacitor for vehicle power demand for these driving cycles. NEDC drive cycle demands more fuel cell energy with fuel cell-ultracapacitor configuration in which the ultracapacitor alone cannot supply the desired vehicle power demand at cold start condition of drive cycle; meanwhile the fuel

cell supplies power along with energy storage system. However, with the fuel cell-battery configuration, the battery alone assists the vehicle startup condition.

Figure 5.13 Vehicle energy consumption



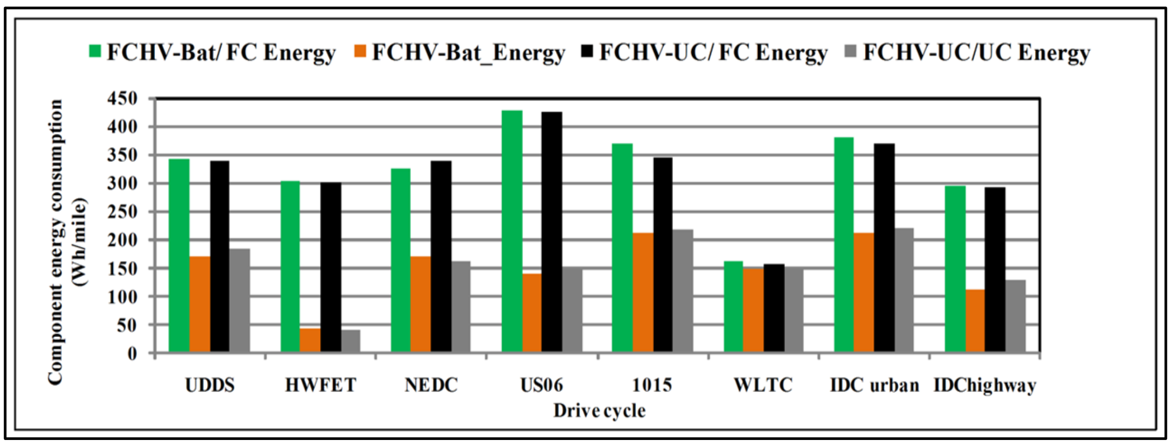


Figure 5.14 Component energy consumption

The vehicle energy consumption at wheels over different drive cycles is shown in Figure 5.13, among the drive cycles WLTC consumed less energy (i.e. Wh/mile basis). Meanwhile, the US06 cycle demands maximum fuel cell energy due to its aggressive driving behavior. Both NEDC and UDDS drive cycles demand approximately 36% more energy compared with WLTC drive cycle. Figure 5.14 depicts energy consumption of each component for two hybrid energy storage powertrains over different drive cycles. For WLTC drive cycle, the component energy consumptions are lower in comparison with other specified drive cycles. The Indian highway cycle consumes relatively low energy from both fuel cell and auxiliary energy source. US06 drive cycle demands maximum fuel cell energy in contrast with the other standard driving cycles because of its peak acceleration demands.

5.11 Results and discussions

- The new Worldwide Harmonized Light Vehicle Test Cycle (WLTC) cycle gained more than 50 % fuel economy in terms of miles per gallon of gasoline equivalent (mpgge) compared with NEDC driving cycle. Approximately 36 % more energy was saved over WLTC drive cycle compared with NEDC and UDDS cycles for the proposed downsized vehicle.

- Surge power is completely delivered by ultracapacitor only for an instance due to its high power density nature. So, the coupling of ultracapacitor pack to the battery pack act as a dual energy storage system for hybrid vehicles, which reduce the fuel cell system cost.

- About 50 % of fuel economy decreases when road grade increases from 1 % to 6 %. Hence, the vehicle achieved better fuel economy at lower road grades in comparison with higher road grades.

- Fuel cell-ultracapacitor hybrid power train gives better acceleration performance at higher (80% and 70%) ultracapacitor state of charge (SOC) compared with Fuel cell-battery powertrain. The ultracapacitor cannot assist the vehicle during acceleration demand at lower SOC values.

- Fuel cell-battery powertrain achieved better fuel economy in terms of MPGe, mpgge and driving ranges compared with fuel cell-ultracapacitor combination.

- Gradeability performance is achieved for fuel cell-battery configuration is 40 % more in comparison with pure fuel cell vehicle.

CHAPTER - 6

PERFORMANCE COMPARISON OF DOWNSIZED FCHV WITH TOYOTA MIRAI 2017 FCEV ANL TEST DATA

In this chapter, the performance of downsized Fuel cell- battery hybrid electric vehicle (HEV) is compared with Toyota Mirai 2017 FCEV ANL test data**.** The Vehicle energy level consumption, hybrid component level energy consumption and the performance of vehicle for low and aggressive speed driving conditions are presented. The new INRETS_NEDC cycle is considered as NEDC low speed driving condition and US06 cycle is considered as aggressive driving condition. vehicle energy consumption is estimated for UDDS×1, UDDS×2, UDDS×3, HWFET×2, US06×2, NEDC×2, WLTC×2, Japanese 1015×2, Indian driving cycle urban×2 and Indian driving cycle highway×2. Whereas, the each energy component consumption for UDDS, HWFET, US06, NEDC, WLTC, Japanese 1015, Indian urban and Indian highway driving cycles repeated for 2 simulated runs.

Figure 6.1 Toyota Mirai 2017 at ANL test Laboratory [137]

6.1 Objective

- To establish vehicle level energy consumption in terms of Watt-hour/mile, efficiency, and performance data on varying drive cycles and to measure the performance envelopes and synergies between the fuel cell system and the hybrid system.
- To estimate the performance of vehicle for low and aggressive speed driving conditions.

Table 6.1 Vehicle energy consumption [138].

Vehicle	Toyota Mirai FCEV 2017	Downsized FCHV
Drive cycle	**Vehicle energy consumption (Wh/mile)**	
UDDS#1	**239**	**223.8**
UDDS#2	**243**	**225.3**
UDDS#3	**249**	**224.8**
HWFET#2	**235**	**208**
US06#2	**321**	**345.1**
NEDC#2	295.4	295.3
WLTC#2	141.6	141.4
1015#2	216.1	215.5
IDC Urban#2	204.4	204
IDC_Highway#2	206.2	205.7

Table 6.2 Component energy consumption

Vehicle	Toyota Mirai FCEV 2017	Downsized FCHV	Toyota Mirai FCEV 2017	Downsized FCHV
Drive cycle	**Fuel cell energy consumption (Wh/mile)**		**Battery energy consumption (Wh/mile)**	
UDDS#2	349.7	348	211	168.3
HWFET#2	354	308	60.7	36.3
US06#2	594.2	431	146.2	138.6
NEDC#2	380.5	397	136.2	137.8
WLTC#2	441.6	163.8	139.3	148.6
1015#2	344.8	349.3	207.9	187.9
IDC Urban#2	396.5	378.5	264.8	215
IDC_Highway#2	308.2	292.6	146.3	117.2

Figure 6.1 shows the Toyota Mirai 2017 at ANL test laboratory. The vehicle energy consumption for UDDS×1, UDDS×2, UDDS×3, HWFET×2 , US06×2, NEDC×2, WLTC×2, Japanese 1015×2, Indian driving cycle urban×2 and Indian driving cycle highway×2 repeated each driving cycle for 1 and 2 simulated runs are shown in Table.6.1 The downsized fuel cell hybrid powertrain consumes low vehicle energy in comparison with 2017 Toyota Mirai Fuel cell electric vehicle (FCEV). Among these drive cycles, WLTC driving cycle consumes low vehicle energy consumption. UDDS cycle consumes approximately 7% less energy for downsized FCHV in comparison with Toyota Mirai FCEV.

However, US06 drive cycle consumes more vehicle energy compared with other drive cycles because of its aggressive driving nature. Table 6.2 represents energy component consumption for UDDS, HWFET,US06, NEDC, WLTC, Japanese 1015, Indian urban and Indian highway driving cycles repeated for 2 simulated runs. The fuel cell energy consumption is low for downsized vehicle compared with 2017 Toyota Mirai FCEV. The WLTC drive cycle consumes significantly less energy in contrast with other standard drive cycles. Battery energy consumption is relatively low for the downsized vehicle. Meanwhile, the WLTC drive cycle demands more battery energy because of its versatile driving condition. It can be seen that the equivalent fuel cell energy consumption is observed for Indian driving cycle urban and highway driving cycles for both Toyota Mirai FCEV and downsized fuel cell hybrid powertrains. US06 and WLTC drive cycles consume approximately 27% and 63 % less fuel cell energy (i.e. Wh/mile) for downsized FCHV in comparison with Toyota Mirai FCEV.

6.2 Fuel cell hybrid powertrain operation on low power driving cycle (NEDC)

The fuel cell hybrid powertrain operates on low power driving cycle (i.e. For NEDC×2 run) as shown in Figure 6.2 (a) and Figure 6.2 (b) respectively. The battery is charged during braking period and later it is discharged according to the vehicle acceleration condition.

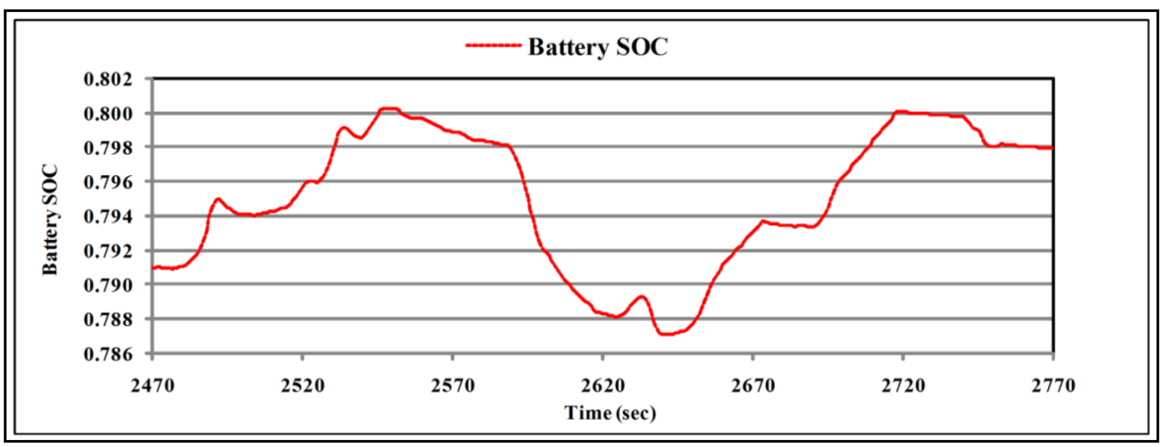


Figure 6.2 (a) Battery SOC over NEDC×2 run drive cycle

Fuel cell provides majority of the power for vehicle acceleration demand while the battery charged by the fuel cell. During acceleration, the fuel cell power increases and the battery provides assisted power. Fuel cell provides the power to cruise at a steady state speed and the battery is inactive. For the vehicle, low speed demand battery assists the vehicle while the fuel cell is inactive. Both the fuel cell and battery are in idle condition, when the vehicle is stopped. When the vehicle is running in low speed condition, the battery supplies the demand power. Meanwhile, the fuel cell is in idle condition for a minute over the driving cycle as shown in Figure 6.2 (c).

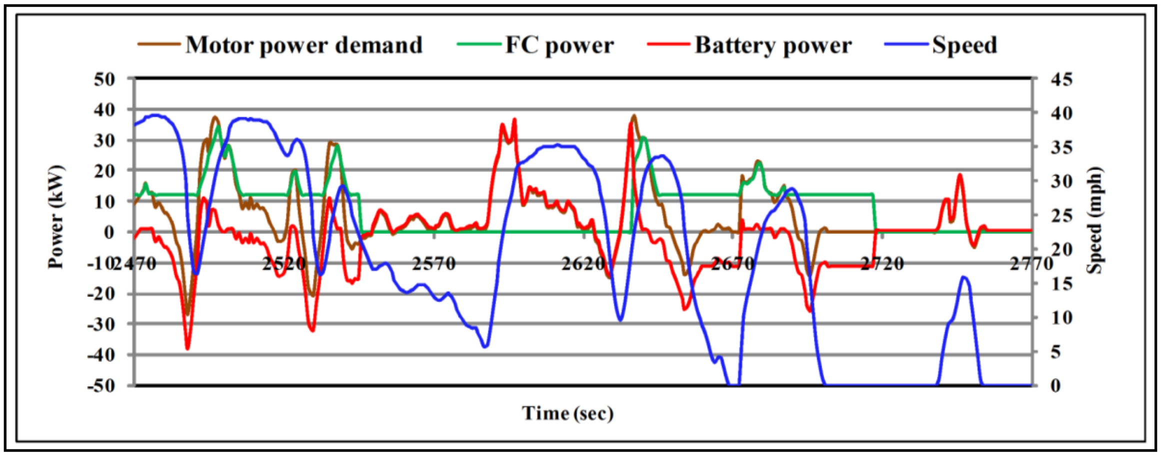


Figure 6.2 (b) Power output over NEDC×2 run driving cycle

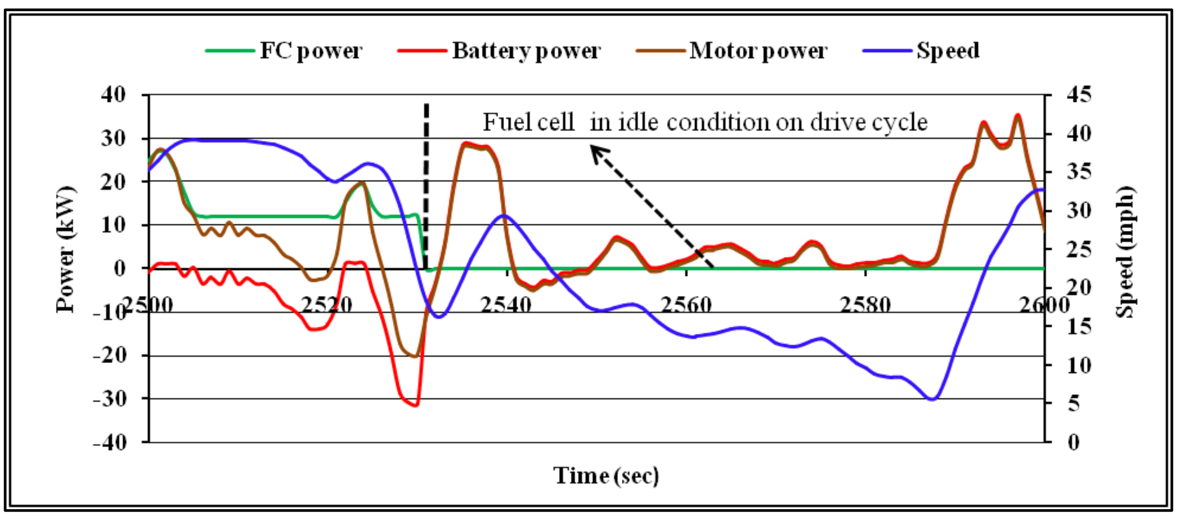


Figure 6.2 (c) Fuel cell in idle condition over NEDC×2 run driving cycle

6.3 Fuel cell hybrid powertrain operation on aggressive driving cycle (US06)

The fuel cell hybrid powertrain operation on aggressive driving cycle (i.e. For US06×2 run) is as shown in Figure 6.3 (a) and Figure 6.3 (b) respectively. The battery SOC variation is quite low during the dynamic load changes, whereas it is in charging mode for the sequence of accelerations. In US06 drive cycle, highly dynamic speed changes occurred while the vehicle was cruising and the fuel cell follows the dynamic load changes along with battery assistance. Meanwhile, the fuel cell is inactive when the vehicle in decelerating condition. Both fuel cell and battery supply the power for the sequence of heavy accelerations.

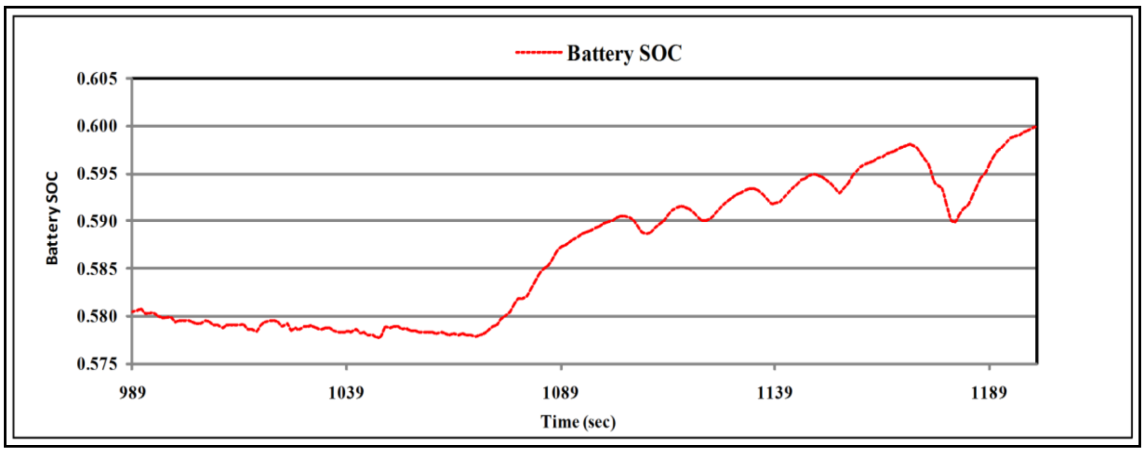


Figure 6.3 (a) Battery SOC over US06×2 run drive cycle

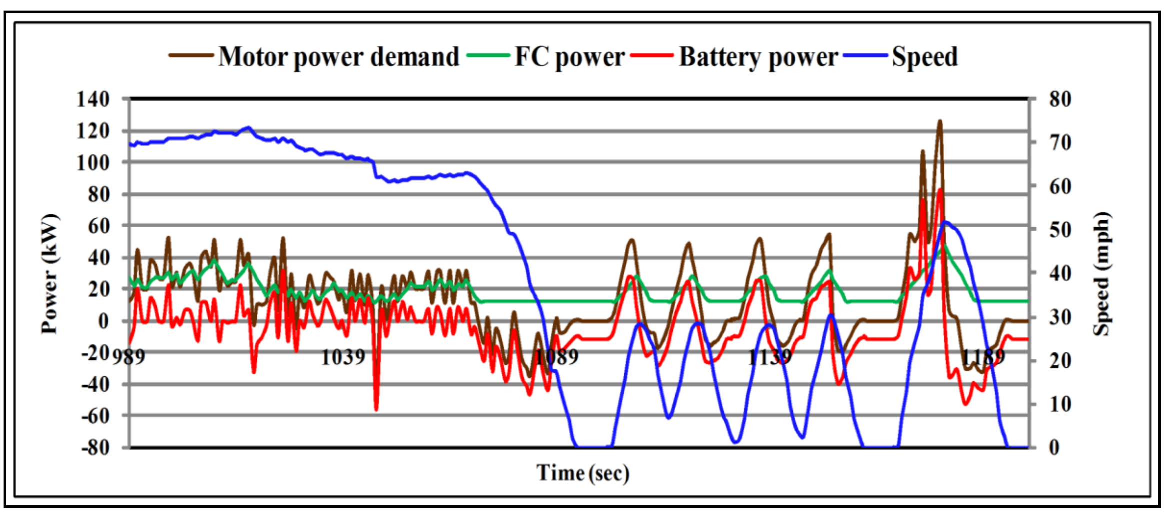


Figure 6.3 (b) Power output over US06×2 run driving cycle

Fuel cell provides majority of the power for vehicle acceleration demand while the battery is charged by the fuel cell. Fuel cell and battery instantaneously supply maximum power to meet the large peak power demand. Figure 6.3 (c) depicts the component of hybrid power variation according to dynamic load changes. Thus, both fuel cell and battery supply power for motor tractive power.

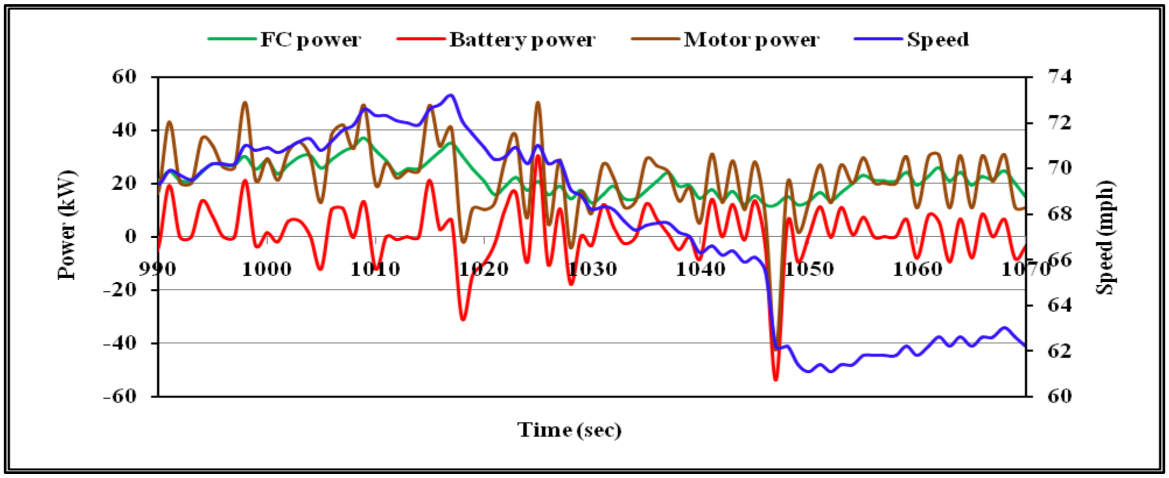


Figure 6.3 (c) Component power variation with high dynamic speed changes

6.4 Energy consumption over different drive cycles

The vehicle energy consumption on Watt-hour per mile basis is shown in Figure.6.4 (a). over different 2- run standard drive cycles for both downsized FCHV and Toyota Mirai FCEV. It is found that WLTC drive cycle consumes very low energy compared with other standard drive cycles. NEDC and US06 consume more Wh energy because of driving behavior. Almost an equivalent vehicle energy consumption is noticed over UDDS, HWFET, Japanese 1015 and Indian driving conditions.

The downsized FCHV which consumes low fuel cell energy on Watt-hour per miles basis is shown in Figure 6.4 (b). Compared to all other standard driving cycles, WLTC cycle demands low fuel cell energy for downsized FCHV than Toyota benchmark vehicle. Thus, the fuel consumption is reduced for the proposed downsized FCHV over WLTC driving condition. WLTC cycle achieved better energy storage system (ESS) assistance for downsized vehicle shown in Figure 6.4 (c). Figure 6.1 (d) shows the overall efficiency of downsized vehicle and Toyota Mirai 2017 vehicle.

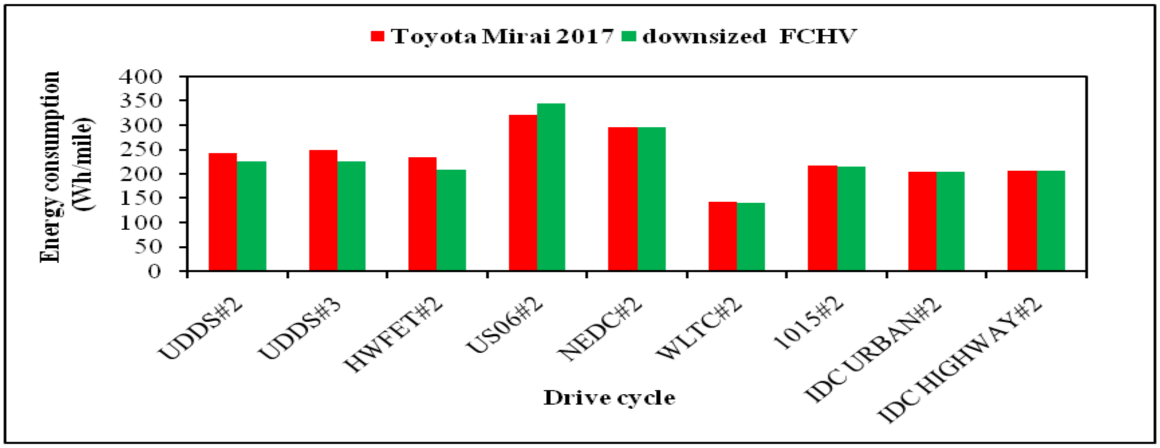


Figure 6.4 (a) Vehicle energy consumption

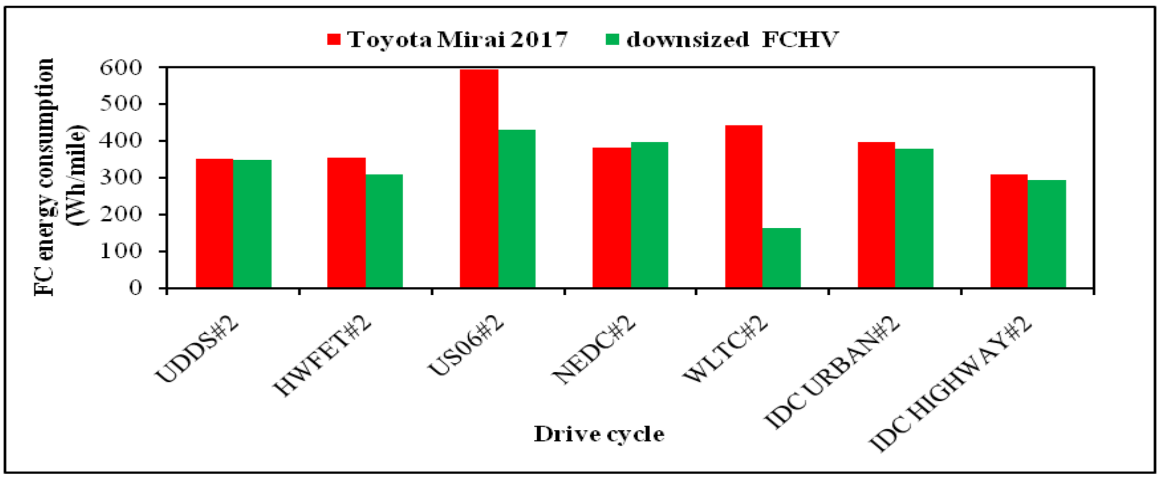


Figure 6.4 (b) Fuel cell energy consumption

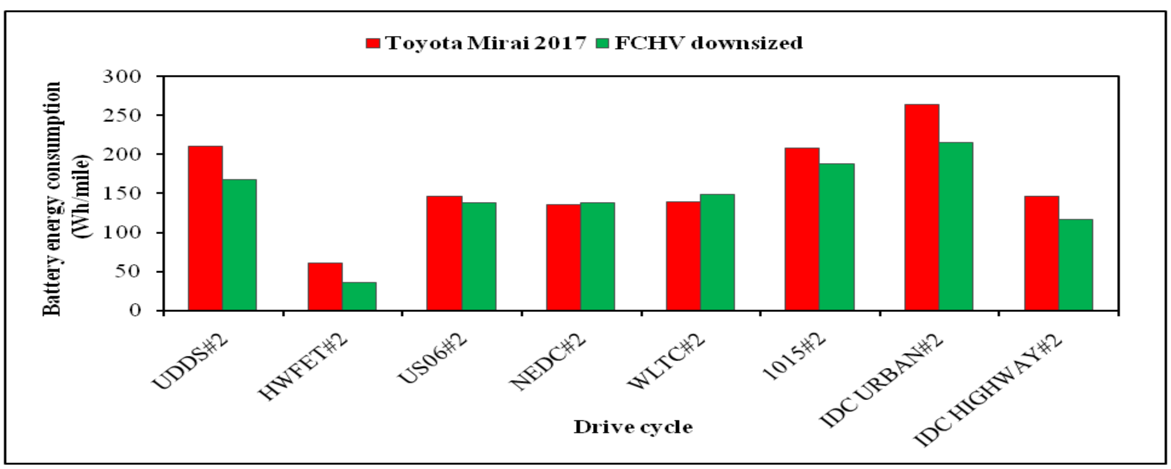


Figure 6.4 (c) Battery energy consumption

The WLTC drive cycle achieved an overall efficiency of 60%, which is far better than other standard driving cycles for downsized FCHV in comparison with 2017 Toyota Mirai FCEV.

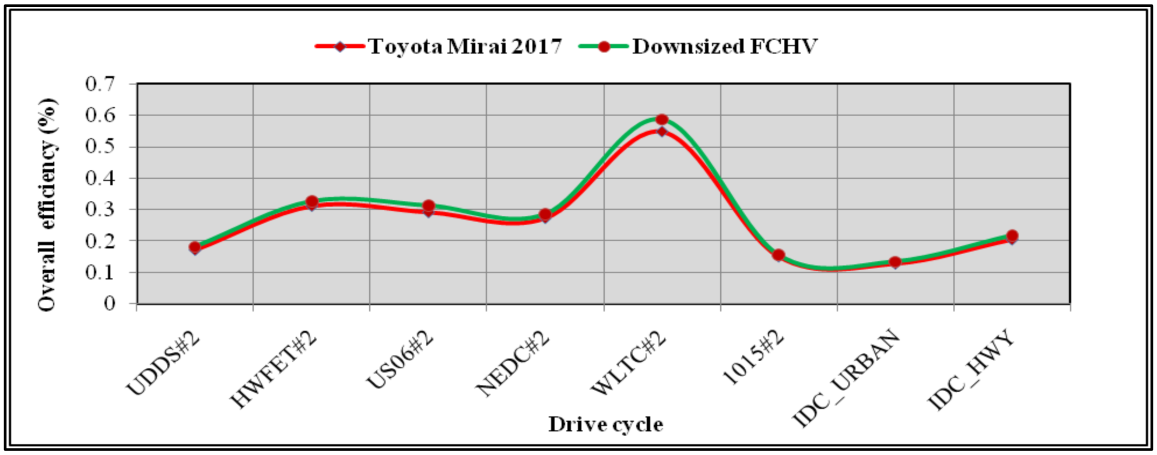


Figure 6.4 (d) Overall efficiency

6.5 Results and discussions

- Fuel cell provides majority of the power during acceleration period and the battery provides the support power. During the steady speed condition fuel cell provides power while the battery is inactive. Battery is charged by the fuel cell at low speed conditions. Fuel cell power follows the dynamic load changes while cruising.
- UDDS cycle consumes approximately 7% less energy for downsized FCHV in comparison with Toyota Mirai FCEV.
- Downsized FCHV demands low vehicle energy and low fuel cell component energy on Watt-hour per mile basis compared with 2017 Toyota Mirai FCEV.
- Both US06 and WLTC drive cycles consume approximately 27% and 63 % less fuel cell energy (i.e. Wh/mile) for the proposed downsized FCHV in comparison with Toyota Mirai FCEV.

Therefore, the proposed downsized FCHV achieved better performance in terms of fuel economy, energy consumption (Wh/mile), driving nature in comparison with 2017 Toyota Mirai ANL test data.

Chapter- 7

Conclusions

The aim of the present research work is to estimate the energy interactions of fuel cell, batteries and ultracapacitors and to identify an optimal energy management. Fuel cell hybrid (FCH) mid-size car is modeled and simulated in Advanced Vehicle Simulator (ADVISOR) by downsizing the fuel cell stack power by 30% with corresponding increase in the battery pack size to achieve equivalent performance in terms of fuel economy and better acceleration performance in comparison with 2017 Toyota Mirai Fuel Cell Electric Vehicle (FCEV). Moreover, the new real time advanced drive cycle World harmonized Light Vehicle Test cycle (WLTC) is embedded into the ADVISOR tool to estimate the driving performance. Finally, the downsized FCHV performance is compared with Toyota Mirai 2017 FCEV ANL test data. The following conclusions were made from this study.

- The degree of hybridization for fuel economy depends on the dynamics of the drive cycle. For highway drive cycle, the initial increase is due to the increase in fuel cell power. The fuel economy is relatively constant. Hybridization improves the fuel economy and vehicle performance.

- As the fuel cell power continues to decrease and the ultracapacitor capacity increases, the interaction between the power spectrum of the drive cycle, the minimum fuel cell power and the energy processed through the ultracapacitor produces peaks in fuel economy at the rate of 0.9 to 1.0 hybrid ratio.

- The fuel economy rises up to 70% hybridization and decreases significantly at higher hybridization ratios due to low power assistance from fuel cell for HWFET, US06 and C65 drive cycles. Large amount of energy conversion occurs at the minimum fuel cell power level enforced by control strategy, which results in increase of fuel cell efficiency. Fuel cell system may benefit by downsizing to avoid excessive operation at light load or on/off operation due to minimum power demand.

- The proposed downsized Fuel Cell Hybrid Vehicle (FCHV) achieved an equivalent fuel economy of 67.67 MPGe compared with benchmark vehicle Toyota Fuel Cell Electric Vehicle (FCEV). Moreover, the acceleration performance also increased by 16.67% for 0 to 60 mph speed range. It is concluded that the downsized vehicle achieved good performance in terms of fuel economy and dynamic performance.

- By increasing the battery modules, the pulse power capability of battery pack was enhanced. From the cost analysis, (i.e. Figure 4.8) it can be emphasized that the estimated cost reduction achieved for downsized FCHV is 26 % approximately.

- The new Worldwide Harmonized Light Vehicle Test Cycle (WLTC) cycle gained more than 50 % fuel economy in terms of miles per gallon gasoline equivalent (mpgge) compared with NEDC driving cycle.

- Approximately 36 % more energy was saved over the WLTC drive cycle compared with NEDC and UDDS cycles for the proposed downsized vehicle.

- Surge power is completely delivered by ultracapacitor only for an instance due it's high power density nature. So, the coupling of ultracapacitor pack to the battery pack, which can act as a dual energy storage system for hybrid vehicles, which reduce the fuel cell system cost.

- About 50 % of fuel economy decreases when road grade increases from 1 % to 6 %. Hence, the vehicle achieved better fuel economy at lower road grades in comparison with higher road grades.

- Fuel cell-ultracapacitor hybrid power train gives better acceleration performance at higher (80% and 70%) ultracapacitor state of charge (SOC) compared with fuel cell-battery powertrain. This is because; the ultracapacitor cannot assist the vehicle during acceleration demand at lower SOC values. Whereas, the battery can assist the vehicle even at 40% SOC level. For the same vehicle, Wh/mile energy demand Fuel cell-ultracapacitor hybrid power train consumes relatively less energy compared with Fuel cell-battery powertrain.

- Fuel cell-battery powertrain achieved better fuel economy in terms of MPGe, mpgge and driving ranges compared with Fuel cell-ultracapacitor combination. From the results it can be concluded that the Fuel cell-Battery-Ultracapacitor configuration will be an ideal hybrid powertrain, which can meet both dynamic performance, and fuel economy as well as reduce powertrain cost.

- Both US06 and WLTC drive cycles consume approximately 27% and 63 % less fuel cell energy (i.e. Wh/mile) for the proposed downsized FCHV in comparison with Toyota Mirai FCEV.

- Vehicle Watt-hour demand, fuel cell energy and battery energy consumptions are low for downsized HEV compared with Toyota Mirai 2017 AVL test data. The new WLTC cycle consumes low energy at wheels and low fuel cell energy compared with other standard driving cycles.

From this study, it is observed that downsizing of fuel cell power for the proposed Fuel Cell Hybrid Vehicle (FCHV) is beneficial in terms of equivalent fuel economy of 67.67 MPGe, an increase of 17 % dynamic performance, increase in battery pulse power capability and 26 % powertrain cost reduction in comparison with 2017 Toyota Mirai Fuel Cell Electric Vehicle (FCEV). From this investigation it is also concluded that the new Worldwide Harmonized Light Vehicle Test Cycle (WLTC) is advantageous in terms of 36 % less vehicle energy consumption and more than 50 % less fuel energy consumption on Wh/mile basis in comparison with benchmark vehicle. The Fuel cell-battery-ultracapacitor hybrid power source option will be optimal hybrid configuration to further reduce the cost of fuel cell system and hydrogen consumption.

Scope for the Future Work

In the present study, Fuel cell-battery and Fuel cell-ultracapacitor powertrains were investigated. However, there is scope in future for the following areas:

- The peak power density of ultracapacitors in combination with high-energy density of batteries can reduce fuel cell stack size and total cost of the hybrid powertrain in order to meet the advancements in vehicle energy management strategies, which can be extended for future version of this study.
- Potential new energy management techniques, méthodologies can enhance FCHEV performance.
- Cost estimation analysis to predict the cost of FCHEV can be investigated.
- Real time simulation of FCHEV by combining Fuel cell-Battery-Ultracapacitor using Opal-RT Simulator is another exciting area of study.

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Appendix-A

Table A.1: Performance comparison of Downsized FCHV, Gasoline Hybrid Electric Vehicle (HEV) and Honda city petrol based vehicle [137,138]

Drive Cycle	Downsized Fuel Cell -Battery Hybrid Vehicle (FCHV)			Gasoline Hybrid Electric Vehicle(HEV)			Honda City 1.5 litre i-VTEC Petrol engine		
	mpgge (kW-hr/100 miles)	**MPGe (miles/ 1 gallon gasoline**	**Average engine efficiency (%)**	**MPGe (miles/ 1 gallon gasoline**	**MPGe (miles/ 1 gallon diesel**	**Average engine efficiency (%)**	**MPGe (miles/ 1 gallon gasoline**	**MPGe (miles/ 1 gallon diesel**	**Average engine efficiency (%)**
UDDS	49.8	67.67	51.25	27.5	31.5	31.20	25.6	29.3	17.2
HWFET	58.5	57.6	53.0	31.6	36.1	31.38	34.3	39.2	21.29
NEDC	53.4	63.11	51.6	28.7	32.8	31.0	25.8	29.6	17.21
US06	42.8	78.74	54.57	22.7	22.9	31.46	24.7	28.3	22.90
Japanese 1015	44.9	75.06	49.7	27	30.8	30.0	21.6	24.7	13.64
NREL2VAIL	45.3	74.40	57.5	23.4	26.7	32.24	27.7	31.7	24.92
WLTC	105.3	32.0	57.5	60.5	69.35	31.0	35.6	40.74	11.35
Acceleration Performance	**0-60 mph - 7.5 seconds**			**0-60 mph - 7.3 seconds**			**0-60 mph - 11.8 seconds**		
	40-60 mph - 5.9 seconds			40-60 mph - 3.4 seconds			40-60 mph - 5.7 seconds		
	0-85 mph - 23 seconds			0-85 mph - 14.4 seconds			0-85 mph - 33.6 seconds		
Gradeability performance	Gradeability at 55 mph - 19.3 %			Gradeability at 55 mph - 21.8 %			Gradeability at 55 mph - 15.3 %		

Table A. 2: Simulation results for various driving cycles

Drive Cycle	**2017 Toyota Mirai Fuel Cell Electric Vehicle (FCEV)**			**Downsized Fuel Cell -Battery Hybrid Vehicle (FCHV)**			**Downsized Fuel Cell -Ultracapacitor Hybrid Vehicle (FCHV))**		
	mpgge (kW-hr/100 miles)	**mpdge (kW-hr/100 miles)**	**Average engine efficiency (%)**	**mpgge (kW-hr/100 miles)**	**mpdge (kW-hr/100 miles)**	**Average engine efficiency (%)**	**mpgge (kW-hr/100 miles)**	**mpdge (kW-hr/100 miles)**	**Average engine efficiency (%)**
UDDS	46.5	53.2	50.2	49.8	57.1	51.25	50	57.28	51
HWFET	54	61.8	50.7	58.5	67	53.0	58.6	67.1	52.8
NEDC	**46.1**	**52.8**	**50.7**	**53.4**	**61.1**	**51.6**	**50.7**	**58**	**51.3**
US06	39.1	44.7	53	42.8	49	54.57	43	49.2	54.4
Japanese 1015	57.5	66	49.2	44.9	51.4	49.7	48	55	49.6
NREL2VAIL	44.4	50.8	57.2	45.3	51.8	57.5	45.7	52.4	57.7
WLTC	**96.2**	**110.1**	**50.5**	**105.3**	**120.56**	**57.5**	**109.6**	**125.5**	**51.2**
ECE	41.6	47.6	49	48.7	55.7	49.68	45.5	52.1	49.1
FTP	48	55	50.7	50.2	57.45	52.13	51.6	59	52
INRETS	43.7	50	53.4	46.6	53.34	54.72	47.2	54	55
OCC	39.3	45	49.7	41.3	47.28	50.58	41.9	48	50.4
SCO3	43.3	49.5	49.6	48.2	55.18	50.43	49	56.1	50.7
Constant 65	48.7	55.8	52	51.7	59.17	54.27	51	58.4	54
CSHVR	43.9	50.3	49.6	45.8	52.47	50.5	47.4	54.2	50.5
LA92	42.9	49.1	51.5	46.5	53.2	53	47.2	54	53
MAHATTAN	30.8	35.2	49	31.8	36.4	49.3	32.5	37.2	49.2
US06 HIGHWAY	43.5	49.7	52.5	45.3	51.8	54	46	52.6	54
WVUCITY	36.5	41.8	49.2	38.9	44.5	49.9	39	44.6	49.6
WVUSUB	48.5	55.5	49.6	51.9	59.4	50.4	51.6	59	50.5
NYCC	27.3	31.2	49.2	32	36.63	49.45	30.4	34.8	49.3
Acceleration Performance	**0-60 mph - 9 seconds**			**0-60 mph - 7.5 seconds**			**0-60 mph - 6.4 seconds**		
	40-60 mph - 5.9 seconds			40-60 mph - 3.4 seconds			40-60 mph - 2.7 seconds		
	0-85 mph - 23 seconds			0-85 mph - 14.4 seconds			0-85 mph - 33.6 seconds		
Gradeability performance	Gradeability at 55 mph - 19.3 %			Gradeability at 55 mph - 21.8 %			Gradeability at 55 mph - 21.8 %		