A Modeling Approach for Assessing Energy Performance and Influential Factors of Vehicles Powered by Battery, Fuel cell and Ultracapacitor

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Abstract

This research work aims to assess the parameters that determine the performance and range of vehicle powered by battery, fuel cell, ultra-capacitor and combination of the former. A flexible vehicle simulation model is developed in MATLAB-Simulink and vehicle performance is evaluated in various test cases (e.g. 1 Hz certified cycles) enabling the assessment of SOC, energy consumption/km, overall range and other performance details.

The proposed model accurately estimates energy consumption and range of passenger vehicle with an average absolute error less than 4%, and error less than 2% for the electric bus. The study showed that BEV has the least energy consumption (23%), followed by FCEV (65%) compared to ICE vehicles. The performance analysis showed increasing the battery capacity of BEV by three-fold, the range is extended by 294%, while the battery with higher energy density helps to reduce 2-4% in energy consumption.

Simulation results point out that aggressive driving and higher average speed have a negative influence on vehicle range based on acceleration profiles. Also, the varying atmospheric conditions in northern and southern European countries can result in a range difference of 25-35%. Combination of the battery-fuel cell shows an increase in range by 10%, while combining ultra-capacitor with battery enables a lifetime extension of battery life by 10%, with negligible change in range. For buses, ultra-capacitors are highly recommended for short-frequent trips with a life of 20 years, with the highest cost-benefit ratio. The fuel cell as the primary energy source is recommended for long-range drive, for coaches and trucks.

Keywords: *Electric vehicle, fuel cell vehicle, Ultra-capacitor vehicle, performance on different climate, energy consumption, simulation of alternative powertrains, passenger cars, buses*

Resumo

Este trabalho de investigação tem como objetivo avaliar os parâmetros determinantes de desempenho e alcance do veículo movido a bateria, célula de combustível, supercondensadores e sua combinação. Foi desenvolvido um modelo flexível de simulação de veículos em MATLAB-Simulink, permitindo avaliar o desempenho do veículo em diferentes condições (por exemplo, ciclos certificados de 1 Hz), permitindo a avaliação do SOC, consumo de energia / km, autonomia do veículo e outros detalhes de desempenho.

O modelo proposto estima com precisão o consumo de energia e a autonomia dos veículos de passageiros com um erro absoluto médio inferior a 4% e 2% para o autocarro elétrico. O estudo mostrou que o BEV tem um menor consumo de energia (23%), seguido pelo FCEV (65%) em comparação aos veículos ICE. A análise de desempenho mostrou aumentar em três vezes a capacidade da bateria do BEV, a autonomia é estendida em 294%, enquanto a bateria com maior densidade de energia ajuda a reduzir o consumo de energia em 2 a 4%.

Os resultados das simulações indicam que a condução agressiva e a velocidade média mais alta influenciam negativamente a autonomia do veículo com base nos perfis de aceleração. Além disso, as diferentes condições atmosféricas nos países do norte e do sul da Europa podem resultar em uma diferença de intervalo de 25 a 35% na autonomia do veículo. A combinação de célula de combustível da bateria mostra um aumento na autonomia de 10%, enquanto a combinação de super-condensadores com a bateria permite uma extensão da vida útil da bateria em 10%, com uma mudança insignificante na autonomia. Para o autocarro, os super-condensadores são altamente recomendados para viagens curtas e frequentes, com uma vida útil de 20 anos, com a maior relação custo-benefício. A célula de combustível como fonte de energia primária é recomendada para maiores distâncias percorridas, em autocarros e camiões.

Palavras-chave: *veículo elétrico, veículo com célula de combustível, veículo com super-condensadores, desempenho em diferentes climas, consumo de energia, simulação de tecnologias alternativas, veículos ligeiros de passageiros, autocarros*

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1. INTRODUCTION

One of the main foundation of any economy Automotive Sector and it plays a vital role in the development and gross domestic product (GDP) of every country. Automotive sector behaves as the heart of the supply chain that feeds the country. It makes the corners around the world accessible by each one of us, brings ideas, technology and innovation together which improves the quality of life better each day. With time, automotive sector developed to facilitate the movement of commodities beyond humans and goods.

Even though the development enabled us to reach the dark corners of the world, it also led to rising concerns regarding environmental degradation in the form of air pollution, global warming, noise and safety. Due to these reasons, it is important to channel the automotive sector into a sustainable path, which helps to reduce these negative effects in the future. The transportation sector is divide into three dimensions:

- Mobility dimension –provides adequate and affordable transportation options to satisfy society's needs for access and mobility and to move goods;
- Social dimension – delivers the adequate transport services for everyone, not damaging the safety, health, congestion and equal access to services for different groups of society;
- Environmental dimension – provides transportation services with no harmful impacts on the environment or hinders people's ability to obtain other required resources or carry out other needed functions with those resources.

This thesis is mainly focused with the social dimensions of the transportation sector, which has direct influence to human life, addresses different power sources for the powertrain, energy consumption and influencing factors which affects the performance of different types of vehicles.

1.1. MOTIVATION

The overexploitation of natural resources is paving way for an increasing amount of greenhouse gas (GHG) emissions and global warming impacts around the globe [1]. Even though the primary cause is not the automotive field, the former holds a considerable amount of responsibility to the overall emissions [2]. As per the European Commission statistics for 2017, the transportation sector is responsible for around 31% of the final energy consumption in Europe, of which 94% is consumed by road transportation, which is around 306.2 MTOE, with the emission of 4483.1 million ton of CO_2 equivalent [3]. In past years, regulation has been designed to promote the mitigation of emissions from the transportation sector by moving towards zero-emission vehicles, speeding up the deployment of low emission alternative energy for transport and by encouraging more efficient transport systems. However, despite these efforts, the GHG emission trend in the transportation sector has continued to increase [4]. As a result of this regulatory push, vehicle manufacturers have started focusing on more efficient powertrains with vehicle hybridization and electrification, in an attempt to reduce emissions and also the dependency towards fossil fuels [5], [6], [7].

The interest in electric and other alternative fuel vehicles has increased due to growing concern over the energy dependency problems associated with conventional vehicle and additional benefits associated with the reduction of local emissions, noise improvements and possibility to include high shares of renewable energy sources [6]. Even though the initial investment in electric vehicles (EV), hybrid vehicles (HEV) and plug-in hybrid electric vehicles (PHEV) is still higher than the conventionally powered vehicle, the operational cost is cheaper, which makes the electric/hybrid vehicle inexpensive on the long term run. It is estimated that on shifting to electric mobility, the energy consumption can be reduced by 75% and by 57% during the energy production stage [8]. Furthermore, it is expected that the economic competitiveness of electric technologies improves, with a breakeven point between the two technologies to be expected in the next 10 years [9], even without the presence of governmental incentives.

The paradigm shift in the automobile field towards electric powertrain vehicles with batteries, ultra-capacitors and hydrogen is mainly because of their potential to reduce GHG emissions. EV has the potential to reduce life cycle GHG emissions by 1100 MMT(million metric ton) to 500 MMT in 2050 compared to conventional vehicles [10]. Also, hydrogen is gaining importance for its high specific energy per unit mass and energy density per unit volume (33.3kWh/kg and 14kWh/L respectively) and has considerable potential in the automotive sector, with the possibility of reducing life-cycle GHG emissions by 64% [11], while considering green hydrogen will take the number even lower to 105g CO_2 eq/MJ [12]. However, with the least specific energy (0.15kWh/kg) and energy density (0.375kWh/L) compared to former energy sources, EV are gaining more importance in the market due to reduced purchase costs, lower maintenance costs and running cost, as well as increasing availability of EVSE [13]. Also, used Li-ion batteries can be reused to store off-peak clean electricity and can be used to serve during peak demand period, which reduces the CO_2 emission by 56% compared to using natural gas [14].Table 1 shows detailed information about fuel and energy contents.

Despite the existing advantages, EV also has some operational constraints which constitute a barrier to adoption. The recharge time is also one unattractive point, since it may take around 6-8 hours to fully recharge with slow charging, while for gasoline vehicles, refuelling takes a maximum of 3-5 minutes.

Table 1: Energy contents in fuels

Fuel	Units	Gasoline (C_8H_{18})	Diesel ($C_{12}H_{23}$)	Natural Gas (CH_4)	Hydrogen (H_2)	Li-ion
Specific Energy	(kWh/kg)	11.1-11.6	11.9-12	11.2 – 13.0	33.3	0.15
	(kJ/kg)	40.1-41.9	42.9-43.1	40.2-46.7	120	0.54
Density	(kg/L)	0.72-0.78	0.82-0.85	0.2	0.42	2.5
Energy density	(kWh/L)	8.0-9.0	9.8-10.1	2.8	14	0.375
CO2 emission	($kgCO_2$/kg fuel)	3.09	3.16	2.75	0	0
	(gCO_2/kwh)	266	268	198	0	0

In the wake of higher demand for the electric powertrain, diverse studies have been carried out based on theoretical and practical experiments. The key technologies that have helped the success of EV and HEV include up to 95% efficient motor drive technology [15], which enables flexibility in design and weight reduction based on vehicle requirements. Based on studies, permanent magnet brushless DC motors were introduced with a high torque density of 15Nm/kg, peak efficiency of 98% and enhanced torque vs speed characteristics helped to gain importance in EV powertrain [16]. The advancement in power electronics technology and microelectronic and control technology helped to make more reliable guidance and vehicle control system [17] [18]. Development in sustainable material technology helped to come up with lighter and denser materials which contributed to the reduction of vehicle mass and improve their physical properties [19]. Continuously developing energy storage technologies brought in remarkable changes in energy storage methods and to deliver more power, which contributed towards increased top speed and range of EV [20]. Integration of all these technologies has been a key aspect in the success of EV, resulting in sales of 2919 vehicle in 2010 to 97,687 vehicle in 2015 and 223,284 vehicles in 2018 around the Europe [21].

On the other hand, hydrogen fuel has the potential for fuel cell revolution around the globe. Hydrogen when compressed into a fuel cell, generates electric power to run the vehicle. The hydrogen fuel cell can be integrated with an electric motor, which produces low air pollution and noise pollution. The hydrogen fuel cell has several benefits such as easy maintenance, lower gas emissions, silent functioning of the vehicle that reduces noise pollution, low-temperature fuel cells that have less heat transmission, which is ideal for military applications. Based on the data, fuel-cell fleets in California is doubled in 2020 as that in 2019 [22] and new initiatives were taken by many EU countries like Portugal and Germany [23] to implement them. Nevertheless, hydrogen economy also has some serious setbacks; higher initial cost, high fuel price and lack of refuelling infrastructure are holding back the growth in the field.

Battery storage is one of the dominant energy storage systems in vehicles. But due to its low power density, more batteries will increase the size, and subsequently mass of vehicle along with the recharging time. This dent is filled by the introduction of ultra-capacitors to the automotive industry. The characteristics of ultra-capacitor includes high power density (1000-2000kW/kg) and fast charging ability. Combining low voltage battery with ultra-capacitor helps to generate high voltage power with even lesser cost [24]. The ultra-capacitors can be charged quickly and release a large amount of power without excessive energy losses, with a significant amount of charge/discharge cycles. In addition to the robustness of UC's, their capability for delivering high power/current values in a significantly short time without facing structural damage is a key advantage over available battery technologies [25]. However, the usage of ultra-capacitor is limited due to the major challenging problem for UC's with their high capital costs.

Automotive segments consist of a variety of vehicle segments from low power electric vehicle to high load carrying heavy-duty trucks. Due to the different characteristics of energy storage systems for the automotive systems, a single energy source cannot be employed to all vehicle segments. This has been discussed widely over the last couple of years by different manufacturers. Nikola Motors is now developing the fuel cell trucks for the future, claiming the future relies on hydrogen, while Tesla Motors are resisting with revolutionising various battery electric vehicle. To test these hypotheses, investing in experimental models can be highly risky due to the uncertainty of the outcome. The optimal option will be to carry out modelling and simulation to validate these options and realise the facts, without financial and time risking processes. This thesis aims at the same, to test the validity of vehicle powertrains and study how different energy source can be chosen based on the requirement. Section 1.2 explains the objectives of this study in details and section 1.3 gives an outline of this thesis.

1.2. OBJECTIVES OF THE STUDY

This work aims to study the energy-efficient and cost-effective powertrain design focusing on different vehicle technologies (focused on energy storage with batteries or hydrogen or ultra-capacitors) and vehicle segments (light-duty vehicles and buses), based on certification and real-world driving cycles. For this purpose, the following tasks were performed:

- Developing and validating the vehicle model in Simulink toolbar in MATLAB, considering a road load model and dimensioning the efficiency of the different components involved to estimate energy consumption under different real-world driving conditions.
- Modelling the various components of the vehicle such as vehicle physical model, motor, battery system, fuel cell system, ultra-capacitor system and regenerative braking system through programming blocks.

- Applying the model to both light-duty vehicles and buses, assessing different powertrain designs to learn the financial benefits with CAPEX and environmental benefits for different types of vehicles, considering both certification and real-world drive-cycles.
- Computing and comparing the total ownership cost of the light-duty passenger vehicle to understand the long term and short-term benefit associated with different vehicles.

With the primary objectives to achieve with the developed model, detailed study is carried out and is explained in the following sections.

1.3. THESIS OUTLINE

The present thesis is subdivided into 5 sections, containing a total of 6 chapters

The thesis initially presents **INTRODUCTION** section, where an introduction to current technologies in the automotive sector is discussed on **MOTIVATION** section. **OBJECTIVES OF THE STUDY** explain the main expected results from the study and an overview of the thesis is described in **THESIS OUTLINE**.

Section **STATE-OF-THE-ART** discuss the existing vehicle types, **SHIFTING TOWARDS ALTERNATIVE VEHICLE TECHNOLOGIES** review the different types of vehicle powertrain in the automotive market. **LITERATURE REVIEW** examines the researchers conducted in relation to the area under the scope of the thesis.

Section **DATA AND METHODS** explain the development of the study, where MODEL DEVELOPMENT explain the mathematical equation, expression, and modelling of different components, APPLICATIONS OF THE MODEL discusses the scope of the study, utilisation of the model for different studies. **TOTAL OWNERSHIP COST ANALYSIS** shows the data gathered for the testing of the developed model related to the real-world model.

Section **RESULTS AND DISCUSSION** present the validation and results of the model, where PASSENGER CARS explain the results of the studies carried out in light-duty passenger vehicle and **BUSES** explain the studies and results of the bus. TOTAL OWNERSHIP COST ANALYSIS shows the results of the comparison study on financial effectiveness with real-world models.

Section **CONCLUSIONS AND FUTURE WORK** presents the analysis of the results and inferences that points, explaining the important findings and future steps ahead of this research work.

Section **REFERENCES** show the details of research articles, thesis articles, webpages, annual report and other references of the data which is used to carry out this research work.

2. STATE-OF-THE-ART

From the introduction, it is seen that the energy storage system is different from one another with respect to energy density, power density and other characteristics. This can lead to different energy consumption and range profiles. Before diving into the studies, it is important to understand and plan the study accordingly to achieve accurate results. For this, a background study has been conducted to analyse the present vehicle technologies, energy sources and mobility patterns.

Following subsections present a brief overview of the introduction to alternate vehicle technologies and energy source in the automotive field, proving the current technologies used, future forecasts and objective, researches and studies conducted. It shows how a better understanding of the future behaviour of the automotive sector is acquired according to different choices related to the vehicle powertrain, power source and other factors.

2.1. SHIFTING TOWARDS ALTERNATIVE VEHICLE TECHNOLOGIES

Facing the challenges on global warming and GHG emissions, the EU claims that cars are responsible for around 12% of EU emission of carbon dioxide (CO_2) to the atmosphere [26]. To control the emission various measures such as new regulation and alternate vehicle technologies has been adopted.

During the past decades, the EU was strictly following and updating new regulation to control the emission from the cars. A target of 130 grams of CO_2 per kilometre was the milestone set as the average emissions for new cars produced between 2015 and 2019. This emission corresponds to fuel consumption of 5.6 litres per 100 km. Surprisingly, the EU managed to achieve the milestone in 2013, two years ahead of the schedule. Currently, the European Parliament has adopted Regulation (EU) 2019/631, which introduces new CO_2 emission performances for new passenger cars and vans for 2025 and 2030. The new target is to achieve emission of 95g CO_2/km for the new cars, which is equivalent to 4.1 l/100 km in gasoline. The new regulation started applying on 1st of January 2020 and replaced the repealed regulation (EC) 443/2009 [27]. To motivate the manufacturers, additional incentives were introduced for zero and low emission cars with emission less than 50g CO_2/km. Besides, EU policy, 2009/28/EC promotes the integration of renewable energy into the road transportation sector [26]. The target is to include biofuel and alternative fuels into the transportation sector to reduce the use of fossil fuels and to increase the share of alternative fuels.

Currently, there are 5 main types of vehicles available in the market. Internal combustion vehicle (ICE), hybrid vehicles (HEV), plugin hybrid electric vehicles (PHEV), battery electric vehicle (BEV) and fuel cell electric vehicles (FCEV). ICE is the most common vehicle than can be seen around the world. Due to industrialisation in the last century, gasoline vehicles got popular than the rest. However, the uncontrolled emission made the world notice its defects and also the price volatility of fossil fuel raises concerns. Hybrid vehicles, introduced in the 1990s, are a bit more efficient, with small electrification of the powertrain, enabling multiple energy sources. Further, PHEV combines electricity coming from the battery with an additional IC serving as a range extender.

The penetration of alternative vehicle technologies has been slow, but the market has started to recognise the benefits of electric vehicles. Higher powertrain efficiency, zero-emission and nearly cheaper maintenance and operational cost attracted more customers and increased the demand for BEV. FCEV has also been introduced into the market to support long-range drive with zero-emission and lesser refuelling time. Even though the powertrain is less efficient than BEV, the performance is equal to or superior, and quick refuelling option made it an option in the market.

The presence of an alternative energy source is not only limited to the automotive sector, but also in aviation and cruise industries. Instead of the battery as the power source, the fuel cell is tested widely by different research institutes to reduce the carbon footprint of aviation and cruise sector [28]. One of the complimentary reason for this is the by-product of the fuel cell. The heat energy released from the fuel cell is used for space heating and another by-product, water is used for other purposes.

Compared to conventional vehicles, hybrid electric vehicles (HEVs) are more fuel-efficient due to the optimization of the engine operation and recovery of kinetic energy during braking. With the plug-in option (PHEV), the vehicle can be operated on electric-only modes for a driving range of up to 30–60 km or combined with gasoline for 300 km, while battery electric vehicle (BEV) option can cover the same distance without the usage of gasoline. The BEVs are charged overnight from the electric power grid where energy can be generated from renewable sources such as wind energy. Fuel cell vehicles (FCV) use hydrogen as a fuel to produce electricity, therefore they are emission-free during the operation phase. When connected to the electric power grid (V2G), the BEV and FCV can provide electricity for emergency power backup during a power outage. Due to hydrogen production, storage, and the technical limitations of fuel cells at present, FCVs are not available widely, but as a demonstration in specific markets. HEVs are likely to dominate the advanced propulsion in the coming years. Hybrid technologies can be used for almost all kinds of fuels and engines. Table 2 shows the characteristics of different types of vehicles based on their powertrain.

Table 2: Common vehicle characteristics with different powertrain [6]

Type of vehicle	Battery EV	Hybrid EV	Fuel cell EV
Propulsion system	• Electric motor drive	• Electric motor drive • IC engines	• Electric motor drive
Energy system	• Battery • Ultra-capacitor	• Battery • Ultra-capacitor • IC engine unit • Fuel cell	• Fuel cells • Battery/Ultra-capacitor
Energy Source	• Electric grid charging facilities	• Gasoline stations • Electric grid charging	• Hydrogen stations
Characteristics	• Zero-emission • High energy efficiency • Independent on oil • Relatively short range • High initial cost • High recharging time • Low unit energy cost	• Low emissions • High fuel economy compared to ICE; less efficient w.r.t BEV • Long driving range • High initial cost • Less recharging and refuelling time • Dependent on oil • Moderate unit energy cost	• Zero-emission • Comparatively less efficient w.r.t BEV • Independent to oil • Long driving range • Very high initial cost • Under the development phase • Very high unit cost
Major Issues	• Battery and battery management • Charging facilities	• Maintenance for multiple powertrains • Battery sizing and management	• Hydrogen refuelling station • Fuel cell cost

In BEVs and FCVs, there are more electrical components used, such as electric machines, power electronic converters, batteries, sensors, and microcontrollers. In addition to these electrification components or subsystems, and mechanical and hydraulic systems may still be present. The challenge presented by these advanced propulsion systems includes advanced powertrain components design, such as power electronic converters, electric machines and energy storage; power management; modelling and simulation of the powertrain system; hybrid control theory and optimization of vehicle control.

Traditionally, there are two basic categories of powertrain architecture, namely series hybrids and parallel connections. Normally such architectures are accommodated in hybrid electric vehicles. In series HEV, the ICE mechanical output is first converted to electricity using a generator. The converted electricity either charges the battery or bypasses the battery to propel the wheels via an electric motor. This electric motor is also used to capture energy during braking. A parallel HEV, on the other hand, has both the ICE and an electric motor coupled to the final drive shaft of the wheels via clutches. This configuration allows the ICE and the electric motor to deliver power to drive the wheels in combined mode, or ICE alone, or motor alone modes. The electric motor is also used for regenerative braking and for capturing the excess energy of the ICE during coasting. Recently, series-parallel and complex HEVs have been developed to improve the power performance and fuel economy [6]. More details of motor, battery, fuel cell and ultra-capacitors are discussed late in the thesis.

2.2. LITERATURE REVIEW

The thesis is based on the experimental and simulation work in a relatively pioneering field. This section gives an overview of scientific papers, book, webpages and other experiments carried out, whose scope is wider or lesser extent related to simulation and design of powertrain. Referring to and consulting those materials helped to have deeper insight on this thesis topic and to consider the right methodology and technological option for the design and simulation process, and also to carry out other specific tasks within the scope of this thesis. These studies are aggregated based on the powertrain design and modelling approaches by different authors and studies carried out on systems used for energy storage in vehicles. The reviewed studies are consolidated based on power train simulation and energy storage advancements.

- **Studies on Powertrain simulation**

The research study has been conducted to improve fuel economy and performance of fuel cell hybrid electric vehicles using optimized energy management strategy [29]. For the studies, the fuel cell is considered as primary energy source, and battery or ultra-capacitor as secondary source with intelligent control technique created in fuzzy logic control. The powertrain is designed in ADVISOR and performance for 22 different cycles are evaluated. The results show that the improvement of the vehicle system by 18.8% - 26% in 0-100km/h speed tests with improved fuel economy.

Different studies has been done on range, state-of-charge(SOC), and traction system efficiency estimation of the electric vehicle [30]. For the studies, an algorithm was developed which resembles the vehicle model. The model was tested in on-road conditions and the model was considered reliable with an error of 0.5% with an average traction efficiency of 84%.

To study the vehicle range, a multi-objective optimization model was developed to predict the range of the electric vehicle at a constant speed [31]. Two approaches were introduced for the studies, approach 1: constant battery voltage approach, and approach 2: battery voltage as a function of SOC. The study shows that at the higher velocity the energy consumption is also higher in both approaches, while range prediction from approach 2 was lower than the approach 1, whereas both approaches resulted in same curve pattern for different speeds.

Studies were conducted to identify the vehicle auxiliary loads through on-road and dynamometer evaluation [32]. Four different vehicles were tested to analyse the auxiliary consumption and are tested in the laboratory for various certified drive cycles and also on-road. The authors concluded that the on-road auxiliary load can be varied from 135W to over 1200W for normal vehicles based on ambient conditions and utilization factor.

The effect of ambient temperature in energy consumption and range is studied with standard drive cycles in the Nissan leaf BEV [33]. A model is developed and is tested against Urban Driving Schedule (FUDS), simplified FUDS (SFUDS), and New European Driving Cycle (NEDC) driving cycles. The results have shown that the range is estimated as 150km at an ambient temperature of 20°C and the range decreased to 85km and 60km when temperature changes 0°C and -15°C respectively.

The environmental and economic benefits of less aggressive driving has been studied to learn the advantages in real world driving in Lisbon, Portugal [34]. Data from two sample sets were recorded and collected and is evaluated to determine the energy consumption and emission impacts. The results show the aggressive driving results in an increase in energy consumption by ~200% and emission by 300%. The economic analysis showed that a saving of 52.5 k€ can be saved daily within the urban region with respect to emission compensations.

A new energy and power management control strategy for battery electric vehicle with superconductors based on speed command and acceleration estimation is presented to improve the performance of the vehicle [35]. The purpose of the control strategy was to increase the energy extraction through regenerative braking and to improve DC bus voltage regulation. The model shows improvement in size, weight, cost and acceleration with 0-100km/h within 20 seconds. The proposed method by the author saves the energy by 6%, and the DC bus voltage regulation reduces by 4.2%.

Experiments on thermoelectric generator were carried out to study the electrical performance for automotive waste heat recovery [36]. The thermoelectric generator generates electricity from waste heat energy from automotive exhaust. The results portraits that the TEG helps to reduce the power loss by 11% from theoretical maximum power and the energy production increases to 22.5% of power loss with the reduction of thermal insulation thickness.

- **Studies on energy storage**

Several studies has been carried out on various categories of energy storage systems. According to the article [37], authors discuss specific energy, energy density, specific power, energy-efficient and operating temperature of different energy storage systems. They concludes that in the battery category, Li-ion batteries are a far better option due to high energy density, a wide range of operating temperature, efficient application and also due to researches in low-cost lithium battery systems.

Experimental studies were conducted on ultra-batteries for hybrid electric automotive vehicles to assess the performance [38]. Ultra battery is a hybrid energy storage device, consisting of asymmetric superconductors and a battery (lead-acid) in an unit. Authors claim that it helps to merge the best from both the technologies without extra electronic controls. The test results showed that the discharge and charge power of ultra-battery has been improved by 50-60%, have higher service lifetime (~370,000 cycles), and comparatively in a lesser size.

Several research papers details the developments of electric vehicles and hydrogen fuel cell vehicles over the years [39]. The authors points out the different power sources for hybrid vehicles and advantages over others. Reference [40] defines on the economic and commercial viability of hydrogen fuel cell in the automotive sector, and [41] describes the economic and environmental concerns of the fuel cell in the automotive field. They also explained about different kind of fuel cells that are in use and about the applications of fuel cell and auxiliary systems in the automobile field.

A comparative study have been done on different fuel cells to learn its advantages and flaws on electric vehicles [42]. The authors concluded different fuel cell operate similarly, however, alkaline fuel cell (AFC) is the most efficient fuel cell with 60%, followed by polymer electrolyte membrane (PEMFC) with 58%. Even though AFC is more efficient than PEMFC, PEMFC is favoured for automotive application. The author concludes that direct methanol fuel cell (DMFC) and phosphoric acid fuel cell (PAFC) more economical than other fuel cells, but they are less efficient which makes them less attractive.

The concentration of the platinum catalyst on proton exchange membrane fuel cell (PEMFC) analysis has been carried out for a detailed study to analyse the influence on economic assessment of fuels cell in the automotive sector [43]. From the point of the author, PEMFC is suitable due to the good performance and durability of stack component and improvement of balance of stack. The closing remarks point out that the cost and durability objectives of the fuel cell and PGM (platinum group metal) - free ORR (oxygen reduction reaction) catalysts, that will be met in the next eras, and provides a viable alternative for the internal combustion engines with fuel cells.

Technical studies on hydrogen energy systems for the sustainable road transportation system were carried out to know more about the emission of greenhouse gases (GHG), technical issues (such as hydrogen production storage and utilization) and its control strategy of using hydrogen as fuel [7]. The author concludes that the transformation from liquid fuel to gaseous fuel (CNG) with hydrogen (18% hydrogen – CNG blend) is the first step towards sustainable transportation.

Experimental studies on ultra-capacitor storage unit is done to analyse the effectiveness during regenerative braking system [44]. Electricity generated from the braking process through the rotating machinery has been done at a designed test rig to monitor and analyse the charging voltage at different states of 16.2V 65F ultra-capacitor. The results pointed out that the ultra-capacitor can absorb more energy when it is in a low voltage state.

Review study on supercapacitor modelling, estimation and its application highlights the development of technology, control management and application of supercapacitors [45]. The article summarises that the supercapacitors are a promising energy storage technology with peak power delivery, high power density, low internal resistance and durability of 1 million charging cycles for a wide range of operating temperature.

Multiple experimental studies of the application of ultra-batteries were carried out with hybrid fuel cell vehicles [46]. The result of the studies showed lithium battery recycles 0.1% more work than ultra-battery, while the ultra-battery is 0.1% inferior to a lithium battery with fuel economy. Also, the paper points out the expected cost of ultra-batteries for same application is 35% less than that of lithium batteries.

The studies on the benefits of adding ultra-capacitor to a fuel cell battery hybrid bus through simulations was done to analyse the heavy duty vehicle performance [47]. The test was conducted on Manhattan Bus Cycle and UDDS drive cycle. A combination of 6 different combinations was tested and the results showed improvements in battery C rates and results in saving cost by 10% and weight by 5% when using ultracapacitor with a battery than using 2x battery.

The review article on different type of electrochemical hydrogen storage system, explains the new opportunities in fuel storage, batteries, fuel cell and supercapacitors [48]. The author details that the electrochemical storage of hydrogen can be conducted at low temperature and pressure with simple reversible devices. It is possible to develop supercapacitors with exceptionally high specific capacitance in the order of 4000F/gm, however, there is no solid strategy to track the most capable material.

An experimental studies has been carried out about fuel cell and lithium iron phosphate battery hybrid powertrain with direct parallel structure of the ultra-capacitors bank [49]. The DC bus voltage is stabilized using a fuzzy logic controller via bi-directional DC/DC converter. The test results show that the fuel cell system has the narrowest power distribution during a dynamic cycle to satisfy the slow dynamic variation, the changing trend of LiFePO4 battery pack power is coincident with the fuel cell system, and the ultra-capacitor bank is controlled to meet fast dynamic load requirements.

Technical analysis of the application of open-pore cellular foam (OPCF) as flow distributor in PEM fuel cell is performed [50]. Also, comparative analysis of the performance of air-breathing PEM (ABPEM) and pressurised air PEM (PAPEM) is conducted. The results showed that the ABPEM fuel cell, using OFCP showed a better performance than the conventional flow plates. On having polytetrafluoroethylene (PTFE) coating on OPCF, PTFE coating improved the in-situ and ex-situ performance of the PEM fuel cell environment.

These references give an outline of the existing studies regarding this research. Consequently, few studies have developed a vehicle segment modelling approach to evaluate the powertrain design of the electric vehicle, capable of assessing energy performance and cost-effectiveness. However, they are prescriptive in nature and do not give any actual insight into the powertrain system nor vehicle performance assessment with multiple power sources. It lacks flexibility, insights and restricts the possibilities of developing a hypothesis for new hybrid models that can be experimented. This work aims to develop a model that helps to understand and study the possibilities of combining different energy sources and assess the performance, energy consumption and range in different operational conditions.

3. DATA AND METHODS

Numerous simulation and testing softwares were released in the market in the earlier period. Most of the softwares were developed and licenced by private organisations for private simulation purposes. Facing the lack accessibility to such softwares, and lack of flexibility to combine different power source to carry out the studies as prescribed, a new simulation model is required which is adaptable to simulate different vehicle model and the change in available energy for traction in different energy sources. A new model was developed in Simulink toolbox in MATLAB, which satisfies the requirements. Simulink is a tool developed by the company MathWorks, for modelling, simulation and analysis of dynamic systems. Its primary interface is a graphical block diagramming tool and customizable block libraries. The software offers high integration with the rest of the MATLAB environment. The structure of the simulation model is explained in section 3.1.

3.1. MODEL DEVELOPMENT

The ultimate aim of this model is to generate a flexible model which is compatible for the simulation of different vehicle types with minimal revision or no revision during the simulations. To achieve this, simple mathematical operations and relations were used and the graphical-based model is built. The whole model is divided into several smaller subsystems, which is easily understandable by a third person and allows to modify based on the requirements in the future. Modelling of each subsection are presented in detail from section 3.1.1 to section 3.1.7. Figure 1 shows the developed model in Simulink.

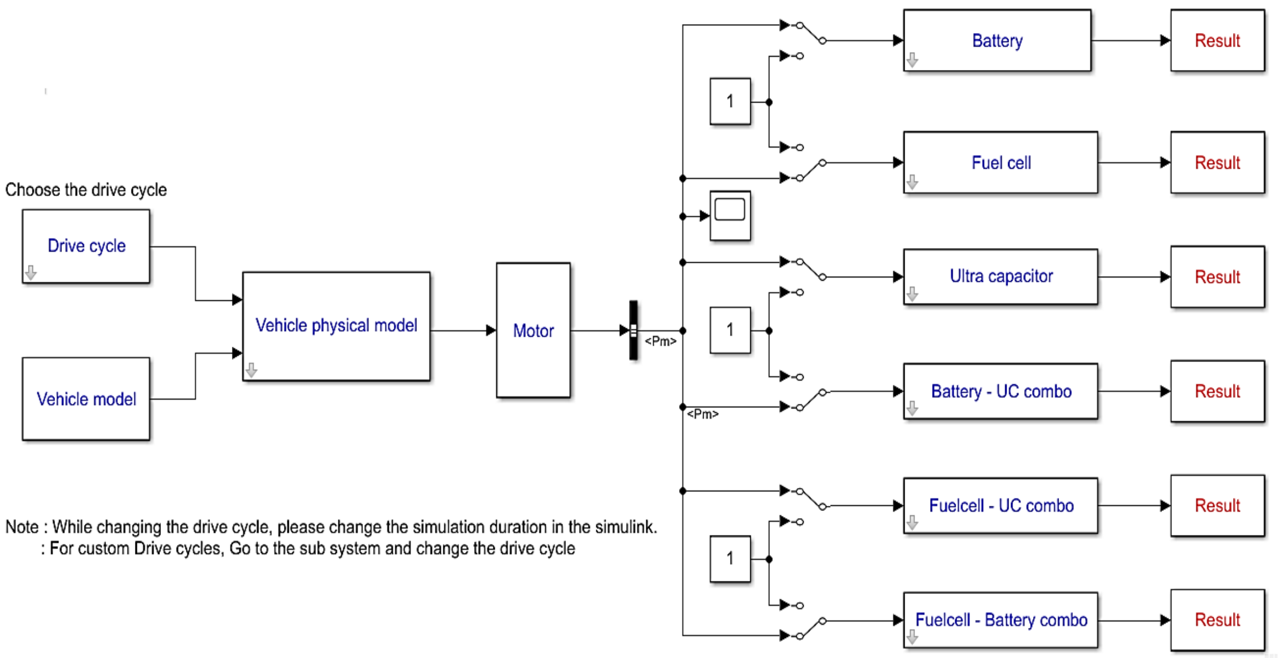

Figure 1: Diagram of the model in Simulink

A simulation model is developed in Simulink toolbox in MATLAB 2018b which allows simulating different types of vehicles such as an electric vehicle (EV) and Fuel cell electric vehicle (FCEV) with combination of different energy sources such as battery, fuel cell and ultra-capacitor. The simulation model for different vehicle types receives the drive cycle data and estimates the energy consumption and range of the vehicle. This model focuses only on energy use during the vehicle usage stage (Tank-to-Wheel) and does not consider the energy production stage (Well-to-Tank).

This model permits to simulate a wide range of vehicles in the market, as well as possible future vehicle design with different powertrains. The model is developed based on mathematical equations which consider different physical and design variables. The model comprises of 7 subsystems, namely drive cycle, vehicle model, vehicle physical model, motor, battery system, fuel cell system and ultra-capacitor system. The inputs for the simulation are given in the subsystem: vehicle model, which includes vehicle specifications such as mass, drag co-efficient, vehicle dimension and, powertrain requirements. Figure 2 shows the subsystems of the vehicle in the simulation model.

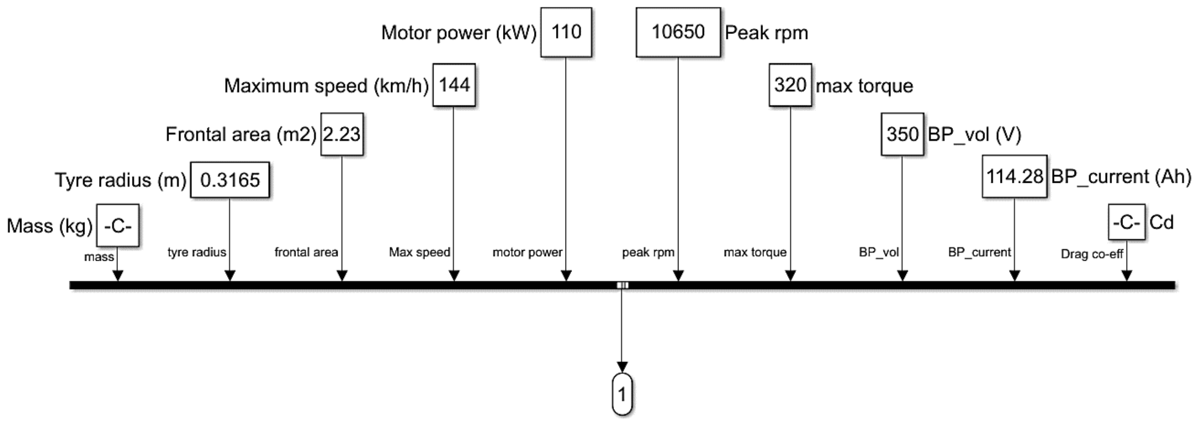

Figure 2: Vehicle model subsystem (example with Nissan Leaf 40 kWh specs)

3.1.1. DRIVE CYCLES

Drive cycle is a set point that represents the speed of the vehicle with respect to the time(s). The energy consumption of the vehicle primarily depends upon the drive cycle. The drive cycle data can be obtained by a real-world drive cycle (recording the speed of the moving vehicle on on-road conditions), or from a theoretical standard drive cycle developed by countries or organisation to perform certification and test of the vehicle in comparable conditions. Routinely standard drive cycles are used to estimate the range, efficiency, fuel consumption and emission of pollutants such as carbon monoxide (CO), Nitrogen oxides (NO), volatile organic compounds (VOC) and particle matters (PM) of the vehicles.

Concerning certification drive cycles, the different automotive markets or countries have their own specific certification cycles which resemble the driving condition and patterns ranging from the European drive cycle, American drive cycle, Japanese drive cycle, ARTEMIS, etc.[51]. Some of the most commonly used drive cycles for simulation purposes in the developed model are NEDC drive cycle, WLTP drive cycle, FTP 75 cycle, and HWFET drive cycle.

- **NEDC cycle (New European Drive cycle)**

The New European Drive cycle represents the typical usage of the vehicle in European road conditions. It is intended to forecast the fuel economy and emission in conventional vehicles, and electric energy consumption and range prediction in electric vehicles. The NEDC drive cycle consists of four repeated ECE-15 urban drive cycle (UDC) with one Extra Urban Drive Cycle (EUDC). The cycle was introduced in the early period of the 1990's and was last updated in 1997, then is used till 2016 for vehicle testing and validations until WLTP cycle got introduced. Figure 3 shows the NEDC drive cycle with total distance and average speed.

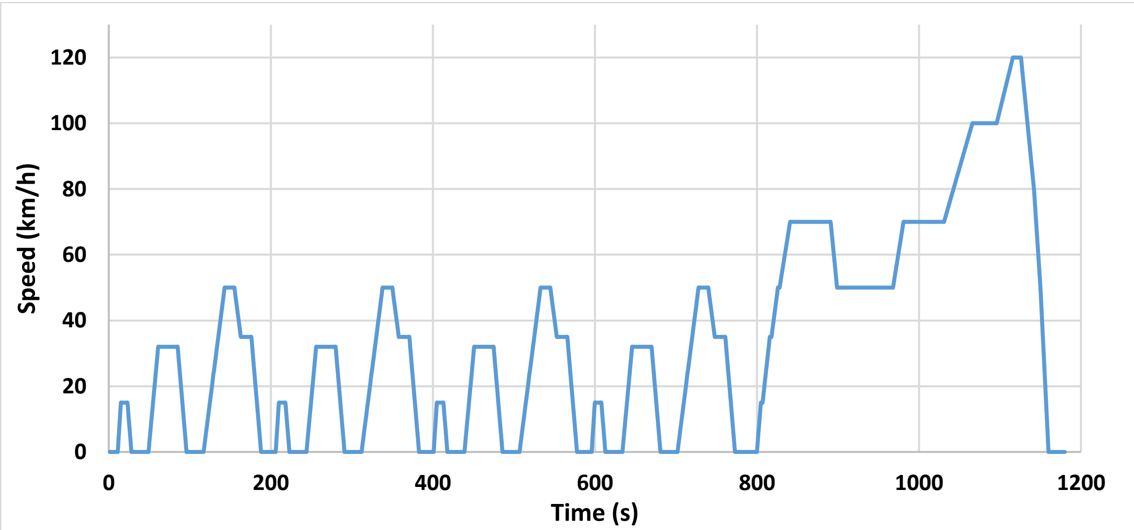

Figure 3: NEDC drive cycle (Avg. Speed – 33.35 km/h; Distance – 10.9 km)

The cycle is recommended to test vehicles at an ambient temperature between 20-30°C and on a flat road. Like most of the drive cycles, road grade is not included in the NEDC certified drive cycle. ECE-15 UDC cycle duration is 195s with an average speed of 18.35km/h covers 0.994km. This cycle is repeated 4 times and reaches 780s of NEDC cycle. It is then combined with EUDC cycle with a duration of 400s, with average speed 62.6km/h, covering a distance of 6.96km for the NEDC cycle, to get a total duration of 1180s with an average speed of 33.35 km/h, covers a distance of 10.9 km with a maximum speed of 120 km/h.

- **WLTP cycle (Worldwide harmonised Light vehicle Test Procedure)**

Worldwide harmonised Light vehicle Test Procedure is a worldwide recognised standard drive cycle to determine emission and fuel consumption in traditional vehicles, and electric energy consumption and range prediction in electric vehicles. This certified drive cycle was developed by the United Nations Economic Commission for Europe (UNECE) to replace the NEDC cycle. The drive cycle was released in 2015 and is used globally to estimate the energy consumption and emission with the on-road conditions. Besides Europe, WLTP is the standard fuel economy and emission test for other countries like India, South Korea and Japan. From 2016, vehicles started to test under the WLTP cycle and from 2019 September, all light-duty vehicle must comply with the WLTP cycle to get registered in EU. The new standards have been designed to be more representative of real driving conditions and are achieved through dynamic velocity profile, quick acceleration followed by short braking and longer test time.

WLTP consist of three drive cycle. The test cycle depends on the vehicle class, which is determined by power to weight ratio (*PWr*) of the vehicle.

$$PWr = \frac{Rated\ engine/motor\ power\ (W)}{Curb\ weight\ (kg)} \quad \text{Equation 1}$$

- <u>Class 1</u>

Class 1 vehicle is low powered vehicle with the power to weight ratio less than or equal to 22(W/kg). The cycle duration is 1022s with a maximum speed of 64.4km/h, the average speed of 28.5km/h covers a distance of 8.09km. Figure 4 shows the WLTP class 1 drive cycle.

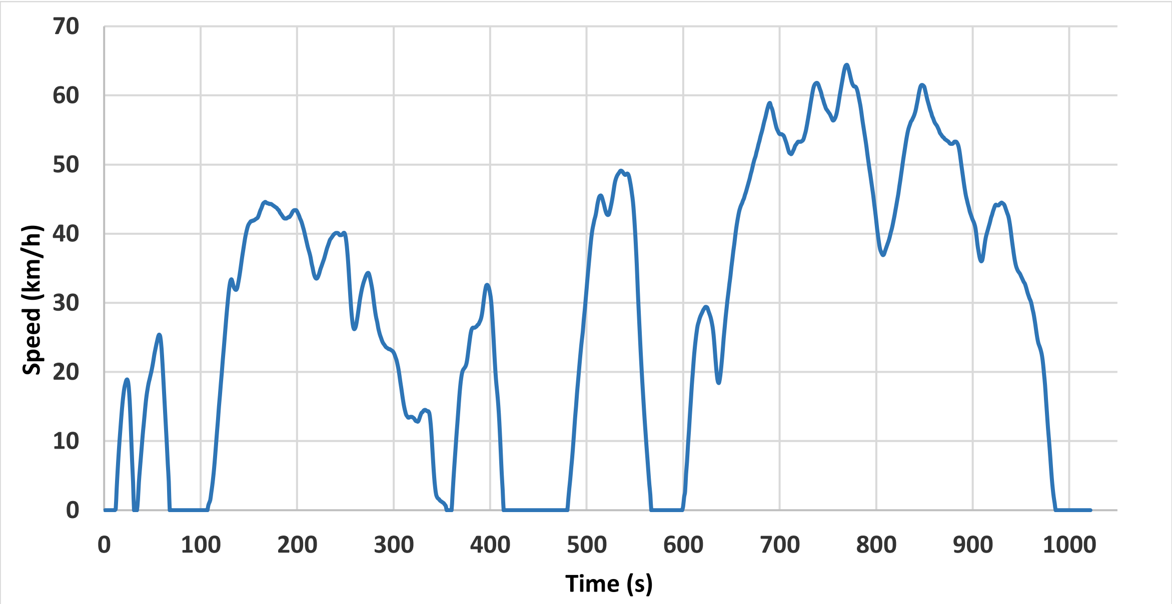

Figure 4: WLTP class 1 drive cycle (Average speed – 28.5 km/h, Distance – 8.09 km)

- <u>Class 2</u>

Class 2 vehicle are those with the power to weight ratio in between 22 and 34W/kg. A wide range of vehicles like vans or buses falls under this category due to higher curb weight. The cycle duration is 1477s with a maximum speed of 85.2km/h, the average speed of 35.7 km/h and covers a distance of 14.66 km. Figure 5 shows the WLTP class 2 drive cycle.

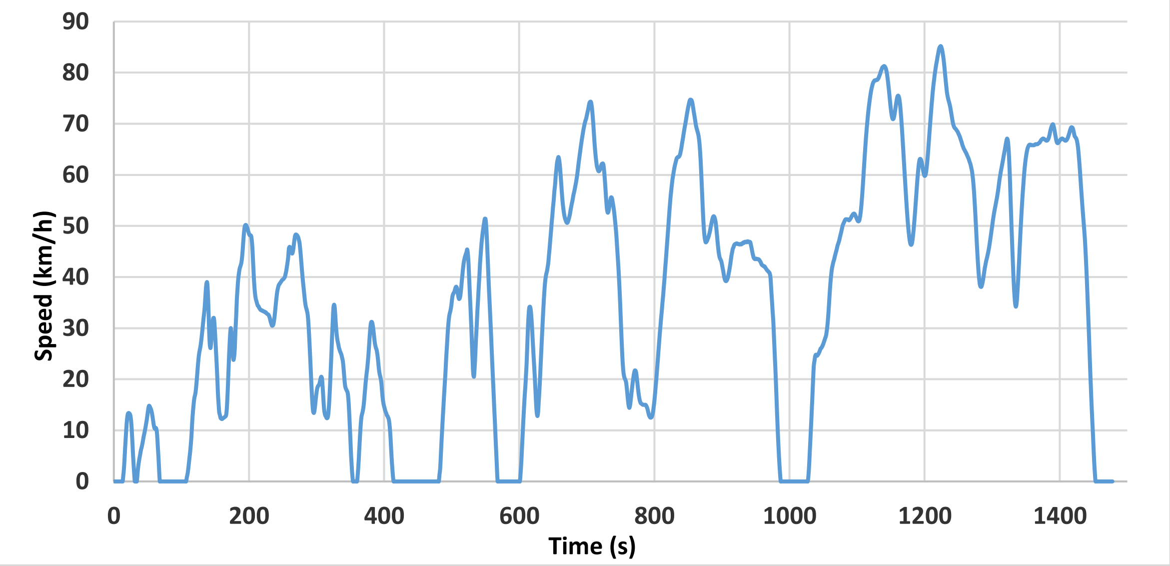

Figure 5: WLTP class 2 drive cycle (Average speed – 35.7 km/h, Distance – 14.66 km)

- <u>Class 3</u>

Class 3 vehicle is high power vehicle, with the power to weight ratio greater than 34W/kg. Most light-duty vehicles fall under this category with a power to weight ratio between 40 – 100W/kg. The cycle duration is 1800 seconds with a maximum and average speed of 131.3km/h and 46.5km/h respectively, covers a distance of 23.26km. Figure 6 shows the WLTP class 3 drive cycle.

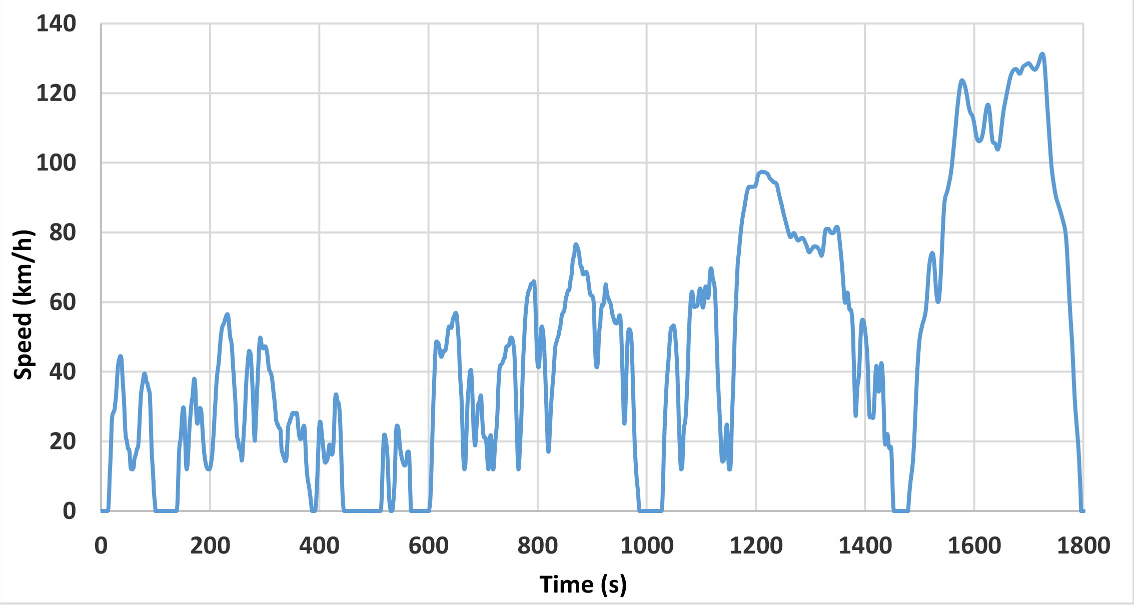

Figure 6: WLTP class 3 drive cycle (Average speed – 46.5 km/h, Distance –23.26 km)

- **FTP 75 cycle (Federal Test Procedure 75)**

Federal test procedure 75 is used for emission certification and fuel economy testing of light-duty vehicles or passenger cars in the United States. The FTP-75 cycle consists of 3 phases; cold start transient phase, stabilized phase and hot start transient phase. The cold and hot transient phase is similar to the first 505s of Urban Dynamometer Driving Schedule (UDDS) cycle. Apart from the US, many other countries such as Australia uses the FTP-75 cycle for the certification process. Figure 7 shows the FTP-75 cycle. The cycle duration is 1877s with a maximum speed of 91.25km/h, the average speed of 34.12km/h covers a distance of 17.77km.

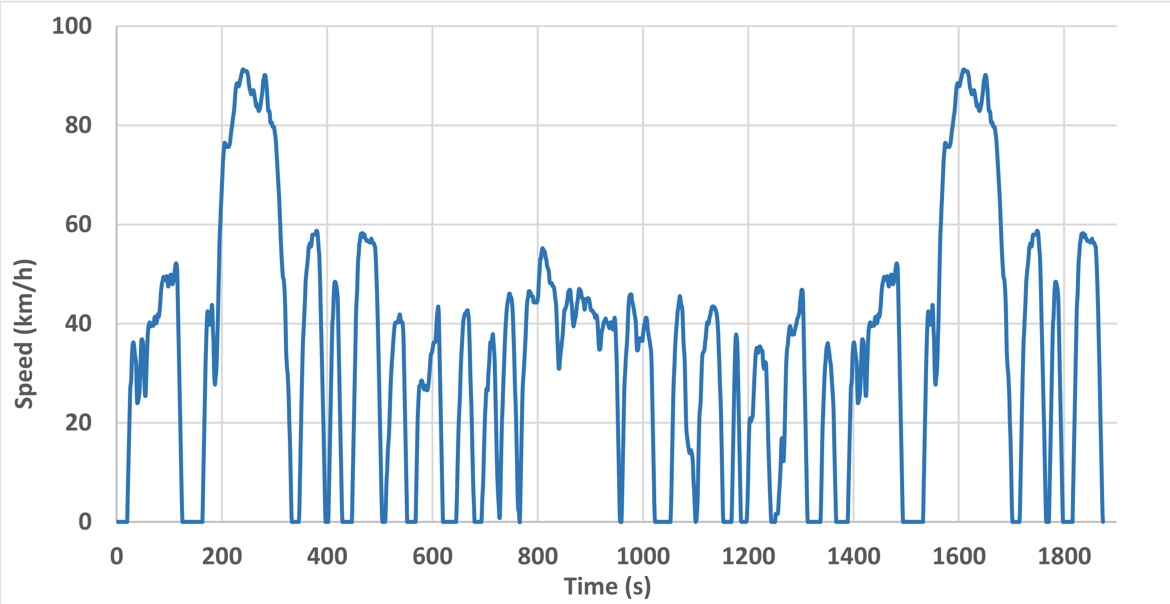

Figure 7: FTP-75 drive cycle (Avg. speed – 34.12 km/h; Distance – 17.77 km)

- **HWFET cycle (Highway Fuel Economy Test)**

Highway Fuel Economy Test is developed by the Environmental Protection Agency (EPA), USA, is used to determine the fuel economy rates in the highway for light-duty vehicles. This cycle is unique form other considered cycles due to its non-stop driving behaviour. The cycle duration is 765s with a maximum speed of 97km/h, the average speed of 77.7km/h over a distance of 16.45km. Figure 8 shows the HWFET drive cycle.

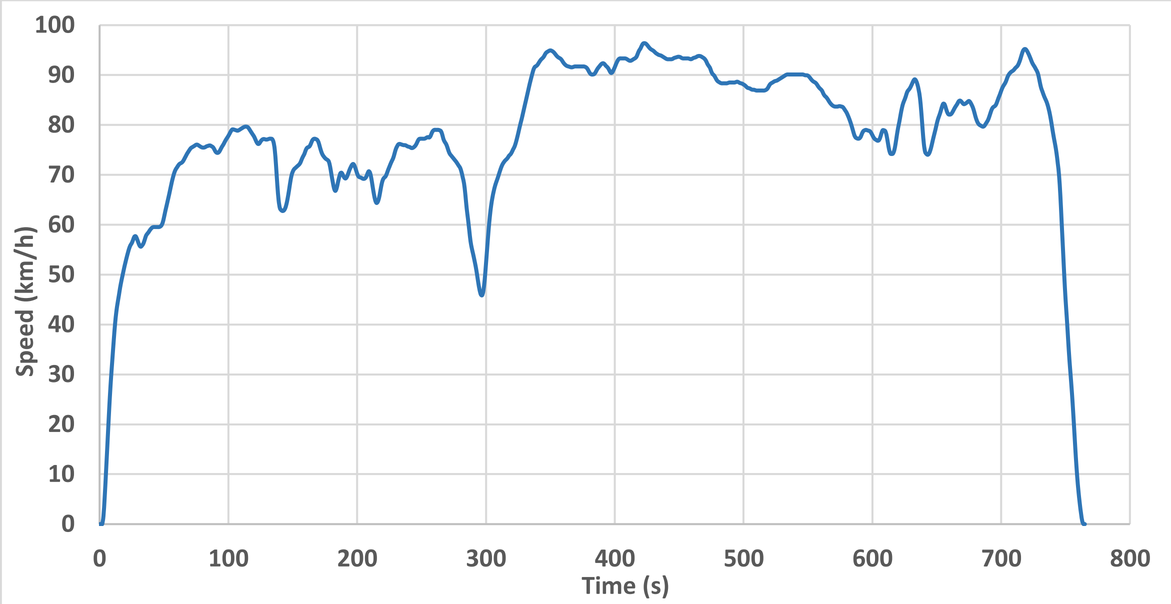

Figure 8: HWFET drive cycle (Avg. Speed – 77.7 km/h; Distance – 16.47 km)

3.1.2. VEHICLE PHYSICAL MODELLING

A generic vehicle model is created in Simulink, comprises of mechanical and mathematical principles which describe the behaviour of an operational vehicle. The application of road load models is consistently used in the literature to describe the behaviour of vehicles [52], but limited attention has been given to vehicle physical model and its powertrain. Considering a one-dimensional movement vehicle fundamentals, the power requirement of the vehicle in each second in a specific drive-cycle depends upon the basic vehicle loads forces, such as aerodynamic drag, rolling resistance and acceleration force, as presented in Figure 9.

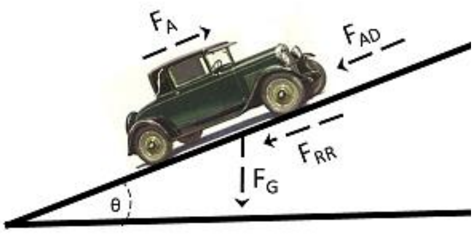

Figure 9: Forces acting on a vehicle, where F_A is the acceleration force, F_G is the grade force, F_{RR} is the rolling resistance force and F_{AD} is the aerodynamic drag force.

Figure 10 shows the developed model with the vehicle fundamentals and basic vehicle loads as explained above.

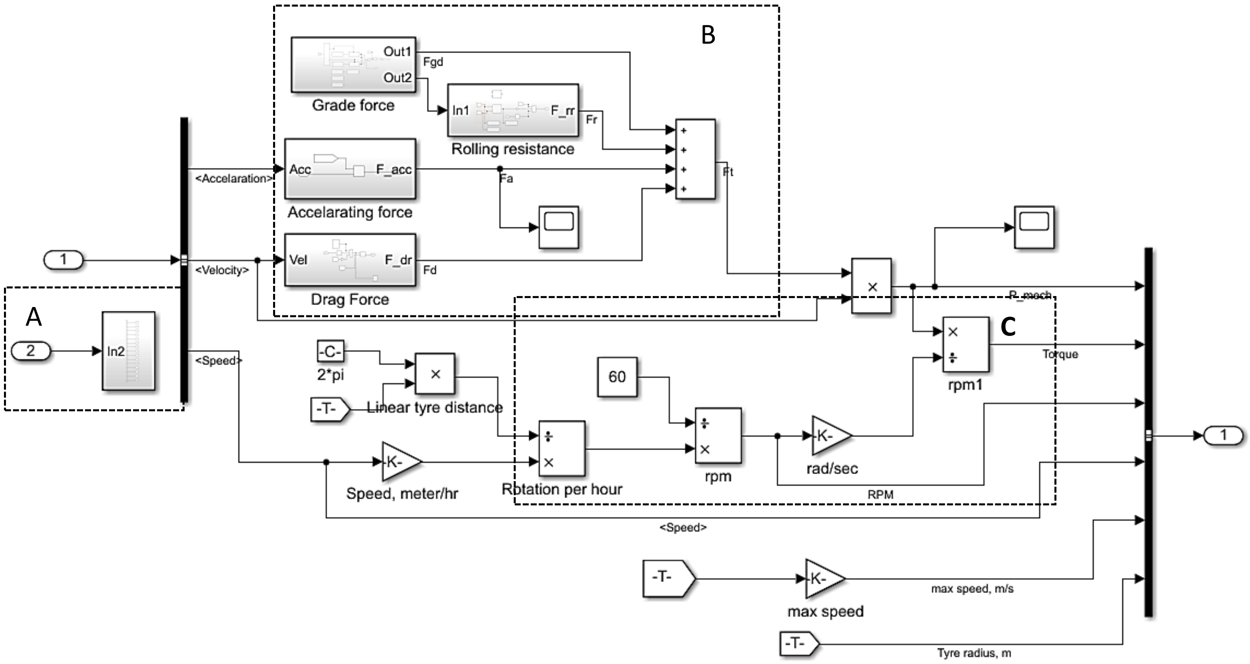

Figure 10: Vehicle physical model

Section A shows the inputs received from the vehicle model subsystem. These inputs are stored as variables and is used as global inputs throughout the simulation. Section B represents the calculation of traction force, which requires to move the vehicle during acceleration. The calculation of traction force is defined in detail through equation 2 to 7, while section C shows the calculations of torque and rpm at the wheel of the vehicle.

The traction force (F_T) required to move the vehicle is calculated by equation 2.

$$F_T = F_A + F_G + F_{RR} + F_{AD} \qquad \text{Equation 2}$$

Where F_A is the acceleration force(N), F_G is the grade force(N), F_{RR} is the rolling resistance force(N), and F_{AD} is the aerodynamic drag force(N).

The acceleration force is defined as the force required to move an object of mass m(kg) with an acceleration of a(m/s^2), as expressed in equation 3.

$$F_A = m*a \qquad \text{Equation 3}$$

F_A becomes positive if the vehicle is accelerating and become negatives if the vehicle is on deceleration. The gravitational force acting on the vehicle depends upon the slope of the road, as expressed in equation 4.

$$F_G = m*g*\sin\theta \qquad \text{Equation 4}$$

Where g is the acceleration due to gravity(m/s^2) and θ is the angle of inclination of the surface(degrees). The force that restricts the rolling motion on a surface is termed as rolling resistance force and is produced at the contact surface of the flattened area of tires on the road. It is also termed as rolling friction and is given by equation 5.

$$F_{RR} = Cr*m*g*\cos\theta \qquad \text{Equation 5}$$

Where Cr is the coefficient of rolling resistance. Aerodynamic drag is the resistance force developed by the air on the moving direction of the vehicle. The force is given by equation 6.

$$F_{AD} = \frac{1}{2}*Cd*\rho*A_f*v^2 \qquad \text{Equation 6}$$

Where Cd is the coefficient of drag, v is the velocity (m/s), ρ is the density of air(kg/m^3) and A_f is the frontal area of the vehicle(m^2). Incorporating all the parameters, the total traction force, F_T at the driving wheels is expressed as:

$$F_T\,(N) = m*a + \frac{1}{2}*Cd*\rho*A_f*v^2 + Cr*m*g*\cos\theta + m*g*\sin\theta \qquad \text{Equation 7}$$

The torque, τ(N.m) is defined as the rotational equivalent of linear force. Torque produced in the wheel is an important parameter to be defined to determine the characteristics of vehicles and for further calculations. To find the torque, initially, the rotational speed, $\omega(rpm)$, of the wheel is calculated using equation 8.

$$\text{Rotational speed, } \omega(rpm) = {s*1000}/{l*60} \qquad \text{Equation 8}$$

Where s is the speed of the vehicle(km/h) and l is the linear distance of the tire(m). Torque is calculated as defined in equation 9.

$$\text{Torque, } \tau\,(Nm) = \frac{F_T*v}{\left(\omega*\frac{2\pi}{60}\right)} \qquad \text{Equation 9}$$

Since these studies aim to simulate different vehicle in different conditions, the model is made adaptable and flexible. The ambient temperature is given as input in the vehicle model and the model calculates the required auxiliary power, rolling resistance and air density of the vehicle by itself. It is observed that the auxiliary power consumption is higher during lower temperature, optimal in between 20°C and 30°C and again rises as temperature increases (due to air conditioning) [53]. While for rolling resistance, when the temperature drops, the pressure inside the tyre also drop. It results in more area of the tyre to be in contact with the road and, hence more resistance. For the studies, a range of rolling resistance is considered based on the researches carried out in different temperature [54]. Considering constant pressure, the temperature is inversely proportional to air density. As the temperature decreases, the air density will increase [55]. As shown in equation 6, the increase in air density will lead to an increase in aerodynamic force.

3.1.3. MOTOR MODELLING

Electric vehicles are now seen as the future of automobile because of its capability to replace the environmental problems caused by IC engines. Electric motors have proven to be a suitable substitute for the role of the IC engine in the automobile field. Vehicle propulsion has specific requirements which distinguish stationary and on-board motors. As the weight increases by 1kg, it represents the increase of structural load and thus energy consumption. Due to this, it is important to have a high efficiency motor for the reduction of energy demand and thus the battery weight. Permanent Magnet (PM) motors have the highest efficiency, thus appears to be the suitable option. Table 3 shows different EV manufacturers, models and motors used in the powertrain.

Table 3: Electric vehicles in the market and type of motor installed

MANUFACTURER	MODEL	TYPE OF MOTOR
AUDI	Q4 E-Tron	AC Induction
AUDI	E-Tron Quattro	
BMW	SÉRIE i3	BMW eDrive Hybrid Synchronous Motor
CHEVROLET	Spark EV	Permanent Magnet Synchronous
CHEVROLET	BOLT EV	
CITROËN	C-ZERO	
FORD	FOCUS Electric	
HYUNDAI	IONIQ Electric	
HYUNDAI	KAUAI Electric	
HYUNDAI	ix35 FCEV	
JAGUAR	I-Pace	
KIA	SOUL	
MERCEDES-BENZ	CLASSE B	Asynchronous motor
MERCEDES-BENZ	EQC 400	AC Induction
MITSUBISHI	I-MIEV	Permanent Magnet Synchronous
NIO	ES8	AC Induction
NISSAN	LEAF	Permanent Magnet Synchronous
NISSAN	LEAF PLUS	
PEUGEOT	ION	
PEUGEOT	E-208 GT	
RENAULT	ZOE	Coil Rotor synchronous motor
RENAULT	Twizy	Permanent Magnet Synchronous
RENAULT	KANGOO MAX Z.E.	
SMART	FORTWO	Coil Rotor synchronous motor
SMART	FORFOUR	
TESLA	Model 3	Permanent magnet synchronous reluctance Motor
TESLA	Model S	AC Induction
TESLA	Model X	
VOLKSWAGEN	UP!	Permanent Magnet Synchronous
VOLKSWAGEN	E-GOLF	

For an electric motor to be incorporated into the powertrain, the motor should have high efficiency, high starting torque, high power density and it has to be cost-effective. The most commonly used electric motors in EV are:

- **DC Series Motor**

Direct current (DC) series motor has been used from the 1900s for traction purpose due to its high starting torque capability. A DC series motor converts the DC in the armature coil into AC through brush and commutator. The electromagnetic field repels the nearby magnets with the same polarity when the current flows and causes the winding to turn to the attracting magnets of opposite polarity. This motor is mostly used in low-cost applications as it can be driven by DC power. The main advantage of this motor is easy to speed control and that it can withstand a sudden increase in load. These main characteristics made the motor popular, however, it has high wear and tear, and maintenance due to brushes and commutators. Nowadays, these types of motors are mostly used in applications where high efficiencies are not a concern and are rarely used in electric vehicle applications.

- **Brushless DC Motor (BLDC)**

Brushless DC motors are similar to the DC series motor but without commutator and brush arrangement. This motor is built with a permanent magnet rotor and wire-wound stator poles. The rotor is formed from the permanent magnet and can alter from two-pole to eight-pole pairs with alternate North (N) and South (S) poles. Uniform flux density is generated in the gaps when the permanent magnet in the rotor rotates around the stator. This permits the stator coil to be driven by a constant DC voltage. In addition to this, the cost and the size of the motor can be reduced by eliminating the position sensors and replaced by sensor-less control strategies. The main advantage of a BLDC motor is that combining with a suitably controlled converter provides several desired characteristics for an efficient drive system. The motor is maintenance-free and has great traction characteristics such as high starting torque, good efficiency, greater than 90%, excellent power density compared to other motors, reduced operational and mechanical noises. Due to these features, BLDC is most popular among EV applications.

- **Permanent Magnet Synchronous Motor (PMSM)**

Permanent Magnet Synchronous Motor shares same similarities with BLDC, but is driven by a sinusoidal signal to achieve lower torque ripples. The motor has a permanent magnet rotor and winding on the stator. The stator of this motor is designed to produce sinusoidal flux density, while BLDC produces trapezoidal flux density. Since there is no stator power dedicated to magnetic field production, the power density of this motor is higher than the induction motors with the same rating. These motors are designed to be more powerful with lesser mass and lower moment of inertia. Even though this motor requires a drive to operate, it can produce torque at zero speed. High torque at low speed is achieved through variable frequency drive (VFD). The main advantage of PMSM motor is the high efficiency and power density. PMSM motors are available for higher power rating, which make it more suitable for high-performance applications likes in cars and buses. However, VFD control technique increases the complexity of the system and hence requires careful attention to precisely control speed. Hence the cost of this motor is on the higher side as compared to the induction motor.

- **Three Phase AC Induction Motors**

Three-phase induction motors consist of stator and rotor, are constructed with the use of highly magnetic core material. It helps to reduce hysteresis and eddy current losses. These induction motors do not have a high starting toque like DC series motors under fixed voltage and fixed-frequency operation. But this characteristic can be altered by using various control techniques like FOC or v/f methods. By using these control methods, the maximum torque is made available at the starting of the motor which is suitable for traction application. Squirrel cage induction motors have a long life due to less maintenance. Induction motors can be designed up to the efficiency of 92%-95%. The drawback of an induction motor is that it requires complex inverter circuit and control of the motor is difficult.

- **Switched Reluctance Motors (SRM)**

Switched reluctance motors are double salient brushless machines with salient pole structure in both stator and rotor. The rotor has neither windings nor PMs. This makes the inertia of the rotor less and helps in high acceleration. The rotor tends to shift towards the position of the excited stator winding, to maximize the inductance, thus aligning the rotor pole with the closest stator pole. To maintain the rotor in motion, it is required to excite the stator poles in a sequence, which is done by an electronic controller. SRM is a simple and inexpensive machine because of its simple construction method. Due to the absence of winding and PMs, these motors are very appealing to gearless EV drives. The robust nature of SRM makes it suitable for the high-speed application. SRM also offers high power density which are some required characteristics of electric vehicles. Since the heat generated is mostly confined to the stator, it is easier to cool the motor. The biggest drawback of the SRM is the complexity in control and increase in the switching circuit. It also has some noise issues.

In this work, Permanent Magnet Synchronous Motors (PMSM) are integrated into the model due to its popularity in the automotive sector. Based on the literature [56], for the simulation purpose, the motor efficiency curve of Nissan Leaf 80 kW motor was considered as generic efficiency curve. Figure 11 shows the modelled motor subsystem in Simulink.

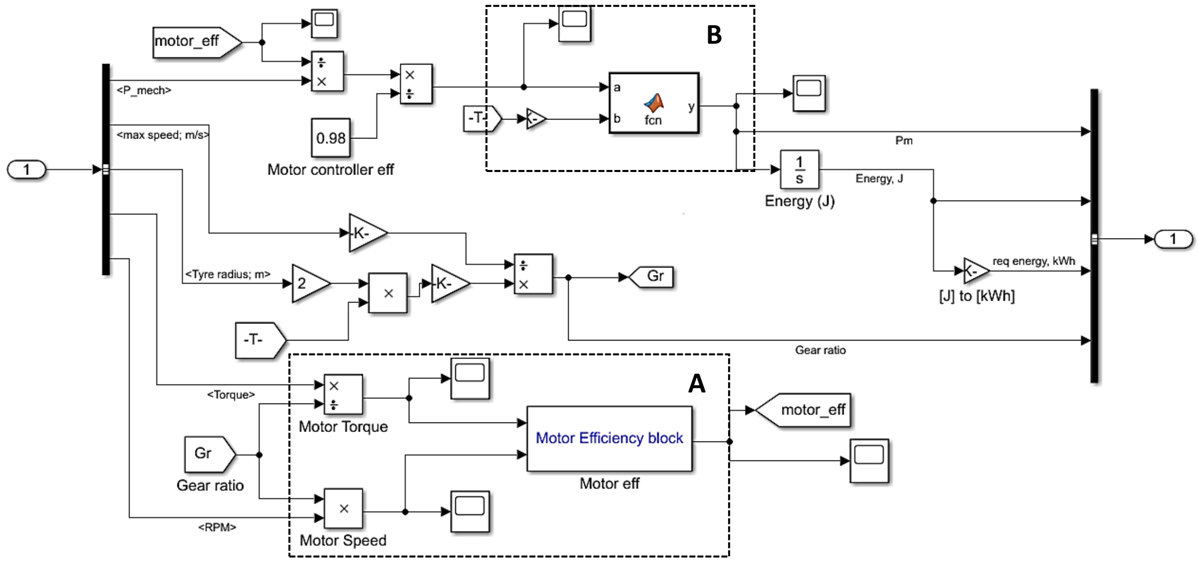

Figure 11: Motor subsystem from the Simulink model

The traction power can be positive or negative based on the acceleration force. If the force is positive, it means acceleration is positive and the permanent magnet synchronous motor (PMSM) motor/generator is working as the motor. If the force is negative, the vehicle is decelerating, and the motor behaves as a generator, produces energy through regenerative braking, which is used to charge the battery. If the PMSM is behaving as motor, then the power required to deliver the traction force to the wheel is expressed by the following equation.

$$P_{wheel}\,(W) = \frac{F_T * v}{\eta_m} \qquad \text{Equation 10}$$

Where η_m(%) is the efficiency of the motor. The efficiency of the motor is determined based on the percentage of motor torque and speed at each second instead of the output power range. Gear ratio, motor torque and motor RPM are defined using the equations as follows:

$$\text{Gear ratio, } Gr = \frac{\pi}{60} * \frac{\omega * t_d}{v} \qquad \text{Equation 11}$$

$$\text{Motor torque, } \tau_m = \frac{\tau}{G_r} \qquad \text{Equation 12}$$

$$\text{Motor rotational speed, } \omega_m = \omega * G_r \qquad \text{Equation 13}$$

Where t_d is the diameter(m) of the tire and G_r is the gear ratio of the vehicle.

From equation 8, the power required to accelerate the vehicle is calculated. The total energy removed from the battery is the sum of the power required for acceleration, power loss during transmission and the power requirement for auxiliary devices. Total power required, P_{total} is expressed in the following equation 14.

$$P_{total}\,(W) = P_{wheel} + P_{AUX} + P_{loss} \qquad \text{Equation 14}$$

Where P_{loss} *(W)* is the power loss during energy transmission within the vehicle. The auxiliary load is associated with secondary electricity used in the vehicle, such as heaters, coolers, heat exchangers, fans, seat warmers and other electrical devices which extracts energy apart from the traction force. Usually, the auxiliary power is drawn from a secondary battery and is recharged from the primary battery using a DC-DC converter. The auxiliary load values vary from 100W to 2kW according to different studies for EV. In this work, the auxiliary power is considered to vary between 800W at 22˚C to 2.8kW at -12.2˚C for light-duty vehicles [53].

If the motor/generator is behaving as a generator, then energy extracted from the traction force is sent back to the battery and is expressed as the following

$$P_{regen}\,(W) = F_T * \eta_{regen} \qquad \text{Equation 15}$$

Where η_{regen} is the regenerative efficiency. The regenerative efficiency at a particular deceleration point is assumed as same as that of the motor efficiency at that particular acceleration point [57]. However, the maximum regenerative energy fed to the battery is limited to 25% of the motor power [58].

Section A in Figure 11 represents the above equation for the calculation of *motor torque* and *motor rotational speed*. Section B in Figure 11 represents the programming which limits the regenerative braking to 25%. Figure 12 shows the standard efficiency curve of PMSM motor.

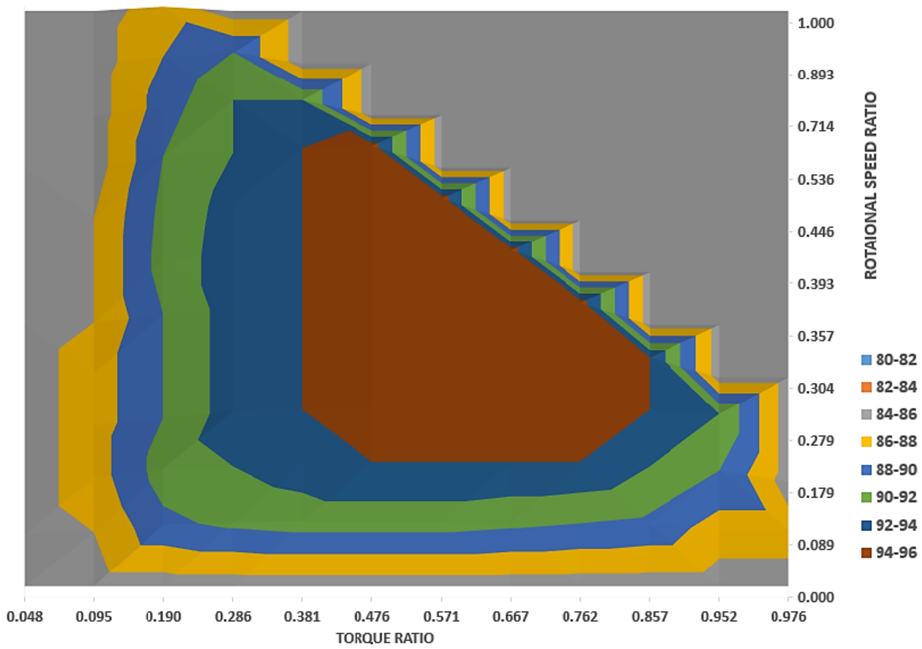

Figure 12: Generic PMSM efficiency curve

3.1.4. CONTROL SYSTEM MODELLING

Control system is a system or a set of devices which manages, regulates or directs the behaviour of other systems to achieve required results. Control system plays a vital role in most of the systems as it helps to regulate the output and thus reduce or eliminate the error from a system. A control system may be operated by electrical or mechanical means, by fluid pressure or by a combination of them. Due to the development in technology, the control system becomes a vital component in all the system from automation sector to transportation, military, space technology, robotics and many more.

Generally, control systems can be divided into two divisions, open-loop and close-loop systems. Open-loop systems are those systems in which the commanding signal is sent to the components only based on the input given to the controller. Based on the input signal to the controller, the action signal is generated and is sent to the components. The control signal can be binary (ON/OFF signal) or instructions.

In a close-loop control system, the commanding signal also considers the output of the component in addition to the input signal to the controller. This extra step is carried out to make sure the desired output is generated from the system. Usually, a feedback loop is connected back to the controller or control system which ensures the process variable is the same as the value of the set point. A range of closed-loop control system has been developed by various organisation to make sure the desired output is generated through the process always. Most commonly used closed-loop control systems are:

- **Linear control system**

These are simple closed-loop control system which are commonly used in appliances and applications. The system consists of a closed-loop which includes sensors, control algorithm and actuators in an attempt to regulate a variable at a set point. One of the main advantages of such systems is that the setpoint can be changed easily, and the system accepts the input from the next process. A good example of this is the thermostat in-room heaters. The desired point is set in the thermostat, which is the set point. Once the temperature drops, the system gets feedback which points out the drop in temperature and a corrective signal (to increase the temperate) will be sent to the radiators.

- **Logic control system**

A logic control system is the advanced version of the linear control systems. The system interconnects electrical relays and timers using ladder logic. Nowadays, most such systems were developed with microcontrollers or specialised programmable logic controllers (PLC). Such systems are mostly used in industrial and commercial applications where the controller signal will result in the machinery to start and stop various operations through a series of actuators. A good example will be the automation in shop floor techniques, where the various automated machine will perform collection, sequential arrangement and packing of commodities.

- **PID control systems**

Proportional-Integral-Derivative controllers are advanced control systems which are widely used when continuous modulated control action is required. A PID controller continuously calculates an error value as the difference between the desired setpoint and a measured process variable and applies a correction based on proportional, integral, and derivative term. A good example for PID controller would be the cruise control on a car, where ascending a hill would lower the speed if only constant engine power were applied. The controller's PID algorithm restores the measured speed to the desired speed with minimal delay and overshoot by increasing the power output of the engine.

- **Fuzzy logic control systems**

A fuzzy logic control system is solely based on fuzzy logic, a mathematical system that analyses analogue input values in terms of logical variables that take on continuous values between 0 and 1. Although alternative approaches such as genetic algorithms and neural networks can perform just as well as fuzzy logic in many cases, fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans.

Based on the complexity of the control, the control systems are divided into two, High-level control system and low-level control system. High-level control system represents the less complex control system. In other words, operations that are more abstract; wherein the overall goals and systemic features are typically more concerned with the wider, macro system as a whole. While low-level control system represents the detailed control system which describes more variable and points which results in generating the controlling signal. It describes more specific individual components of a systematic operation, focusing on the details of rudimentary micro functions rather than macro, complex processes. Low-level classification is typically more concerned with individual components within the system and how they operate.

In this model, the High level open-loop control system is developed as the primary controller. Control system controls the energy distribution from the power source and the amount of energy that is withdrawn from the power source, in case of multiple power sources. In this study, an open-loop high-level control system is developed based on conditional loops, for each combination of energy source. Figure 13 shows the control system on battery ultra-capacitor combination power source.

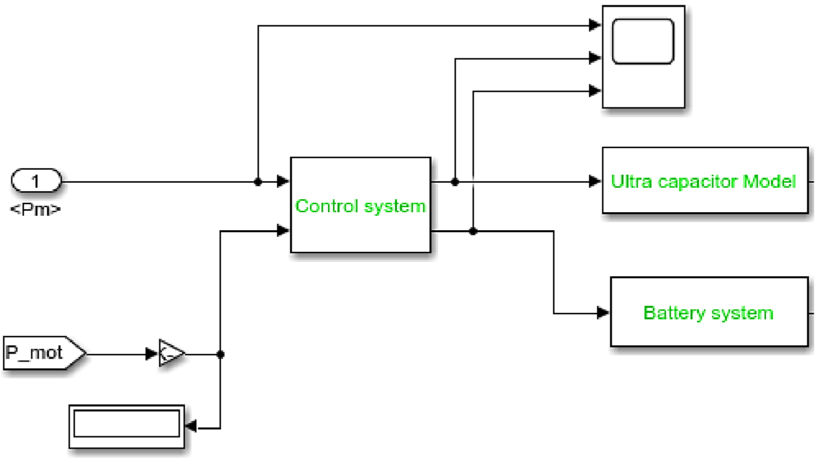

Figure 13: Control system in battery-ultra-capacitor powertrain

The control system controls the energy distribution between the energy sources. For the studies, a threshold point is defined for the primary energy source as the maximum output energy that can be extracted from it. This point is also termed as set point or limit. To explain, the scenario with battery ultra-capacitor combination is described here. During power requirement, battery (primary storage) will be delivering the power till the setpoint and, if more power is required, ultra-capacitor (secondary source) will deliver the additional power required for the acceleration. Figure 14 shows the control system conditional loops during acceleration mode. This setpoint can be modified by the user and is taken as input in the percentage of the motor peak power of the vehicle.

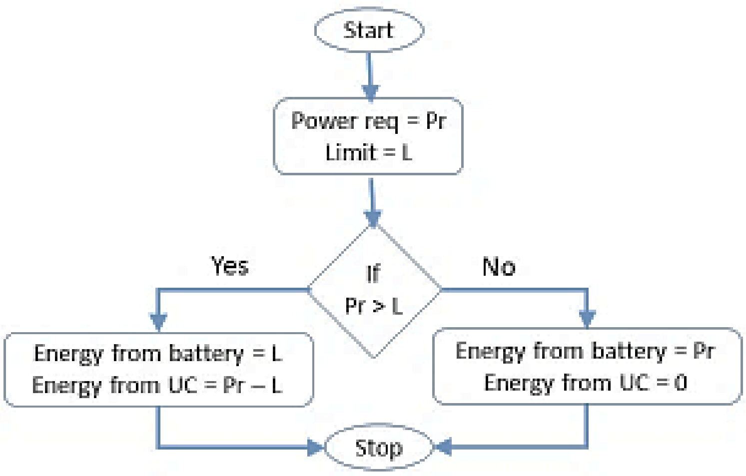

Figure 14: Logic circuit of the control system during motoring mode

Also, control system regulates or controls the power management action during regenerative/deceleration mode. If the state of charge of ultra-capacitor (secondary source) is less than a certain amount (setpoint), the regenerative energy will be used to charge UC, else it goes to the battery. Figure 15 shows the control system conditional loops in the form of the flow chart for regenerative mode. Here the minimum state of charge (SOC) of battery and ultra-capacitor for charging can be varied based on the user requirement for study purposes. If the

SOC of battery and ultra-capacitor is more than the minimum value, the regenerative energy won’t be used.

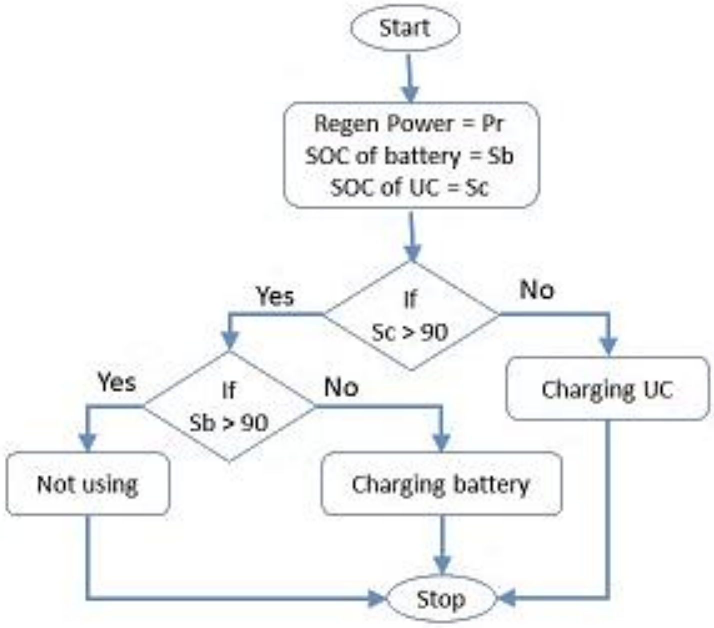

Figure 15: Logic circuit of the control system during regenerative mode

For a system using fuel cell combination (fuel cell – battery and fuel cell – ultra-capacitor combination), a modified control system is used, where battery or UC will be working for the first few seconds for the fuel cell to get started. However, this time can be increased or decreased. After that, the energy requirement is checked, and the fuel cell will be delivering the basic energy and battery/UC will be supplying the excess energy required. During regenerative energy, the generated energy is sent to the battery/UC alone, if the SOC of battery is less than the prescribed for charging.

3.1.5. BATTERY SYSTEM MODELLING

A battery is an energy storage device which consists of two or more electric cells joined together, which converts chemical energy to electricity. The cell consists of positive and negative electrodes joined by an electrolyte. The chemical reaction between the electrodes and electrolyte generates DC current. Batteries can be divided into two, primary battery and secondary batteries. Primary batteries are those which can be used once, while secondary batteries are rechargeable batteries, in which the chemical reaction can be reversed by reversing current and returning to the charged state.

From the electric vehicle designer’s point of view, the battery can be treated as a ‘black box’ which has a range of performance criteria. These criteria will include specific energy, energy density, specific power, typical voltages, amp-hour efficiency, energy efficiency, commercial availability, cost, operating temperatures, self-discharge rates, number of life cycles and recharge rates, terms which will be explained in the following section. Advanced development has been seen in battery technology which improved their performance, properties and energy storage capacity. The most common type of batteries available in the market are:

- **Lead Acid Batteries**

Lead-acid batteries are the most known and widely used battery in electric appliances. In a lead-acid battery, negatively charged plate, lead is the anode (oxidation occurs) and positive material such as lead oxide is used as the cathode (reduction occurs). The plates are submerged in the electrolyte of dilute sulphuric acid. During the chemical reaction, sulphuric acid reacts with lead and lead oxide to produce lead sulphate and water by releasing electrons and heat. The overall reaction is:

$$Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O \qquad \textit{Equation 16}$$

During the discharge process, the lead sulphate is formed as shown by the equation and gradually loses the concentration of the sulphuric acid. While the charging process, the electrode reverts to lead and lead oxide. The lead-acid battery is the most used rechargeable battery used even in smallest of systems. The main reasons are that the main constituents are not expensive, that it performs reliably, and that it has a comparatively high voltage of about 2V per cell. One of the most notable features of the lead-acid battery is its extremely low internal resistance. This means that the fall in voltage as the current is drawn is remarkably small. The capacity of a cell is approximately proportional to the area of the plates, and the internal resistance is approximately inversely proportional to the plate area. The result is that the internal resistance is, to a good approximation, inversely proportional to the capacity.

Manufacturers of lead-acid batteries can supply them in a wide range of heights, widths and lengths so that for a given required volume they can be fairly accommodating. The life of the lead-acid battery is limited to around 700 cycles, though this strongly depends on the depth of the cycles. Experience with industrial trucks (fork-lifts, luggage carriers at train stations, etc.) suggests that service lives of 1200–1500 cycles are possible, over 7–8 years. Fleet experience with electric cars indicates a life of about 5 years or 700 cycles [59]. However, they have low specific energy (35-40Wh/kg), low energy density (80-90Wh/L) and it is hard to rationalise the usage of lead-acid battery in long-range vehicles.

- **Nickel-based batteries.**

Nickel-based batteries uses a nickel as positive electrode. This includes nickel iron, nickel-zinc, nickel-cadmium (NiCd) and nickel-metal hydrides (NiMH). Out of nickel-based batteries, nickel iron batteries are rarely used due to lower energy density (30Wh/L) and specific power

(100W/kg), and nickel-zinc is not favourable due to its very limited life of 300 deep cycles. Nickel-cadmium (NiCd) battery is considered as one of the competitions against lead-acid batteries due to the higher specific energy (40-60Wh/kg). While NiMH batteries have similar performance to the NiCd batteries, being that NiMH battery uses hydrogen as a negative electrode, absorbed in a metal hydride, which makes it free from cadmium (carcinogenic). The NiMH and NiCd batteries are explained further.

NiCd battery uses nickel oxyhydroxide as anode and metallic cadmium for the negative electrode. During discharge, nickel oxy-hydroxide becomes nickel hydroxide and at the negative electrode, will combine to form cadmium hydroxide. Electric energy is obtained through the reaction:

$$Cd + 2\ Ni\ O\ OH + 2H_2O \leftrightarrow Cd(OH)_2 + 2\ Ni(OH)_2 \quad \text{Equation 17}$$

One of the interesting facts of NiCd battery compared to lead-acid battery is that during the discharge process the electrolyte gets more concentrated. NiCd batteries are widely used nowadays in many appliances including electric vehicles. It is a perfect option as it has high specific power (150W/kg), a long cycle (up to 2500 cycles), and a wide range of operating temperature from -40°C to 80°C. On the negative side, the operating voltage of each cell is only about 1.2V, so 10 cells are needed in each nominally 12V battery, compared to 6 cells for lead-acid. A further problem is that the cost of cadmium is several times that of lead, which make the battery expensive than lead-acid. Cadmium is also environmentally harmful and carcinogenic.

NiMH was commercially introduced during the last decade of 20th century. NiMH uses hydrogen as the negative electrode and nickel oxy-hydroxide as the positive electrode. During discharge, nickel oxy-hydroxide becomes nickel hydroxide and at the negative electrode, hydrogen is released from the metal that it was attached, and reacts, producing water and electrons. The chemical reaction is as shown below:

$$MH + NiOOH \leftrightarrow M + Ni(OH)_2 \quad \text{Equation 18}$$

In terms of energy density and power density, the NiMH is somewhat better than the NiCd battery. NiMH batteries have nominal specific energy of 65 - 120Wh/kg and nominal energy density of 150 - 300Wh/L and a maximum specific power of 200-1000W/kg. However, NiMH battery requires a cooling system to take away the heat produced during the chemical reaction. Also, the self-discharge rate of NiMH batteries is higher due to the smaller hydrogen molecules, hence can easily diffuse through the electrolyte to the positive electrode and discharges the battery.

- **Lithium Batteries**

Lithium cells are one of the fast-moving secondary cells in the market for over 4 decades. They offer increased energy density in comparison with other rechargeable batteries, though at a higher cost. Due to the higher energy density, the most expensive and efficient laptops/computers and mobile phones use lithium rechargeable batteries, rather than the comparatively lower cost NiCd or NiMH cells. There are two types of Lithium batteries, Lithium-ion battery and Lithium polymer batteries.

Lithium-ion batteries (Li-ion) contains lithiated transition metal intercalation oxide for the positive electrode and lithiated carbon for the negative electrode. The electrolyte is either a liquid organic solution or a solid polymer. During the discharge process, the lithium from lithium carbon forms lithium metal oxide-releasing heat and electrons. The process is shown below.

$$C_6Li_x + M_yO_z \leftrightarrow 6C + Li_xM_yO_z \quad \text{Equation 19}$$

An important point to be noted is that lithium-ion batteries are that, accurate control of voltage is needed when charging lithium cells. If it is slightly too high it can damage the battery, and if too low the battery will be insufficiently charged. To avoid this, suitable commercial chargers are being developed along with the battery. The lithium-ion battery has a considerable weight advantage over other battery systems, and this makes it a highly attractive candidate for future electric vehicles. The specific energy (100-300Wh/kg), for example, is about 3 - 7 times that of lead-acid batteries, and this could give the car a reasonable range.

For this model, a nonspecific battery system is modelled, which takes the voltage, current and initial state of charge (SOC) as input and calculates the required parameter to determine the state of charge during the ride, estimated energy consumption and range. The main reason to incorporate such a nonspecific battery is to make the model more flexible and compatible. Figure 16 shows the modelled battery system in Simulink.

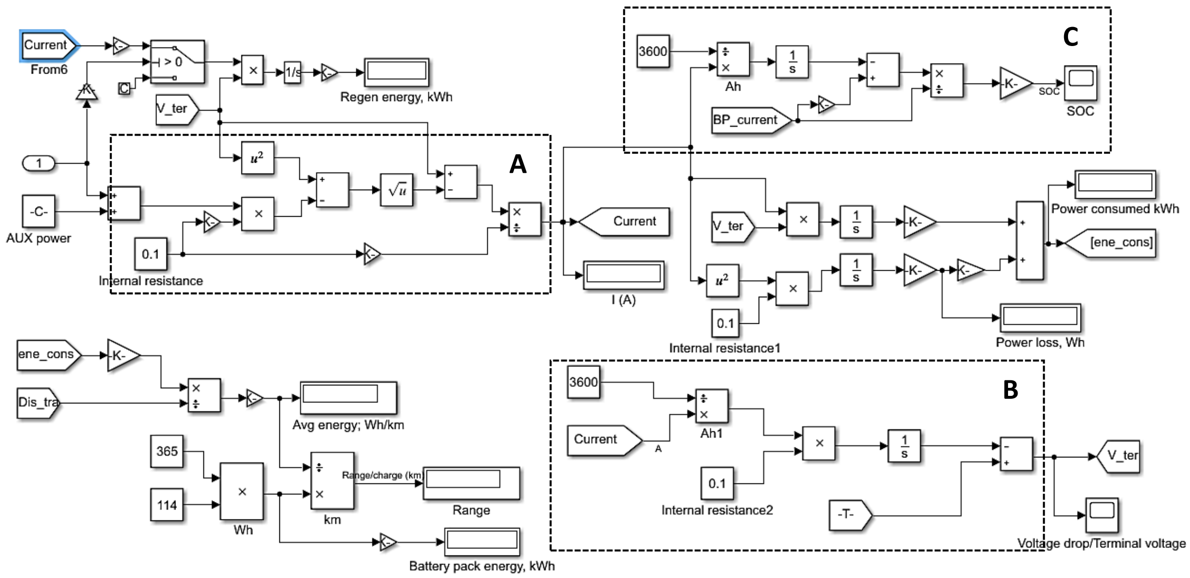

Figure 16: Battery system modelled in Simulink

The total power stored in the battery is defined by equation 20.

$$P_{bat} = V * I \qquad \text{Equation 20}$$

Where *V* is the voltage (V) and *I* is the current (*A*). Voltage and current are taken as input. The charging (regenerative braking) and discharging (acceleration mode) current of the battery is evaluated by equation 21 during each second of the drive cycle. In Figure 16, section A represents the calculation of charging and discharging current during the acceleration and regeneration mode.

$$I\ (A) = \frac{V_t - \sqrt{V_t - 4RP_{wheel}}}{2R} \qquad \text{Equation 21}$$

Where V_t is the terminal voltage (*V*) of the battery and *R* is the battery internal resistance (*Ω*). The resistance of the battery is considered to be of 0.1*Ω* [53]. During the energy flow, a voltage drop (V_{drop}) is observed, which causes the power loss. This voltage drop is calculated (see equation 22) and the terminal voltage of the battery is determined according to equation 23.

$$V_{drop} = I*R \qquad \text{Equation 22}$$

$$V_t = V_t(t-1) - V_{drop} \qquad \text{Equation 23}$$

Where *t* is the time in seconds. The voltage drop calculation is represented by section B in Figure 16. The power loss (P_{loss}) during the transmission of energy is calculated using equation 24.

$$P_{loss} = I^2*R \qquad \text{Equation 24}$$

The total energy consumed during the drive cycle is estimated by summing the power consumed during all seconds of the drive cycle. The sum of regenerative energy produced is deducted from the consumed energy as energy which is fed back to the battery, as presented in equation 25.

$$E_T = \sum_{t=1}^{T} P_{total} - E_{regen}$$ *Equation 25*

The *Average energy consumption* of the vehicle is the amount of energy consumed to reach each unit distance, *km* and is calculated as follows:

$$\text{Average energy consumption (Wh/km)} = {E_T}/{d}$$ *Equation 26*

Where *d* is the distance travelled in the drive cycle (km). It is to be noted that 100% energy capacity available cannot be used, the battery reserves the last 15% of its energy density to avoid full discharge. The *Range* (km) of the vehicle is calculated as:

$$\text{Range} = {P_{bat}}/{Average\ energy\ consumption}$$ *Equation 27*

State of Charge (SOC) is defined as the level of charge of the battery with respect to its capacity. It is represented in percentages; 100% means fully charged battery and 0% represents empty. SOC is calculated at each second by using the coulomb current counting method, equation 28

$$SOC(t) = SOC\,(t-1) \pm {I_t}/{I}$$ *Equation 28*

I is the maximum current stored and I_t is the current charged or discharges at the time *t.* Section C in Figure 16 represents the calculation of SOC in the battery.

3.1.6. FUEL CELL SYSTEM MODELLING

Fuel cells are one of the greatest inventions of the mid-19th century, but they are yet to make their mark as a power source. Fuel cells are nothing but electrochemical cell which uses hydrogen as fuel and oxygen as an oxidant to produce electricity and heat through an electrochemical process. For the redox reaction process, an oxidizer is required and most used oxidising agent is oxygen. The salient feature of the fuel cell is that the energy produced is zero-emission with water as a by-product. The basic electrochemical reaction follows.

$$2H_2 + O_2 \rightarrow 2H_2O + \textit{electricity} + \textit{heat}$$ *Equation 29*

At the anode (negative electrode), hydrogen is oxidized into proton and electrons, while at the cathode (positive electrode) oxygen is reduced into water. Fuel cells are different from most batteries, as it requires a continuous source of fuel and oxygen (usually from air) to sustain the electrochemical reaction, whereas in a battery, the chemical energy usually comes from metals and their ions, or oxide that are present in the battery. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied. Different types of fuel cells are available, however, they all operate with the same basic principles, with varying electrolytes with different characteristics. Depending on the electrolyte, either proton or oxide ions are transported through ion conductor, or electron is transported through the external circuit producing electric energy. Most common fuel cells are:

- **Alkaline fuel cell (AFC)**

The alkaline fuel cell uses hydrogen as fuel and oxygen as the oxidant, and generate electric energy by utilizing an alkaline electrolyte like potassium hydroxide (KOH) in a water-based solution. The presence of the hydroxyl ions travelling across the electrolyte allows a circuit to be made and electrical energy could be extracted. At the anode, hydrogen reacts with hydroxide ions to produce water molecules and electrons. Electrons reach cathode through the external circuit. At the cathode, the oxygen atom reacts with water molecules and produces more hydroxide ions, which is transferred back for anode reaction through the KOH electrolyte.

Oxidation: $2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$ *Equation 30*

Reduction: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ *Equation 31*

AFC can operate between the temperatures ranging from 23°C to 90°C. Nickel is used as the common catalyst to speed up the electrochemical process in cathode and anode. Due to this, AFC is classified as a low-temperature low-cost fuel cell. AFC’s are considered to be the most cost-efficient fuel cell since the electrolyte used is standard potassium hydroxide (KOH). The product of the reaction is water and there is no emission of greenhouse gases. The maximum efficiency of AFC is considered as 70% [60]. Despite this, the water-based alkaline solution (KOH) used in AFCs as the electrolyte, absorbs CO_2 through the conversion of KOH to potassium carbonate (K_2CO_3) and consequently poisons the fuel cell. Therefore, AFCs typically use purified air or pure oxygen which in turn increases the operating costs.

- **Phosphoric fuel cell (PFC)**

Phosphoric acid fuel cells (PAFC) use carbon paper electrodes and liquid phosphoric acid (H_3PO_4) electrolyte. The charge carrier in this type of fuel cell is the hydrogen ions (H^+ or proton). At the cathode side, water is forming as the result of the reaction between electrons, protons and oxygen with the presence of platinum catalyst to speed up the reactions. Expelled water is usually used in heating applications. Continuous operation and system start-up is a concern at 40°C due to solidity of phosphoric acid at this temperature. Oxidation takes place in the anode, where the hydrogen splits into its 4 protons and 4 electrons. The protons pass from the anode to the cathode through the electrolyte and the expelled electrons return to the cathode through the external circuit and generate the electrical current. In cathode, reduction takes place, where 4 protons and 4 electrons combine with the oxygen to form water

Oxidation: $2H_2 \rightarrow 4H+ + 4e^-$ *Equation 32*

Reduction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ *Equation 33*

Through the process, electric energy is produced along with water and heat. The heat is usually exploited for water heating or steam generation at atmospheric pressure; however, steam reforming reactions produce some carbon monoxide (CO) around the electrodes which might poison the fuel cell and affect the PAFC performance. At high temperatures, CO is desorbed in reversed electro-catalyst reaction at the cathode. Contrary to other acid electrolytes that need water for conductivity, concentrated phosphoric acid electrolyte is capable of operating in temperatures higher than the boiling point of water.

PAFC does not require pure oxygen for its operation since CO_2 does not affect electrolyte or cell performance. They run on-air and can be easily operated with reformed fossil fuels. Besides, H_3PO_4 has lower volatility and long-term stability. The initial cost is high since PAFC uses air with ~21% oxygen instead of pure oxygen resulting in 3 times reduction in the current density. Electrical efficiency of this type of fuel cells is between 40% and 50% and CHP efficiency of about 85%. They are typically used for on-site stationary applications. The ionic conductivity of phosphoric acid is low at low temperatures, so PAFC can only be operated at the range of 150°C - 220°C temperature.

- **Solid oxide fuel cell (SOFC)**

Solid oxide fuel cells (SOFCs) are high-temperature fuel cells with metallic oxide solid ceramic electrolyte. SOFCs generally use a mixture of hydrogen and carbon monoxide formed by internally reforming hydrocarbon fuel and air as the oxidant in the fuel cell. Yttrium stabilized zirconia (YSZ) is the most used electrolyte for SOFCs because of its high chemical and thermal stability and pure ionic conductivity.

Oxygen is reduced at the cathode (air electrode) at 1000°C, while, fuel oxidation happens at the anode. The anode should be porous to conduct fuel and transport the products of fuel oxidation away from the electrolyte and fuel electrode interfaces.

Reduction: $\frac{1}{2}O_2\,(g) + 2e^- \rightarrow O^{2-}(s)$ *Equation 34*

Oxidation: $O^{2-}\,(S) + H_2\,(g) \rightarrow H_2O\,(g) + 2e^-$ *Equation 35*

SOFCs are well adopted with large scale distributed power generation systems with the capacity of hundreds of MWs of energy. The by-product heat is usually used to generate more electricity in gas turbines and hence increasing the CHP efficiency between 70% and 80% [61]. SOFC systems are reliable, modular and fuel adaptable with low harmful gas (NO_x and SO_x) emissions. They can be considered as local power generation systems for rural areas with no access to public grids. Furthermore, they have a noise-free operation and low maintenance costs. On the other hand, long start-up and cooling-down times, as well as various mechanical and chemical compatibility issues, limit the use of SOFCs.

- **Molten carbonate fuel cell (MCFC)**

Molten carbonate fuel cells (MCFCs) are high-temperature fuel cells. They use molten carbonate salt mixture as electrolyte suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte (BASE). In MCFC, the reaction at the hydrogen electrode occurs between hydrogen fuel and carbonate ion, which react to form CO_2, water and electrons. At the anode, the feed gas (usually methane) and water are converted to hydrogen (H_2) and carbon monoxide (CO). Then it again undergoes a chemical reaction to form carbon dioxide (CO_2) and further hydrogen.

Reform 1: $CH_4 + H_2O \rightarrow CO + 3H_2$ *Equation 36*

Reform 2: $CO + H_2O \rightarrow CO_2 + H_2$ *Equation 37*

Simultaneously, two electro-chemical reactions by hydrogen and carbon monoxide generate electrons at anode. Both reactions use carbonate ions (CO_3^{2-}) available in the electrolyte:

Oxidation 1: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ *Equation 38*

Oxidation 2: $CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^-$ *Equation 39*

The reduction happens at the cathode and expels new carbonate ions from O_2 and CO_2. The carbonate ions produced at the cathode are transferred through the electrolyte to the anode. Thus, electric current and cell voltage can be collected at electrodes.

Reduction: $\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$ *Equation 40*

MCFCs are currently employed for natural gas and coal-based power plants in the electrical utility, industrial and military applications. The advantages and disadvantages of MCFCs are closely related to its high operating temperature. MCFC may be directly fuelled with hydrogen, carbon monoxide, natural gas and propane. They do not require noble metal catalysts for electrochemical oxidation and reduction. They also do not require any infrastructure development for installation, however, long time is needed to reach the operating temperature and generating power.

- **Proton exchange membrane fuel cell (PEMFC)**

In PEMFCs, the hydrogen is activated by the catalyst to form proton ion and eject electron at the anode. The proton passes through the membrane while the electron is forced to flow to the external circuit performing electric work. The electron then flows back to the cathode and interact with oxygen and proton to form water. The anode and cathode reactions are shown below.

Anode: $H_2\ (g) \rightarrow 2H^+ + 2e^-$ *Equation 41*

Cathode: $O_2\ (g) + 2H+ + 2e^- \rightarrow H_2O\ (l)$ *Equation 42*

Overall reaction: $H_2\ (g) + \frac{1}{2} O_2\ (g) \rightarrow H_2O\ (l)$ *Equation 43*

Basically, the PEMFC is comprised of bipolar plates and membrane electrode assembly (MEA). The MEA is composed of dispersed catalyst layer, carbon cloth or gas diffusion layer and the membrane. The membrane is to transport protons from anode to cathode and block the passage of electron and reactants. The gas diffusion layer is to access the fuel uniformly. Electrons at anode pass through the external circuit and generate electricity. PEMFCs are low-temperature fuel cells with an operating temperature between 50°C and 100°C. They are lightweight compact systems with the rapid start-up process. The sealing of electrodes in PEMFCs is easier than other types of fuel cells because of the solidity of the electrolyte. In addition, they have a longer lifetime and are cheaper to manufacture. From the efficiency point of view, higher the working temperature, higher the efficiency. Electrical efficiency of PEMFCs is between 40% and 50% and the output power can be as high as 250kW. PEMFC systems are usually used in portable and stationary applications. However, among applications of PEMFCs, transportation seems to be the most suitable since they provide continuous electrical energy supply at high power density. They require minimum maintenance as there are no moving parts in the power generating stacks of the fuel cells. Fuel cell vehicles are the most promising application of PEMFC systems because of high specific energy and energy density.

- **Direct methanol fuel cell (DMFC)**

Direct methanol fuel cell (DMFC) is an advanced type of PEMFC. It is a suitable source of power for portable energy purposes due to low-temperature operation, long lifetime and rapid refuelling system characteristics. In addition, they do not need to be recharged and are addressed as a clean renewable energy source. The energy source of the DMFC systems is methanol. At the anode, methanol is oxidised into carbon dioxide (CO_2) while at cathode, steam or water is formed using oxygen available in the air.

Anode: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$ *Equation 44*

Cathode: $\frac{3}{2}O_2 + 6e^- + 6H^+ \rightarrow 3H_2O$ *Equation 45*

DMFC systems are generally classified into active and passive. Active DMFCs are efficient and reliable systems consisting of the methanol feed pump, CO_2 separator, fuel cell stack, methanol sensor, circulation pump, pump drivers and controllers. Using pump for water circulation can significantly increase the efficiency of such systems. Active DMFCs are usually used in control applications for quantities such as flow rate, concentration and temperature.

In the passive DMFC systems, the methanol pumping devices and external process for blowing air into the cell are eliminated. Hence, oxygen of ambient air is defused into the cathode via the air-breathing feature of the cell. Similarly, methanol is defused into the anode from an integrated feed reservoir driven by a concentration gradient between the anode and the reservoir. Passive systems are cheap, simple and capable of the substantial reduction in parasitic power loss and system volume. Methanol is utilized in DMFCs in the form of vapour or liquid. Vapour feed is preferable to liquid feed in term of cell voltage and power density. Methanol does not perform perfectly for mass transfer and requires high localized cooling at the anode. Furthermore, the extent of methanol crossover from anode to cathode and gas release at the electro-catalyst surface leads to the lower performance of liquid feed cells. On the other hand, vapour feed cells have some drawbacks as well, such as dehydrating the membrane, lower lifetime and high temperature requirement for fuel vaporization. Consequently, the more complex and costly reformer is needed. Besides, they are not suitable for portable applications. Proton Exchange Membrane (PEM) is considered as the main part in DMFCs to provide low penetrability and high proton conductivity. Also, it provides high thermal and chemical stability for proper performing of DMFC.

For this model, a PEMFC is developed for simulation and studies. PEMFC is the most commonly used in the automotive sector due to its low operating temperature range, reduced size and weight, high efficiency and wide operating range. The modelling of the fuel cell is carried out based on the polarization curve and the number of cells in the stack. Figure 17 shows the modelled PEMFC in Simulink.

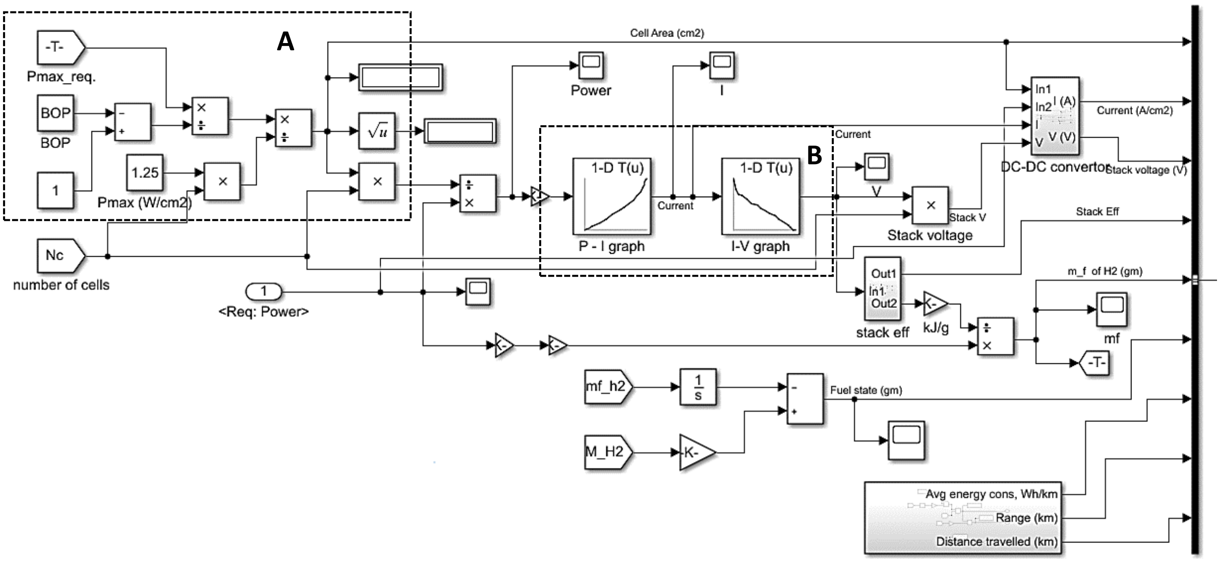

Figure 17: Fuel cell system modelled in Simulink

A particular portion of the output power of the fuel cell is required to maintain the working condition of the fuel cell and is termed as the balance of plant *(BOP).* The power required for the balance of plant is added to the required power for traction. The maximum output of the fuel cell stack *(P_{fcp}),* the energy required for BOP and number of cells (*Nc*) is taken as input for the subsystem. The fuel cell power (P_{fc}) is then calculated through equation 46,

$$P_{fc}(W) = \frac{P_{fcp}}{1-BOP}$$ *Equation 46*

The area (cm^2) of each cell is the ratio of the maximum output power of the stack to the product of the number of cells and maximum specific power, is presented by equation 47.

$$A_{fc} = \frac{P_{fc}}{N_c * P_{sfc}}$$ *Equation 47*

Where P_{sfc} is the specific power density of the fuel cell. Section A in Figure 17 represents the calculations corresponding to equation 46 and 47.

The power required per unit area is received from the control system. Polarization curve is a plot of the fuel cell voltage to the specific current. From the polarization curve, the current and voltage from the fuel cell at that particular moment is calculated. For this modelling, the fuel cell polarization curve of Toyota Mirai 2017 is taken as a reference [62]. Section B of Figure 17 represents the power-current and current-voltage relation regarding the reference curve.

The stack output voltage (V) of the fuel cell is the total voltage produced by the individual cells, which is given by

$$V_{fcp} = N_c * V_{fc}$$ *Equation 48*

Fuel cell electrical efficiency is calculated as the ratio of the electric power output to the energy input from hydrogen. The total efficiency of the module can also be calculated as the product of the factors, as shown in equation 49.

$$\eta = \eta_{th} * \eta_v * \eta_F * \mu_F \qquad \text{Equation 49}$$

Where η_{th} is the thermodynamic efficiency, η_v is the voltage efficiency, η_F is the faradic efficiency, and μ_F is the utilization factor of the fuel cell. The thermodynamic efficiency, faradic efficiency and utilization factor are assumed as 0.83, 0.9 and 1 respectively [63] and voltage efficiency is calculated by equation 50.

$$\eta_V = \frac{V_{fc}}{1.23} \qquad \text{Equation 50}$$

The fuel mass flow rate of hydrogen (gram/second) is calculated as:

$$\dot{m}_{H_2} = \frac{P_{fcp}}{Q * \eta} \qquad \text{Equation 51}$$

Where Q = 120MJ/kg or 33.33kWh, is the lower heating value/specific energy of hydrogen.
The amount of fuel used is calculated by adding the fuel consumption (gms) at each second.

$$\dot{m}_{total} = \sum_1^t \dot{m}_{H_2}(t) \qquad \text{Equation 52}$$

The total energy consumed is estimated by adding the power consumed during each second in the drive cycle duration. The sum of regenerative energy produced is deducted from the consumed energy as feedback energy to the battery in the system, as in equation 53. The *Average energy consumption* of the vehicle is the amount of energy consumed to reach each unit distance (km) and is calculated by equation 54.

$$E_T = \sum_{t=1}^{T} P_{total} - E_{regen} \qquad \text{Equation 53}$$

$$\text{Average energy consumption (Wh/km)} = {E_T}/{d} \qquad \text{Equation 54}$$

where *d* is the distance travelled (km). Since the power requirements vary each second, the current and voltage produced also varies and it will affect the working of the fuel cell. In order to avoid that, a DC-DC converter is used with an efficiency of 90%. *Range* (km) of the vehicle is calculated as:

$$\text{Range (km)} = {M_{H_2} * 33.33 * 1000}/{\text{Average energy consumption}} \qquad \text{Equation 55}$$

Where M_{H_2} is the amount of hydrogen (kg) stored in the vehicle.

3.1.7. ULTRA-CAPACITOR MODELLING

Capacitors are devices in which two conducting plates are separated by an insulator. The energy is stored in between the two plates of the capacitor. A DC voltage is connected across the capacitor, one plate being positive the other negative. The opposite charges on the plates attract and hence store energy.

An ultra-capacitor (UC), also called as super-capacitor, is a capacitor with a high capacitance value with lower voltage limit, which makes the energy storage nearly 20 times more than that of a normal capacitor. It acts as a bridge between the electrolytic capacitor and rechargeable batteries. Even though their energy storage mechanisms and electrode materials are different, they have similar characteristics such as power density, life cycle, and energy efficiency. Figure 18 shows the schematic circuit diagram of a UC model.

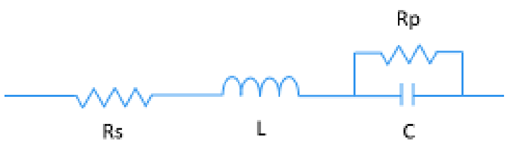

Figure 18: Equivalent circuit of ultra-capacitor

Where *Rs* is the series resistor (Ω), *Rp* is the parallel resistor (Ω), *L* is the series inductor (H) and *C* is capacitance (F) of the UC. During charging or discharging process, the leakage current, *Rp* is always larger than the equivalent series resistance (ESR), *Rs*, due to this *Rp* is ignored always [64][65]. Figure 19 shows the modelled UC in Simulink.

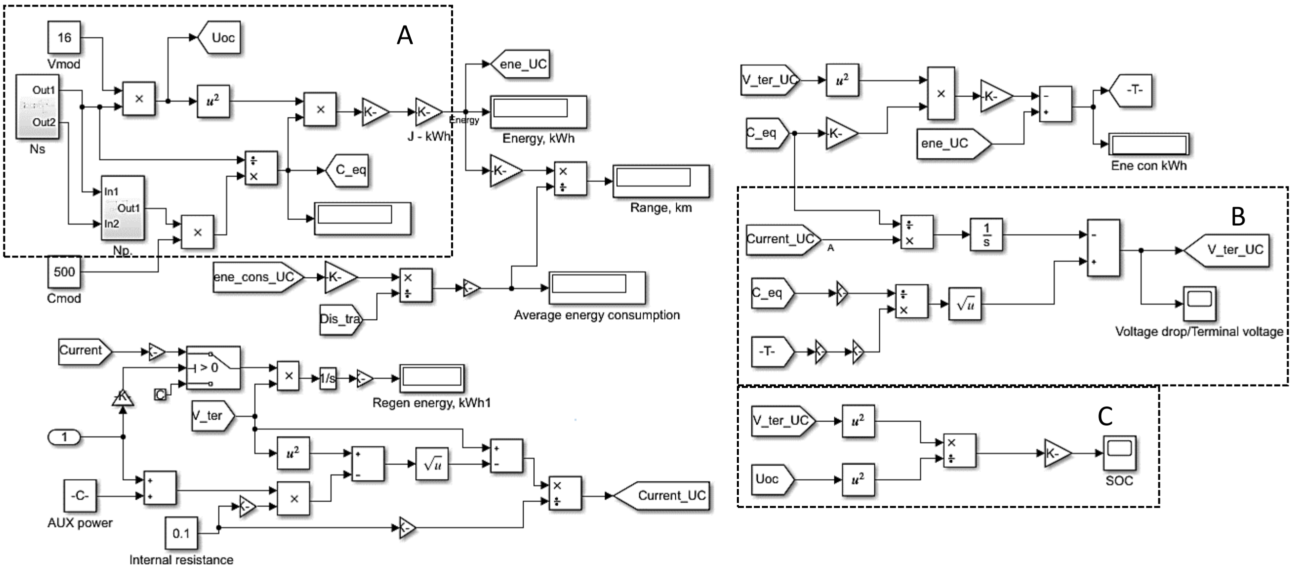

Figure 19: UC modelled in Simulink

An electric field is developed between the two charged electrode plates when an electric field is applied to the capacitor. The applied potential difference will be equal to the product of the distance between the plates and the developed electric field.

$$V = E * d \quad \text{Equation 56}$$

Where V is the potential difference, E is the electric field and d is the distance between the plates. The charge Q stored in a capacitor of capacitance C (Farads) at a voltage of V (Volts) is given by the equation:

$$Q = C * V \quad \text{Equation 57}$$

Capacitors can provide large energy storages, although they are more normally used in small sizes as components in electronic circuits. The energy stored in the electric field in a capacitor is given by the equation

$$W = ½*CV^2 \quad \text{Equation 58}$$

While considering a module, the resultant potential difference, V_{eq} is the sum of the potential difference between each UC cell. The equivalent capacitance in series, C_{eq} of the circuit is calculated by equation 60.

$$V_{eq} = V_1 + V_2 + V_3 + ---- + V_n \quad \text{Equation 59}$$

$$C_{eq\_s} = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\cdots+\frac{1}{C_n}} \quad \text{Equation 60}$$

When equivalent capacitors are combined in a combination of series and parallel connections, the equivalent capacitance will be equal to

$$C_{eq} = C_{cell} * \frac{N_s}{N_p} \quad \text{Equation 61}$$

Where C_{cell} is the capacitance of a single cell, Ns is the number of cells connected in series and N_p is the number of cells connected in parallel. For the modelling purpose, ultra-capacitor pack of 16V, 500F is considered as the standard module. Section A represents the calculations of equation 61.

During the discharging process, a charge equivalent to the current is drawn from the capacitor. The current, I is calculated through equation 21. A voltage drop will occur during the discharging process and present voltage during each second is calculated by equation 62. Section B in Figure 19 represents the voltage drop calculations.

$$V_t = V_{oc} - \int \frac{I}{C}\, dt - IR_s \quad \text{Equation 62}$$

Where V_{oc} is the open-circuit voltage and R_s is the ESR of the ultra-capacitor. When the capacitor is discharged, the voltage drops from the initial voltage V_1 to the voltage V_2, and in the process, it releases some of the stored potential energy as per the following equation

$$\Delta W = ½ * C\ (V_2 - V_1)^2$$ Equation 63

The state of charge of the ultra-capacitor, SoC, is defined as the ratio between the remaining energy and the maximum stored energy of the ultra-capacitor. Using equation 64, the state of charge expressed in terms of terminal voltage becomes:

$$SoC = \frac{W}{W_{max}} = \frac{V^2}{V_{max}^2}$$ Equation 64

Section C in Figure 19 represents the calculation of SoC, described in equation 64. They have relatively high specific power and relatively low specific energy. They can be used as the energy storage for regenerative braking. Although they could be used alone on a vehicle, they would be better used in a hybrid as devices.

3.2. APPLICATIONS OF THE MODEL

As explained in previous sections, different types of energy storage combinations in vehicles can be simulated, analyzed and studied. The model can be used for the study of different factors in a vehicle which influences the range and energy performance of a vehicle. The energy source of the vehicle can be modified from 1 energy source such as a battery or fuel cell or ultra-capacitor to a combination of multi-sources like battery + fuel cell or fuel cell + ultra-capacitor or ultra-capacitor + battery.

The study is carried out in two steps, where the factors affecting the range of an electric vehicle is carried out initially. Through the simulations, a series of range influencing variables in an electric vehicle will be analysed and will assess how much EV range is affected by these factors in an attempt to provide insightful feedback to EV users on how to more effectively use their vehicle to obtain optimal performance. This study aims to provide a clear response with evidence to the question such as

- Will battery capacity and energy density help to extend the range with improved vehicle performance?
- How environmental temperature affects the range?
- Does lower average speed help to increase the range?
- Is aggressive driving changes energy consumption?

On the second stage, emerging technologies in the automotive powertrain were examined. The future possibilities in powertrains are tested by merging more than one power source (battery + fuel cell, battery + ultra-capacitor, and fuel cell + ultra-capacitor) to learn the benefits. Both the light-duty and heavy vehicle is tested with different energy storage options. Also, total ownership cost analysis and real world comparison of passenger vehicles is done to carry out a market analysis with current scenarios. This study aims to provide the possibilities to the question such as

- How vehicle performance differs with more power sources?
- Is it wise to buy a fuel cell vehicle than an electric vehicle?
- Will the life of my car can be extended beyond the current warranty period?
- And which powertrain is economically better for a common person

Answers for these questions will be provided in this section with detailed explanations with justification.

3.2.1. PASSENGER CARS

The number of passenger vehicles on the roads is increasing day by day. Due to easy access, comfort and financial assistance from financial institutions encourage individuals to buy new car own their own. The low operation cost and maintenance made EV so popular among the drivers. However, as compared with conventional vehicles or hydrogen-powered vehicle, the range of BEV is still comparatively lower for more than 65% of the available vehicles [66]. Even though the range of the vehicle is predicted by the manufacturer forehand, it depends upon several factors such as driving context, driver aggressiveness, battery capacity, weather, road conditions, load on the vehicle, etc. In this study, the reference vehicles are simulated and the influence of battery capacity, environmental temperature, driving context and driving behaviour on EV range are studied, as explained next:

- **Influence of battery capacity and energy density**. The simpler way to increase EV range is by increasing battery capacity. However, this has impacts in terms of vehicle weight and consequently on the energy performance of EVs. The basic input parameters such as vehicle mass (without battery mass), drag coefficient, motor power and torque, average speed and similar parameters are set constant and the battery capacity is changed to (0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3) times of standard battery capacity of the vehicle. Energy density is the amount of energy stored in a certain space per unit volume and also plays a vital role in determining the EV range. Since the last decade, the energy density of batteries has been improving with continuous improvement in battery chemistry to store more energy per unit of weight [67]. While considering batteries it can be defined as the energy stored per unit mass (Wh/kg). As the energy density increases, it helps to reduce the weight of the total battery pack, which results in increased range.
- **Influence of environmental temperature**. To know the dependency of range with climate, the model is simulated to a wide range of temperature from -30˚C to 40 ˚C. The model is designed in such a way that as the temperature changes the air density [55],

rolling resistance [54] and auxiliary power [53]. It is assumed that the energy required to maintain an optimal temperature is also included in the auxiliary load, which results in a higher auxiliary load at a lower temperature.

- **Influence of average speed**. The driving environment usually refers to whether the vehicle is urban, rural or highway context, typically inferred from average speed. This study covers a range from 10km/h to 120km/h to assess the influence in energy consumption. For the analysis it is assumed the vehicle is already at the prescribed speed and is simulated for 1800s and results are extracted for analysis and studies.
- **Influence of driving behaviour**. Driving behaviour has a higher influence on the average energy consumption of the vehicle and also the range, which creates the difference of the vehicle performance in real-world with the predicted values. By classifying the points of the drive cycle as aggressive and non-aggressive based on acceleration and deceleration, we can predict the aggressiveness of driving [34]. WLTP class 3 drive cycle is tested to study the relation between the parameters.
- **Influence of combining energy storage source:** The type of power source to the powertrain plays a vital role in vehicle performance. Considering the mass of electric vehicles, the energy source will constitute around 20% of the total mass. As this study helps to analyse how combining different source results in the curb weight of the vehicle and influence the vehicle performance and the amount of energy that can be stored without compromising the performance.

Furthermore, the assessment of vehicle performance in real-world drive cycles is carried out to learn more about the total energy consumption of the vehicle. In this study, the vehicle performance of gasoline vehicle is compared with an electric passenger vehicle in real-world driving scenarios. To study the comparisons, 3 distinct drivers with 3 different vehicles fuelled by gasoline are chosen. This previously collected data were recorded for a period of 10 hours (36000 s) of driving by each driver [68].Table 4 shows the details for the real-world drive cycles.

Table 4 : Real world driving data for passenger vehicles

Driver ID	Period (seconds)	Distance covered (km)	Average speed (km/hr)	Maximum Speed (km/hr)
1	36000	352	35	115
2	35501	276	28	176
3	35423	325	33	116

The recorded drive cycles are simulated with an electric vehicle, Nissan leaf 24 kWh and the results were compared. The Nissan leaf was chosen because of the availability of the vehicle during the time of data acquisition.

3.2.2. BUSES

In Europe, nearly 60% of all public transportation are made by urban and suburban buses. There were 800,000 buses in circulation on Europe's road in 2017 with an average increase of 1.1% per year [3]. As of the records in 2017, buses and heavy-duty vehicles emit a total of 235.2 million tonnes CO_2 equivalent. European Union and the member countries are taking initiatives to mitigate this problem and now there are around 4000 electric buses on the fleet. These electric buses have less maintenance charge, energy loss and are quieter. However, the initial cost is very much higher than the diesel vehicle. Since more battery is stacked for better range, the curb mass is comparatively higher, and also the energy consumption. One of the main problems is the time required to charge the batteries. Due to these, electric buses are still limited and new energy sources are considered. In this study, various energy sources are tested with the simulation model to estimate the most adequate option for the rural and urban public transportation system.

As to check the flexibility of the model with vehicle fleet and to extend the possibilities of the study, electric buses used for public transportation also have been tested. As we know electric buses are gaining importance nowadays due to less operational cost and zero tailpipe emissions. However, more reports are emerging in support of the accommodation of ultra-capacitor and fuel cells as the power source replacing the batteries [69]. A study is done to know how different power sources will help to reduce the operation cost of the vehicle and improving energy efficiency.

3.3. TOTAL OWNERSHIP COST ANALYSIS

Electric vehicles are eco-friendlier and more beneficial in the context of technical features. In this study, the total ownership cost (TOC) of various passenger vehicle powered by battery, fuel cell and gasoline was estimated. Cost of the vehicles often determined by the companies poses as a major barrier between the sales of the vehicles in the market. More manufacturers are trying to sell their vehicles in the market with an optimal profit margin, by comparing with other similar vehicle models, which gives a trade-off between the production cost and selling volume. From the point of customers, it is important to know the financial expenditure and perks along with the product as 30% of the customers give same or more weightage to the money and 15% prefers eco-friendly models with a reasonable price [70]. In the market, the cheapest vehicle available is gasoline-powered and the costliest one is with the hydrogen-powered fuel cell vehicles. Customers prefer vehicles with wide lifetime because of the compensation factor of the initial cost with the lowered running and maintenance cost.

The cost of vehicles with different powertrain differs and, therefore, total ownership costs have been often used to compare the different vehicle powertrains. In this study different electric vehicles, fuel cell vehicles and internal combustions vehicles available in the market are considered and TCO is estimated for a period of 12 years, which is the average life of a vehicle in Europe [71]. The study only considers the cost relates to the ownership, whereas style, looks, driving sensation and dealer's relations cannot be included as economical parameters and thus their influence is not considered. The TOC estimated based on three factors; CAPEX, OPEX and the period over these costs have occurred. The analysis of the cost of ownership considers every cost associated with the use of the vehicle. The following costs flows are considered: road taxes, maintenance, car inspection, fuel (and electricity), and purchase costs and charging infrastructure cost.

Operational cost (OPEX) includes the money spent on the vehicle to operate over time. It includes maintenance cost and fuel cost. Maintenance costs include costs for small and large maintenance. They are different between conventional, electric and fuel cell vehicles. Maintenance costs of electric vehicles are lower than conventional since they do not have an internal combustion engine: they have less moving components; they face less temperature stress and do not need oil and filter replacements [72].

Fuel or electricity price is one of the main concerns related to the passenger vehicle sector. Figure 20 shows the expected fuel price for the next decade.

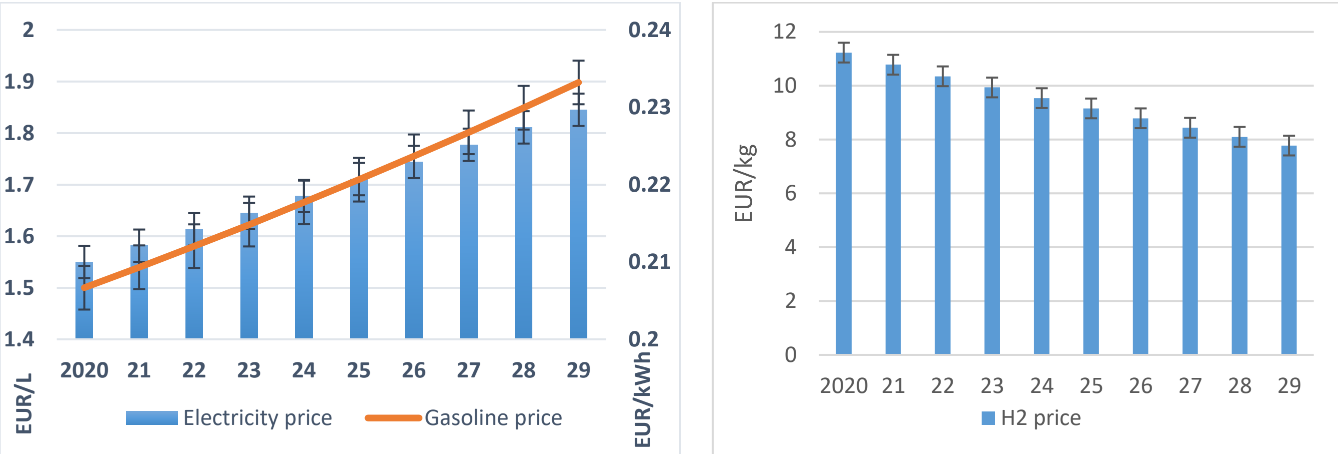

Figure 20: Estimated fuel/electricity price for 1 decade (2020 – 2029)

For this study, the fuel price over the price in the past is taken into account. The average rate of change is assumed to follow in the future. For electric vehicles, the electricity price is estimated to rise 1% each year. The data acquisition is carried out from the past electricity distribution price of Portugal [73]. For fuel cell vehicles, hydrogen fuel price is one of the great concerns. Currently, the hydrogen cost around 11.3€/kg [74] and it is estimated to reduce by 40-50% by 2030 [75]. Gasoline prices are expected to have an increase of 3% with an increase in 10% of oil over coming years [76].

Capital expense (CAPEX) refers to the amount of money spend initially. It includes the vehicle purchase cost and taxes. The Portuguese transportation department collects tax from passenger vehicles through Single circular tax (IUC) and Vehicle tax (ISV). To promote the usage of eco-friendly vehicles, there is a tax reduction for vehicles other than conventional ones. The ISV is paid once during the registration process and IUC is paid on a yearly basis. For conventional vehicles, the ISV is calculated based on the engine capacity and CO_2 emission from the vehicle. As calculated, for hatchback vehicle, the average ISV is approximately 800€, and for SUV its 1200€ during the registration process. IUC is also calculated similarly and depends upon the tail emissions. IUC for a hatchback gasoline vehicle is around 130€/year and for SUV its 160€/year [77]. However, the electric vehicle is exempted from both ISV and IUC taxes. Whereas, fuel cell vehicles are not introduced until now, but due to its eco-friendly nature, taxes for FCEV is also considered zero. With these facts and assumptions, the TCO is calculated and resulted are recorded in the later section.

4. RESULTS AND DISCUSSION

All the simulation results were validated and are presented in section 4.1. The different vehicle simulation models are used to study the impact of influential factors of EV. The study on future energy storage possibilities such as fuel cell, batteries and ultra-capacitor are tested along with combining them to learn the added benefits. In addition to this, the model is validated with heavy-duty vehicle (section 4.2), which shows the model flexibility to accommodate different vehicle types. The best suitable power option for buses is studied in the scope of this thesis. Further, total ownership cost analysis is carried out with different light-duty passenger vehicles to find out the cost-effectiveness of the vehicle in present and in future. Section 4.3 explains TOC analysis in-details.

4.1. PASSENGER CARS

For testing the developed model and validation of BEV, 7 vehicle models from different dominant vehicle manufacturers such as Nissan, Renault, Kia, Hyundai and BMW are selected. The chosen vehicle models are successful in the automotive market for the past years and have been brought and driven by thousands of customers around the world. Performance variables and specifications are given as inputs (as in section 3.1), for validating the simulation model and to check the reliability of the generated model. The specification of the selected vehicles are tabulated in Table 5 [78].

Table 5: Battery electric vehicle specifications

Specifications	Nissan Leaf S	Renault Zoe R110	Kia Niro	Kia Soul	Hyundai IONIQ	BMW i3	Mini Cooper
Mass (kg)	1558	1550	1620	1593	1527	1345	1365
Frontal Area (m^2)	2.2	2.216	2.261	2.304	2.112	2.269	1.988
Tire Radius (m)	0.316	0.31	0.334	0.326	0.326	0.342	0.309
Maximum speed (km/h)	144	135	155	156	165	150	150
Motor power (kW)	110	80	100	100	101	125	135
Maximum torque (Nm)	320	225	395	395	295	250	270
Battery voltage (V)	350	400	327	327	319.4	352	350.4
Drag co-efficient	0.28	0.29	0.29	0.31	0.24	0.29	0.3

The validation results for the specified vehicles through the developed model are tabulated in later sections.

4.1.1. VALIDATION OF THE MODEL

- **Electric vehicle model Validation**

The model was validated through the comparison with the laboratory test performed by independent entities on the different vehicles using WLTP (Worldwide Harmonized Light Vehicles Test Procedure) drive cycles. The WLTP drive cycle consists of 3 classes of certified cycle based on power to weight ratio of the vehicle [79]. Most of the light vehicles will be tested under the WLTP class 3 drive cycle due to the higher power to weight ratio. The formerly mentioned vehicles in Table 5 were tested in the WLTP class 3 drive cycle and the results (including error with respect to certification values in percentage) are presented in Table 6.. The simulation is carried out by considering an atmospheric temperature of 22°C.

Table 6: Simulation results (error compared to reference, %)

Vehicle	Energy consumption (Wh/km)	Range (km)	Battery rated energy (kWh)
Nissan Leaf S	138.6 (-1.7)	288 (1.4)	40.0
Renault Zoe R110	132.5 (0.4)	392 (-0.8)	52.0
Kia Niro	140.2 (3.0)	280 (-3.2)	39.2
Kia Soul EV	145.1 (2.1)	271 (-2.2)	39.2
Hyundai IONIQ	122.1 (-0.7)	313 (0.6)	38.3
BMW i3	129.9 (-2.4)	324 (2.8)	42.0
Mini Cooper	121.9 (-1.7)	267 (1.5)	32.6

From the above results, it can be observed that the simulation results have less than 2% absolute average error of energy consumption and range, which is an acceptable range with the tested results. The difference is justified due to assumptions made in some of the coefficients, such as the rolling resistance, drag coefficient, motor efficiency, auxiliary power demand and efficiency of other electric devices.

- **Fuel cell vehicle validation**

Currently there are only a few numbers of light passenger vehicle in the market which uses fuel cell as the primary power source. Due to the lack of good exposure to the market, the manufacturers are still holding on to their technology, without revealing the design specifications, which made the simulation tougher than the electric vehicle. For the modelling of the fuel cell, the polarization curve of Mirai was chosen. Due to this reason, the Toyota Mirai is tested with the simulation model for validation. The specification of the vehicle Toyota Mirai is shown below in Table 7. The model was validated through the comparison against laboratory test performed by independent entities on the vehicles using FTP 75 and HWFET drive cycles. These cycles were used to test the performance under EPA regulations.

Table 7: Toyota Mirai Specifications

Specifications	Toyota Mirai
Mass (kg)	1850
Frontal Area (m^2)	2.215
Tire Radius (m)	0.356
Maximum speed (km/h)	175
Motor power (kW)	116.4
Maximum torque (Nm)	335
Fuel cell power (kW)	113
Hydrogen stored (kg)	5
Drag coefficient	0.28

The formerly mentioned vehicle in Table 7 was tested in the FTP 75 cycle and then with the HWFET cycle, and the results are presented in Table 8, in comparison with the certification values [80]. The simulation is carried out by considering an atmospheric temperature of 22°C.

Table 8: Simulation results of Toyota Mirai (error compared to reference, %)

Performance variable	FTP 75	HWFET	Combined
Range (km)	496.6 (- 1.5)	561.2 (10.5)	528.8 (4.6)
Energy consumption (MPGe)	64.7 (- 1.9)	69.0 (4.3)	66.8 (1.3)
Energy consumption (Wh/km) [81]	323.3 (- 1.9)	303.5 (4.3)	313.5 (1.3)

From the above results, it can be observed that results obtained from the simulation have less than 3% error in the average absolute values of energy consumption and 6% error in the average absolute values of the range. The difference is justified due to assumptions made in some of the parameters, such as the drag coefficient, motor efficiency, auxiliary power demand and efficiency of other electric devices.

- **UC validation**

Unlike electric vehicles and fuel cell vehicle, ultra-capacitor is not used in the automotive field as a primary source. Due to this reason, it is impossible to validate the model against a passenger vehicle. However, the developed model is tested against the ultra-capacitors tested in the laboratory. The literature [65] shows some of the results of laboratory tested ultra-capacitors. The developed model is simulated for constant current output and the voltage change is compared with the experimental results. The ultra-capacitor with a voltage of 48.6V and capacitance 171.8F is used for the experiment. Figure 21 shows the voltage variation when a constant current is drawn from the ultra-capacitor (experiment results are adapted from [65]).

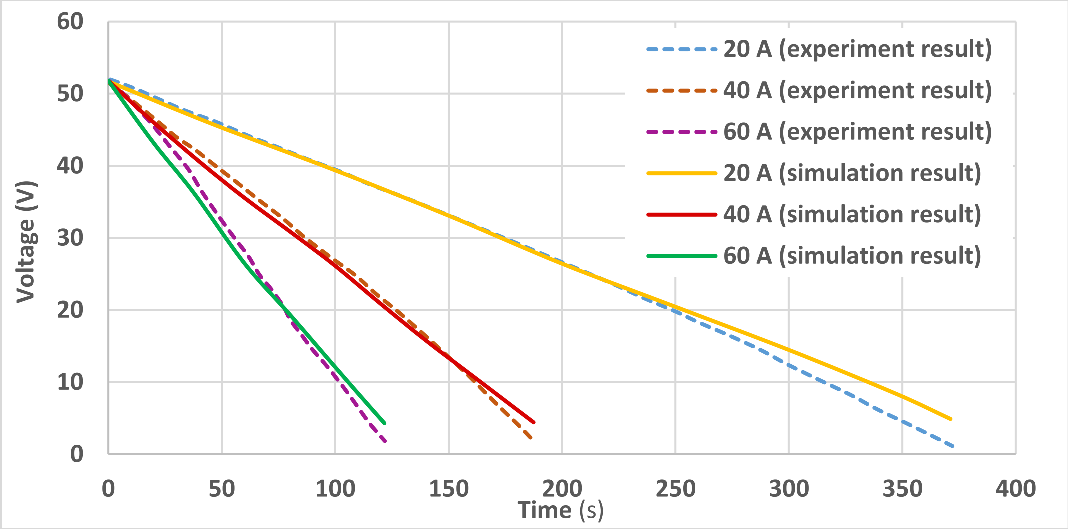

Figure 21: Experimental and simulation result of Ultra-capacitor (adopted from [65]*)*

From the results, it can be observed that the difference in voltage is negligibly small. The average absolute error is 4.8% between the experimental result and simulation results. The difference in results can be justified due to the unavoidable deviations between the experimental setup and simulation.

From the validation process, it is observed that the error in the estimation of simulation results are considerably low for electric vehicle and are acceptable for fuel cell and ultra-capacitor. Overall, the average error is small and thus the model is considered as reliable and consistent.

4.1.2. INFLUENCE OF VARIABLES ON VEHICLE PERFORMANCE

From section 4.1.1, it is clear that the low error percentage shows that the model is capable of generating results equal to that in similar operating conditions. As a result, the proposed study has been carried out to learn how vehicle performance is affected by battery capacity, energy density, atmospheric temperature, driving aggressiveness, average velocity and including different sources of power.

4.1.2.1 Influence of battery capacity and energy density on EV range

For the study, Nissan Leaf S 2014 model (24 kWh) and Nissan leaf S 2019 (40kWh) is considered as the reference. The battery capacity is changed to (0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, and 3) times of standard battery capacity and the rest of the parameters are set constant apart from the total weight. As the battery capacity varied, there is variation in the total curb weight.

Nissan Leaf S model was introduced each year by the manufacturer with different variation based on the battery capacity and range [78] [82]. While studying the Nissan Leaf S previous models, it is understood that each kWh of extra capacity added to the base model of Nissan

Leaf S 24kWh capacity, the weight of the battery system has been increased by 3.5kg and vehicle mass (excluding battery mass) by 1.5kg. The study is carried under the WLTP class 3 drive cycle. Table 9 shows the change in total vehicle mass with battery capacity and the effect on EV range.

Table 9: Battery capacity fraction vs range

Battery capacity (%)	0.25	0.5	0.75	1	1.5	2	2.5	3
Battery pack mass (kg)	210	231	252	273	315	357	399	441
Vehicle Mass (kg)	1387	1417	1447	1477	1537	1597	1657	1717
Average energy consumption (Wh/km)	129.1	130.1	131.1	132.1	134	136	138	140.1
Range (km)	46.5	92.3	137.3	181.8	268.7	353	434.9	514.4
Expected range (km)	45.5	90.9	136.4	181.8	272.7	363.6	454.5	545.4
Difference (%)	2.2	1.5	0.7	-	-1.5	-3.0	-4.5	-6.0

The result shows that, when the battery capacity is less than that of the standard capacity, the range of the vehicle is increased and, when the capacity is increased to 3 times, the range got reduced by around 6% than the expected range, due to the increase of mass of the total curb weight. We considered an increase of 1.5kg in vehicle mass (excluding battery) for an increase of each kWh capacity. It is seen that when the capacity is doubled or tripled, the weight ratio to each kWh gets higher and thus the range is reduced than the predicted result.

While effective research and development activities helped the manufacturer to increase the energy density of the later models of Nissan Leaf S model 24kWh from 157Wh/kg to 224Wh/kg [78] [82]. The change in energy density helps to reduce the battery pack mass, thus the total curb mass resulted in increased range with reduced average energy consumption.

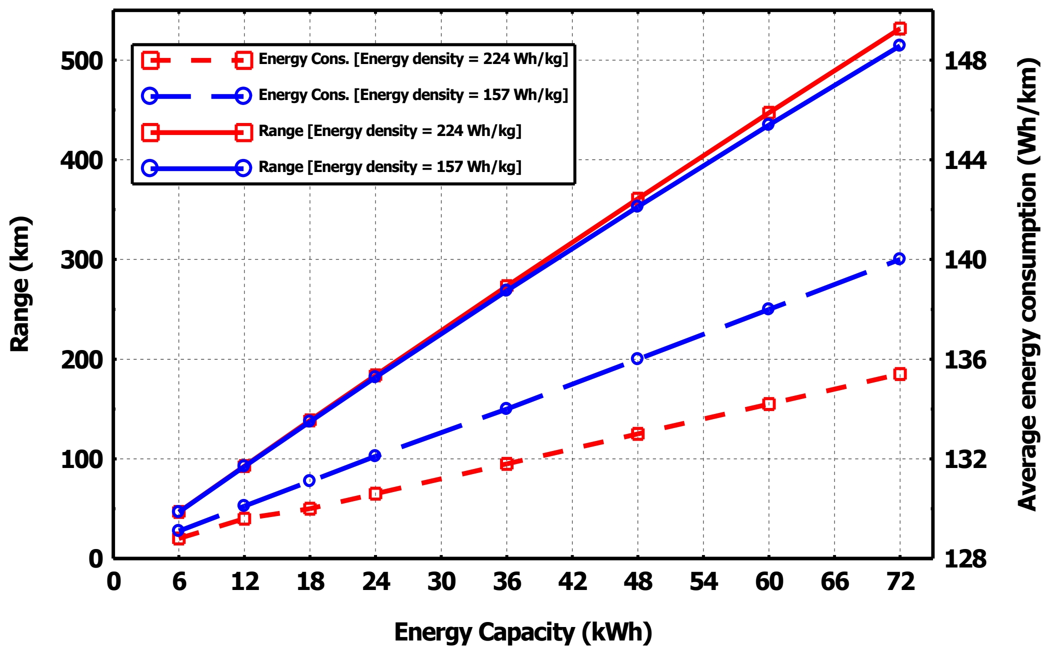

Figure 22: Influence of energy capacity and energy density on the range

Figure 22 shows the range, average energy consumption and battery capacity with different energy densities. We can observe that the energy consumption for battery pack with higher energy density (224Wh/kg) is lower and, as the total capacity increases, it shows a great difference compared to the other one. While on the range, battery pack with less capacity has negligible difference irrespective to the energy density, higher the capacity of the battery pack, change in the range becomes noticeable.

4.1.2.2 Influence of environmental temperature on EV range

The generated model of EV in Simulink is adaptable to the temperature of the atmosphere and based on this, the rolling resistance coefficient, air density and auxiliary power requirement are calculated. Nissan Leaf S 40 kWh, Zoe ZE50, Kia Niro, Hyundai IONIQ and BMW i3 are tested for this study and range is determined for the atmospheric temperature ranges from -30°C to 40°C. Figure 23 shows the change in range with temperature.

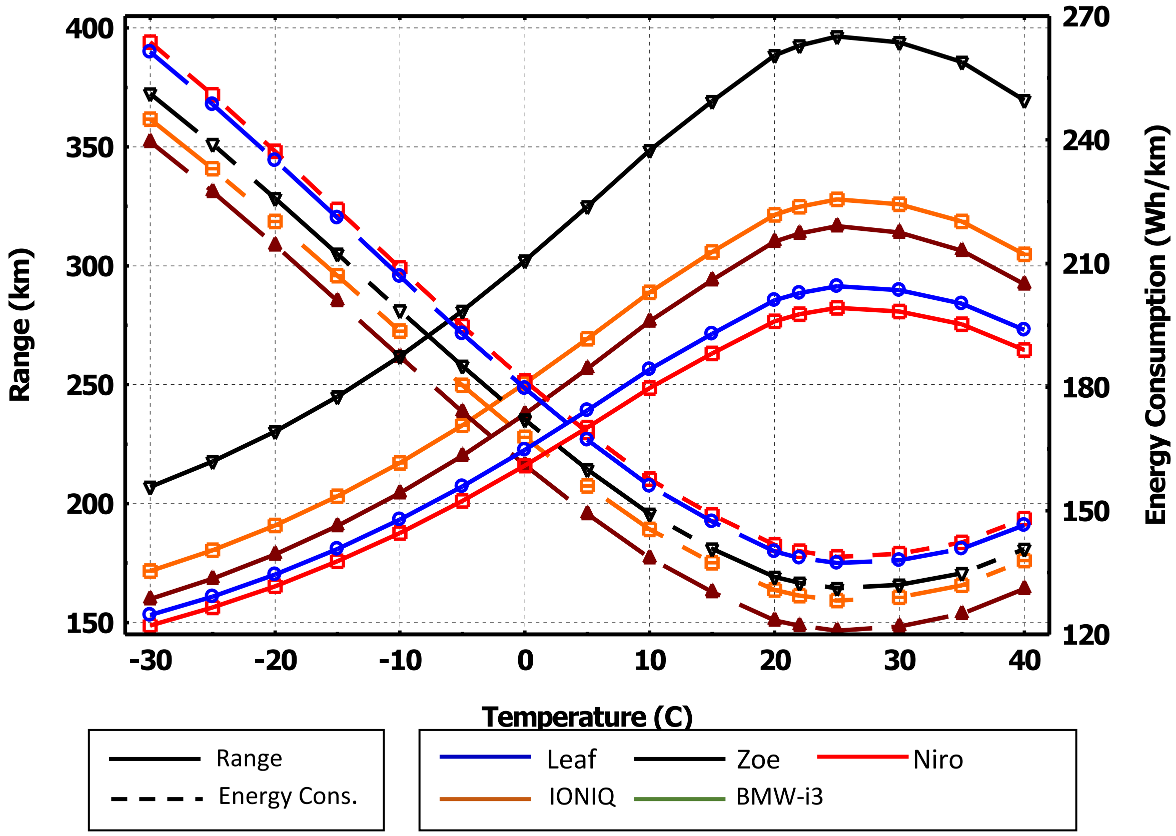

Figure 23: Influence of temperature on energy consumption and the range

From the results, we can see that with negative temperature the average energy consumption is much higher, since heaters, seat warmers, battery heaters and all other accessories are operated to produce suitable indoor comfortable conditions. Along with this, at a lower temperature, the pressure on the tires gets reduced and increases the resistance between the road and the tire, which in turn increase the resistance force acting on the vehicle. Also, air density is higher at lower temperatures.

As temperature increases, the average energy consumption reduces. From Figure 23, we can observe that the nominal condition is between 20°C and 30°C where the auxiliary power is minimal, without air conditioning and heaters. As temperature increases the air conditioning again comes back in action which rises the consumption of energy. For example, the same vehicle (e.g. Nissan Leaf) can be driven up to 250km during winters in Portugal, but only up to 170km or even lower in northern European countries like Sweden or Finland.

4.1.2.3 Influence of the average speed on EV range

The driving environment reflected in the average speed of the vehicle has a great impact on the power extraction from the batteries, as the drag force and acceleration forces are a function of vehicle speed. Nissan Leaf S, Renault Zoe, Kia Niro, Hyundai IONIQ and BMW i3 is taken as the reference vehicle and simulation was run for average speeds from 10km/h to 120km/h. It is assumed that the vehicle is initially at the reference speed for the simulation.

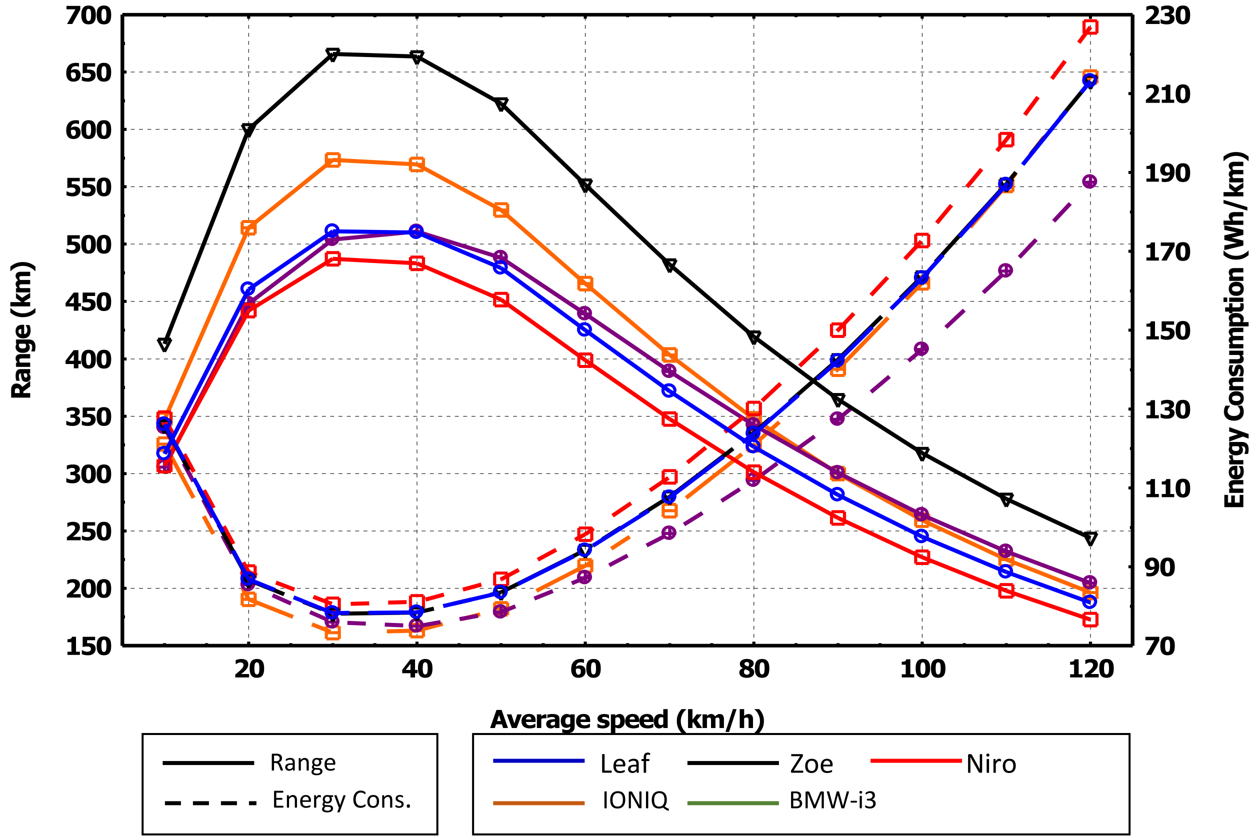

Figure 24: Influence of average speed on the range and energy consumption

The simulation is carried out for a duration of 1800s. From the analysis (Figure 24) we can observe that the energy consumption for unit distance is rapidly increasing when the average speed increases above 30km/h. The energy consumption below 30km/h is also increasing rapidly due to the auxiliaries, while above 30km/h it is due to vehicle speed and the forces that vehicle has to overcome. It is understandable from the graph that the optimal speed for EV is to be between 25 km/h to 40 km/h, where average energy consumption is below 80 Wh/km.

4.1.2.4 Influence of driving behaviour on EV range

The aggressive and non-aggressive behaviour of the drive cycle can have positive and negative impacts and the effect on the range is predicted with the WLTP class 3 drive cycle. Based on the research article [34], the normal aggressiveness of the WLTP class 3 cycle is calculated and is 14.44% including acceleration and deceleration aggressive points. To study the influence of aggressiveness, the acceleration points were modified in the WLTP class 3 drive cycle to make it less aggressive by altering the vehicle speed. Figure 25 shows the real and modified WLTP class 3 drive cycle.

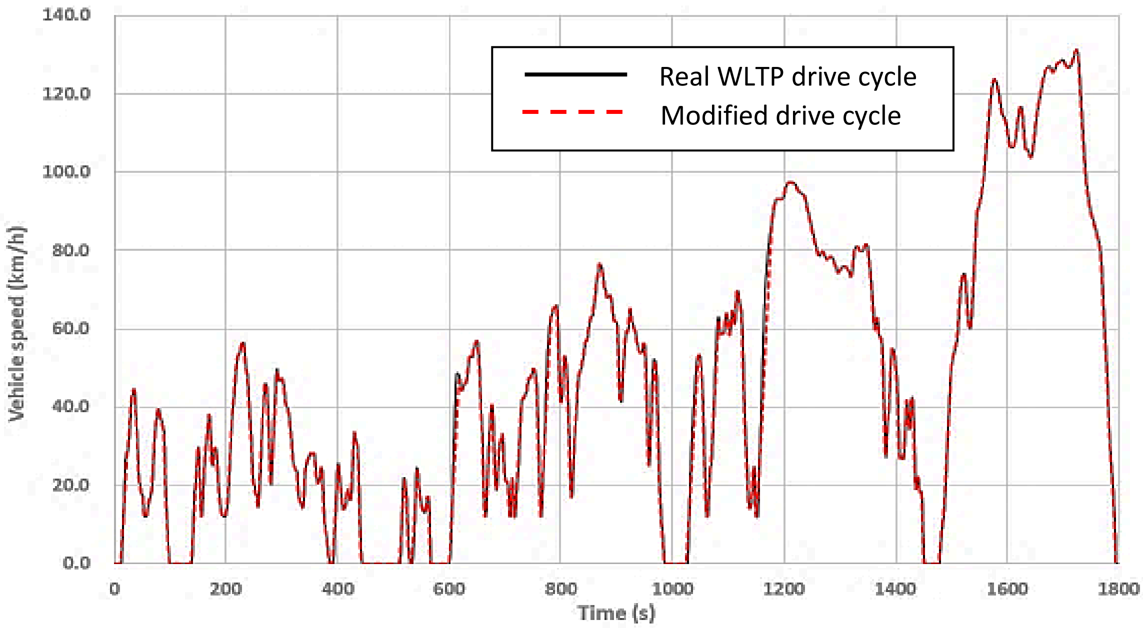

Figure 25: Real and modified WLTP class 3 drive cycle

When the acceleration point is altered with steady and non-aggressive progressive acceleration, the aggressiveness of the modified cycle is reduced to 6.7%. However, it didn't affect the speed profile of the vehicle. Table 10 the related parameters with both drive cycles and results from the simulation of the model.

Table 10: Simulation results and comparison of real WLTP drive cycle with the modified drive cycle

Parameters	Real drive cycle	Modified drive cycle
Duration (s)	1800	1800
Average speed (km/h)	46.5	46
Maximum Vehicle speed (km/h)	131.3 (1724 s)	131.3 (1724 s)
Simulation results (for leaf S 2019)		
Total Energy consumption	3.225	3.184
Energy Consumption (Wh/km)	138.6	136.8
Range	288	292

The results show that limiting the aggressiveness driving in acceleration helped to reduce the total energy consumption of the vehicle by 1.3%, thus the average energy consumption is decreased by same and range is increased by 1.4%. Limiting the aggressiveness can even reduce the energy consumption and increase the range, but deceleration aggressive points cannot be altered by assuming critical braking situation. However, we can limit the aggressiveness by reducing the speed of the vehicle, as discussed in section 3.4 and thus increase the range.

A range of vehicle speed is considered from 60% of the normal drive cycle speed to 140% for the real drive cycle. The aggressiveness is calculated and is tabulated on Table 11 within the considered scope.

Table 11: Change in the speed of the WLTP cycle and effect in the aggressiveness of driving

Speed (%)	60	70	80	90	100	110	120	130	140
Aggressiveness of real drive cycle (%)	3.4	5.9	8.6	11.7	14.5	16.4	18.5	20.6	23.5
Average Speed (km/h)	27.9	32.6	37.2	41.8	46.5	51.2	55.8	60.5	65.1

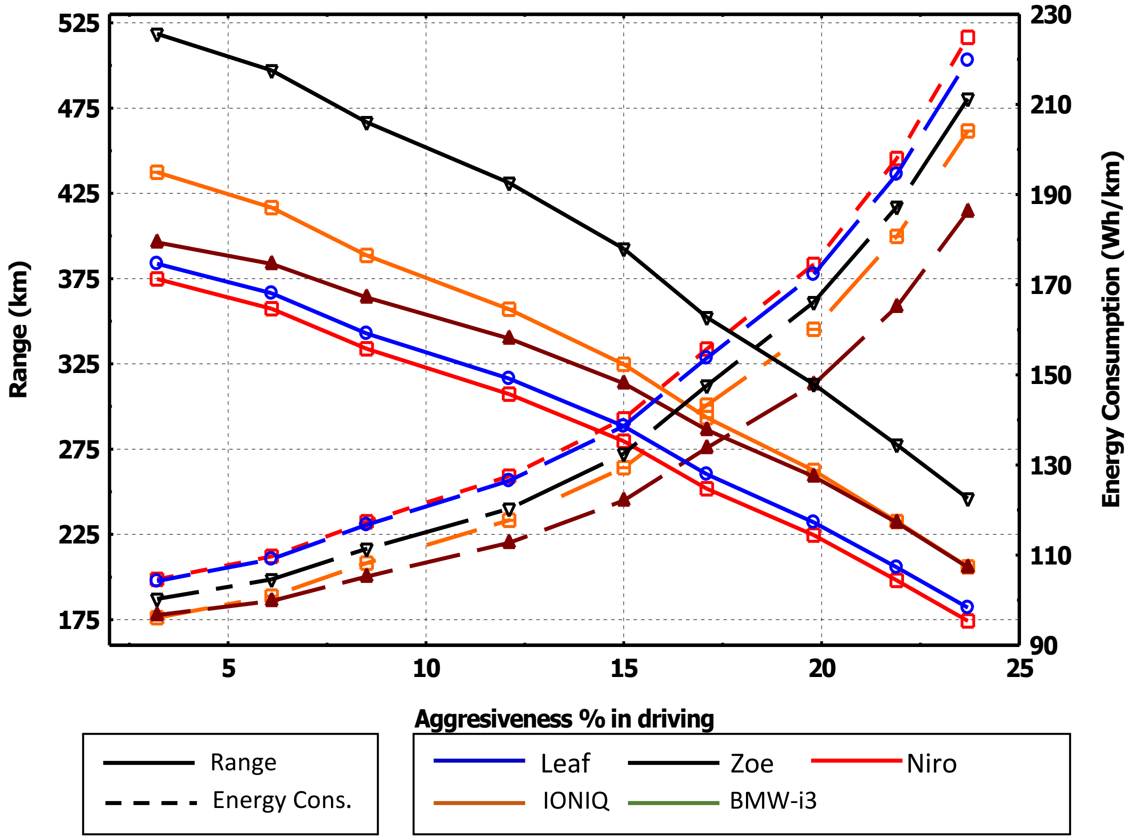

Figure 26: Influence of driving aggressiveness in range

Figure 26 shows the energy consumption and the range of different vehicles, during different aggressiveness of driving. From the results, we can observe that as the aggressiveness increases, the energy consumption is also increasing proportionally, and the range of the vehicle decreases. During aggressive driving, the sudden acceleration drains more energy as acceleration force (F_A) and is the reason for the increase in energy consumption.

4.1.2.5 Influence of combining energy source in vehicle performance

Like modern problems require modern solutions, to hurdle emissions, it is necessary to depend on other developed technologies. Using single power is a good option, however, the life of the battery or fuel cell alone is limited to 7-10 years. As the number of vehicles increases, the amount of dead batteries or fuel cell unit that has to be recycled also increases and it is evident that it will increase the electronic and chemical waste level, requiring further research on finding eco-friendly recycling processes [83]. However, it won't be operational shortly. With this study, we will look at the possibilities to extend the life of power source further, which helps to reduce the number of used batteries or fuel cell over time.

For this study, Honda Clarity is chosen as the reference model for the studies because of its availability in both electric and fuel cell version. Honda developed their Clarity Electric version in 2016 with 25.5 kWh battery and fuel cell model in 2017 with 103 kW PEMFC fuel cell on board with 5.46 kg fuel storage [84]. In comparison with the fuel cell model, the physical specifications were the same for the electric model of Clarity, which was an advantage to the simulations [85].

The electric and fuel cell vehicles were simulated using the developed model under WLTP 3 drive cycle. The results from the simulation are presented in Table 12.

Table 12: Simulation results of Honda clarity models in the WLTP drive cycle

	Energy Consumption (Wh/km)	Range (km)
Clarity Electric	145.7	175
Clarity Fuel cell	363.2	445

After numerous usage of batteries, the ability to store energy gets reduced and battery ages. The period with the amount of energy that can be stored reaches 80% of the initial capacity, the battery is considered as aged and is replaced. It is considered that the battery is dead after 700 – 1000 complete charging-discharging cycles [85]. For the studies, the optimal assumption of 1000 cycles is made. From the simulation results and the assumption, the battery would be supposed to replace after 175,000 km. Similarly, for PEMFC fuel cell, the life is considered to be as 5000 hours and replacement would be carried out after the vehicle reaches 232,500 km. On the other hand, ultra-capacitor is considered to have an unnegotiable advantage over all other power sources with a life cycle of 100,000 cycles to a million cycle with rapid charging process [86].

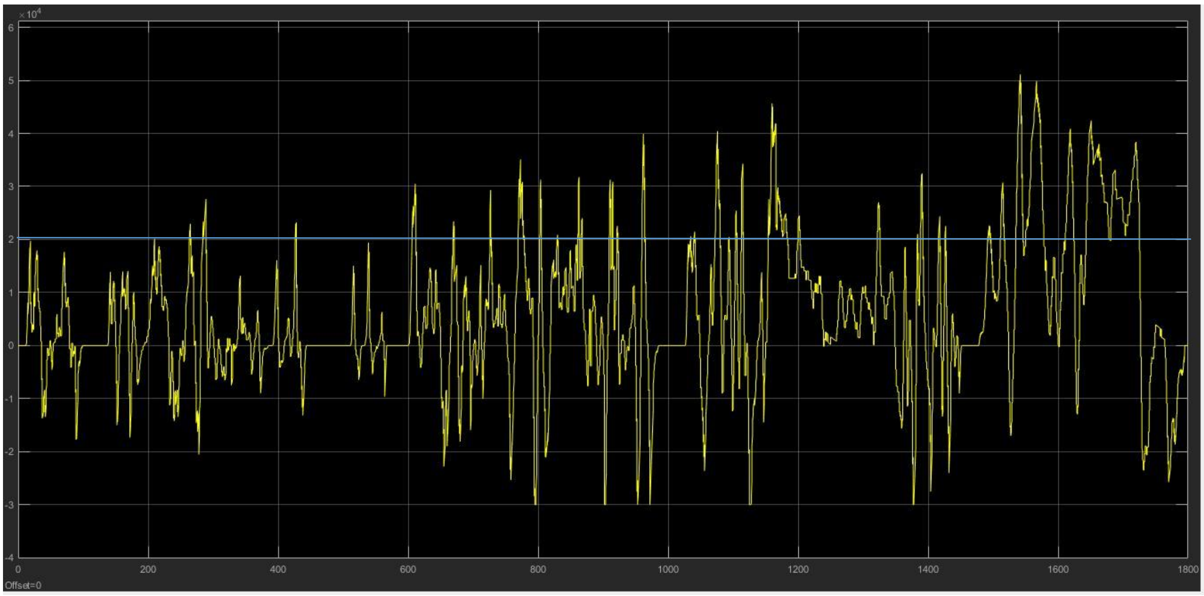

Figure 27: Power consumption profile (X-axis – simulation time; Y-axis – Watts)

Figure 27 shows the power requirement profile of the vehicle during the drive cycle duration. From the power profile, it can be observed that the maximum power consumed during the drive is 51 kW, which is 42% of the motor peak power. During the simulation of the vehicle with a combined power source, a setpoint has to be defined for the control system, which helps for the energy distribution between the energy sources. For this study, the setpoint is set as 20 kW (blue line) as shown in Figure 27. The study is done for a combination of different power sources such as battery + ultra-capacitor, fuel cell + ultra-capacitor and fuel cell + battery.

For simulations, an ultra-capacitor pack of 16V, 500 F (17.7 Wh) is considered as the standard module. Each module weighs around 8kg with insulations [87]. Considering the battery of different vehicles, it is estimated that 1 kWh of battery with insulation weights around 7 kg [78]. Table 13 shows the simulation results of Honda Clarity with different energy storage option with average energy consumption, range and life of the power source.

Table 13: Simulation results for Honda clarity model with different power sources

Primary Source (PS)	Secondary source (SS)	Energy consumption (Wh/km)	Range (km)	Life (PS) (km)	Life (SS) (km)
Battery: 25.5 kWh		146.1	174	175,000	
Battery: 25.5 kWh	UC : 1.6 kWh	151.7	179	193,200	7,916,000
Fuel cell: 103 kW		363.1	442	232,500	
Fuel cell: 103 kW	Battery : 8 kWh	341.8	556	232,500	113,375
Fuel cell: 103 kW	UC : 1.6 kWh	349.6	525	232,500	7,344,000
UC: 4 kWh		161.6	25	2,450,000	

From the results, it can be observed that combining multiple energy sources definitely has benefits. Adding 1.6 kWh ultra-capacitor helps to improve the life of the battery by 18000 km, which is more than the average distance driven in a year in Europe. For fuel cell vehicles, lifetime is determined by working hours and adding energy source helps to reduce the energy production, but not working hours, consequently, they are not showing any change in total life. However, in the fuel cell, adding power source helps to reduce the peak power production point, thus cells required and cost of the vehicle. While considering ultra-capacitor as the single power source, we can observe the range is 25 km, which is low for a passenger vehicle and frequent charging on each 25 km is not a feasible option.

On the contrary, adding more power source has an influence on the curb mass and cost of the vehicle. The average cost of battery per kWh is considered as 165 € [88]. While the average fuel cell cost for 1kW is claimed under 50 €, the price is calculated by an assumption of 500,000 fuel cell unit production. However, the automotive manufacturers are producing around 1000 unit/year, which in turn increases the cost of fuel cells to 175 €/kW [89]. Whereas ultra-capacitors cost 280 €/module and number of modules are calculated using equations 56 – 61. Figure 28 shows the variation in curb weight and the initial cost of the vehicle with respect to the Honda Clarity electric model.

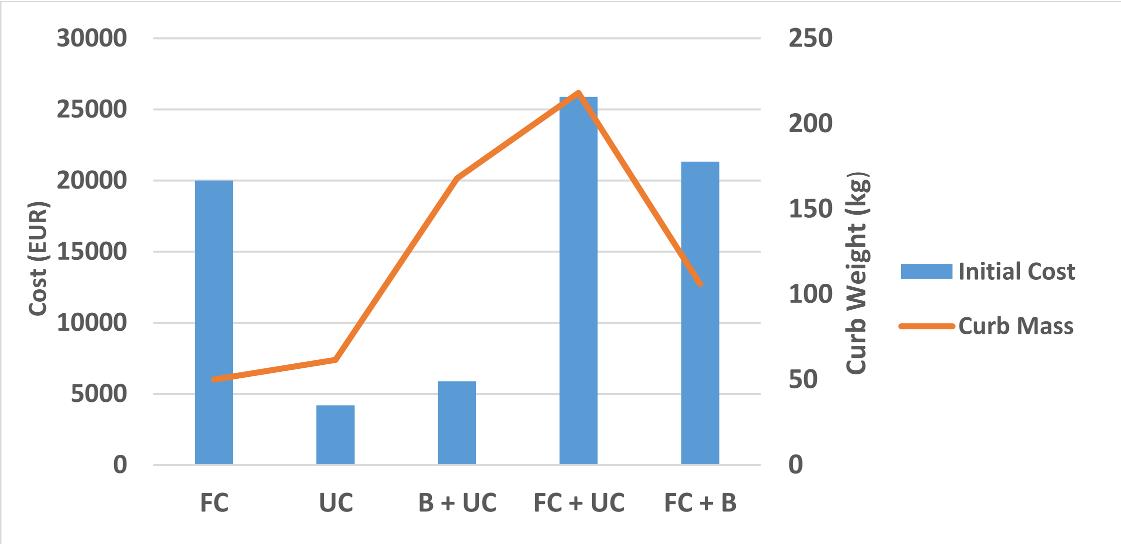

Figure 28: Change in curb weight and the initial cost of the Honda Clarity model with different power sources

From Figure 28, we can observe that accommodating fuel cell is an expensive decision for the moment. And adding more sources with fuel cell only results in increases the cost and vehicle mass. While battery + ultra-capacitor combo shows a positive sign with a small price hike of around 5000 €.

The simulated powertrain shows a range of 25 km – 556 km. On average, these can be considered as the extremes ends required for a passenger vehicle. To compare them with equal scale, a range within 280-300 km is considered and the powertrain is reconfigured for different energy sources. The simulation is carried out with the WLTP class 3 cycle without any road grade. The vehicle specification is made constant except the curb weight. Table 14 shows the simulation results of the reconfigured vehicle for an average range indicated above. The setpoint for the control system is still fixed at 20 kW.

Table 14: Simulation results for the power sources in Honda Clarity model to achieve average range of 280-300 km

Primary Source (PS)	Secondary source (SS)	Energy consumption (Wh/km)	Range (km)	Cost (€)	Curb mass (kg)
Battery: 42 kWh		149.5	281	2728	115
Battery: 41.5 kWh	UC : 1.6 kWh	155.5	278	8525	280
Fuel cell: 60 kW*	Battery : 5 kWh	343.2	306	13311	98
Fuel cell: 60 kW*	UC : 1.6 kWh	353.7	287	18364	- 22

** 3 kg of hydrogen storage is considered*

Cost and curb mass is reported as the difference from the Honda Clarity electric cost and curb mass

From the results we can observe that for a user interested in a passenger vehicle with a range of 280 – 300km, Battery vehicle is still recommended in the current market scenario. In fuel cell vehicles, the cost can be reduced by 8000 € by reducing the fuel cell output by 43 kW, however, it is still more expensive than BEV. It is done by reducing the number of cells in the stack.

4.1.3. POTENTIAL IMPACT IN REAL WORLD DRIVING

The goal of this study is to investigate the effectiveness of electric vehicles in the transportation sector and the cost efficiency of electric vehicles compared to conventional vehicles. As mentioned in section 3.1, 3 different drivers were chosen, and real-world driving data were recorded for 10 hours of driving. The driving data in Table 4 shows the driving pattern is different for each driver. The Nissan leaf 24 kWh BEV model and the same model with a fuel cell unit instead of battery source is simulated with the drive cycle to compare the energy consumption of the vehicle. Table 15 shows the simulation results with battery and fuel cell used as the energy source.

Table 15: Energy consumed during driving and estimated consumption in BEV and FCEV

Driver ID	ICE		BEV			FCEV		
	Total cons. (kWh)	Wh/km	Regen energy (kWh)	Total cons.*		Regen energy (kWh)	Total cons.*	
				kWh	Wh/km		kWh	Wh/km
1	212.9	604	19.5	44.7	127	1.3	130.7	371
2	232.4	842	18.7	46.5	168	0.9	134.2	486
3	158.9	489	18.1	46.5	143	1.1	130.3	400

** Total energy consumption in BEV and FCEV includes regenerative braking*

From the results, it can be seen that electric powertrain is much more efficient than that of the internal combustion engines. In battery electric vehicle, the tank to wheel efficiency is more than 80%, while for fuel cell vehicles, it around 50% and internal combustion it's less than 30%. Over here, BEV only consumes 28 – 35 % of the energy consumed by ICE without regenerative braking. The energy capturing from braking through regenerative property help to reduce this even further lower to 23%. Whereas fuel cell consumes more energy than the BEV, however, it helps to capture some of the waste energy through braking. While when it comes to charging or refuelling, it is to be noted that that the BEV has undergone 3 full charging cycle, while fuel cell EV covered the distance without any refuelling. This proves that real-world mobility patterns may influence the shift in-vehicle technology since autonomy is still a variable highly values by the consumer, which in this case would favour a fuel cell EV.

4.2. BUSES

As mentioned in section 3.2, a heavy-duty vehicle is simulated and tested with the developed model to check the versatility of the model. Due to the easy accessibility of data, Public transportation bus is chosen for the simulation process. Unlike the simulations carried out in passenger cars, it was difficult to find standard simulation results for bus, as each organisation generates customised quotes from the manufacturer based on their requirements. Furthermore, most of the specification of the vehicle was not publically available due to the existence of custom-made solutions.

For testing the developed model and validation for the heavy-duty vehicle, a measured real-world driving cycle was adopted from a previous thesis [71]. The real-world driving data acquisition of the e.City Gold bus was previously done in the Vila Nova de Gaia and Porto region of Portugal. The same vehicle is considered for testing with the model developed in Simulink. Performance variables and specifications are given as inputs as described in section 3.1, for validating the simulation model to check the reliability of the generated model. The specification of the vehicles is tabulated in Table 16.

Table 16: Specification of e.City Gold bus [71]

Specifications	**e. City Gold**
Mass (kg)	12300
Frontal Area (m^2)	6.88
Tire Radius (m)	0.545
Maximum speed (km/h)	70
Motor power (kW)	224
Maximum torque (Nm)	2500
Battery capacity (kWh)	85
Drag coefficient	0.7

Figure 29 shows the drive cycle generated from the data acquired. The vehicle covers a total distance of 71.15 km in 3.7 hours (13353 s). The average speed from the data is calculated as 19.18 km/h with a maximum speed of 74.5 km/h. Also, the acquired data gave the slope or grade of the road. Figure 30 shows the road grade for the above driving profile.

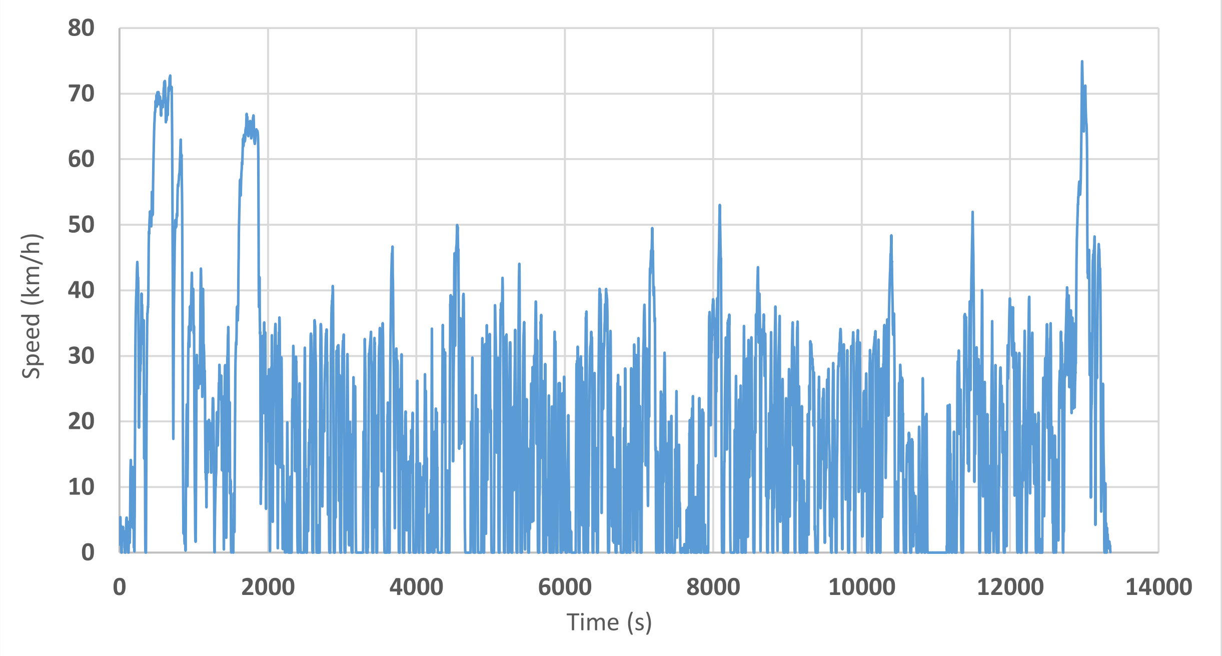

Figure 29: Real world drive cycle for testing of the heavy-duty vehicle (Electric Bus)

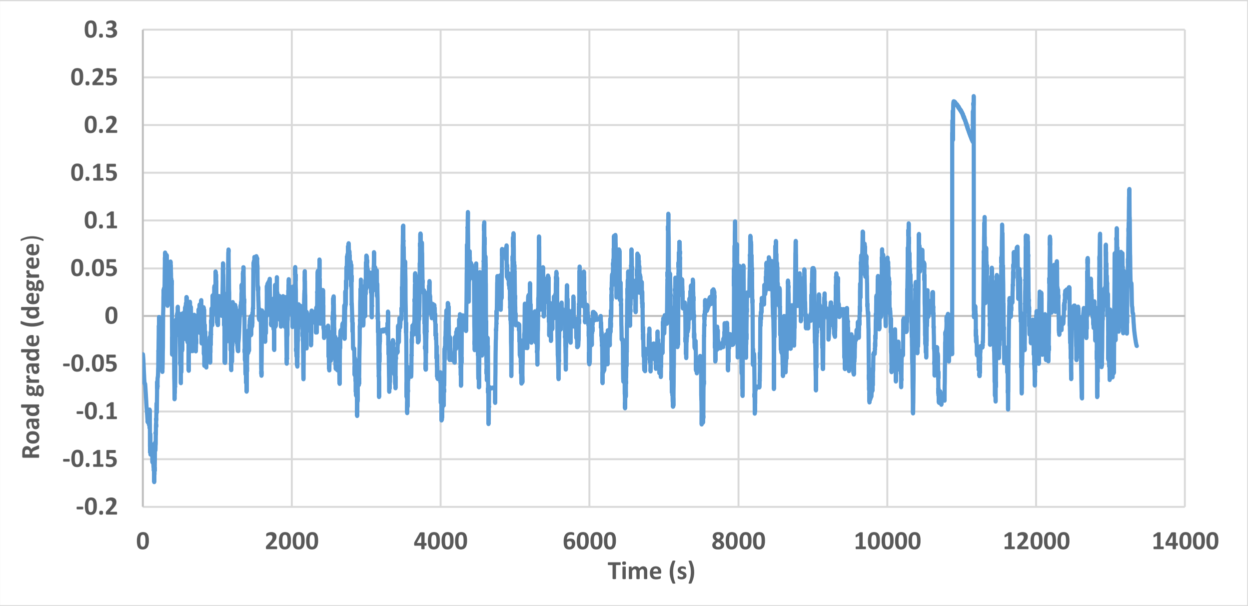

Figure 30: Road grade of the drive cycle for testing of the heavy-duty vehicle (Electric Bus)

4.2.1. VALIDATION OF THE MODEL

The model was validated through the comparison with the results from the study [71]. The simulation was carried out for the above drive cycle along with considering the road grades. The results are presented in Table 17, in comparison with the initial results from the real-world testing [71]. The simulation is carried out by considering an atmospheric temperature of 14 ˚C, which was the average temperature during the period of testing and auxiliary power of 3 kW, which was the average auxiliary power consumption recorded in the data.

Table 17: Simulation results of e.City Gold bus (error compared to reference, %)

Parameters	Results
Total Energy Consumption (kWh)	58.5 (-1.1)
Average energy consumption (Wh/km)*	822.5
Range (km)*	103.3

** Values are obtained through the simulation*

From the results, we can observe that simulated results were close to the recorded energy consumption with a very small error, which is negligible. It points out that the developed model was reliable and can be used to simulate a wide range of electric and fuel cell vehicles. The difference is justified due to assumptions made in some of the coefficients, such as the rolling resistance, drag coefficient, motor efficiency, auxiliary power demand and efficiency of other electric devices. However, it is important to note that the drive cycle tested was made for the studies, without passengers and that the journey was continuous. During the public transportation mode, frequent stopping and door openings are required during at the bus station. It can increase the auxiliary power requirement to an average of 4.5kW to 7kW due to the pistons and cylinders used indoor and brakes [90].

4.2.2. INFLUENCE OF DIFFERENT ENERGY SOURCES ON BUSES

To compensate for the weight factor due to battery for energy storage and higher charging times, alternative energy source were experimented by different organisations. Positive signs have been shown by the fuel cell and ultra-capacitor powered vehicles. In this study, those propositions were tested and studied with the model generated in Simulink. The same vehicle described in Table 16 will be tested with the same drive cycle. It helps to identify the advantages of using different energy sources.

Like described before, batteries will be considered aged after 500-1000 charge-discharge cycles. Unlike passenger vehicles, transportation buses have to be changed frequently. It reduces the lifetime (in years) of battery sooner than the light-duty vehicles. Due to this, frequent battery replacement can be expected. While for fuel cell, the lifetime is considered to be as 5000 hours irrespective to the peak power production, it is expected to last a bit longer than the batteries. While ultra-capacitor is considered to have an unnegotiable advantage over all other power sources with a life cycle of 100,000 cycles to a million cycle with rapid charging process [86]. These points will be validated again with these studies. Simulations are carried out with the same auxiliary power and ambient temperature as described in the last section.

In addition to this, 40 passengers were considered for the simulation with an average weight of 65kg. Table 18 shows the performance of e.City Gold bus with different energy sources.

Table 18: Simulation results of performance of e.City Gold bus with the different energy source

Energy Source	Energy consumption (Wh/km)	Range (km)	Life (km)	Life* (days)
Battery : 85 kWh	996	86	86,000	594
Battery : 120 kWh	1013	119	119,000	820
Battery : 170 kWh	1038	164	164,000	1131
Battery : 200 kWh	1053	190	190,000	1310
Fuel cell : 230 kW; 10 kg H_2	3035	98	96,000	662
Fuel cell : 230 kW; 20 kg H_2	3058	195	96,000	662
UC : 16 kWh	1084	15	1,500,000	10344
UC : 20 kWh	1117	18	1,800,000	12413
UC : 30 kWh	1189	25	2.500.000	17241

** 2 trips are assumed on daily basis throughout the year*

From the results, it can be observed that with passengers, the expected distance travelled by bus with the standard specification is around 86km. The drive cycle tested covers a distance of 71.15km in one trip. For e. City Gold bus to do a continuous service, it is required to charge after each trip. Unlike passenger vehicles, 1000 charging cycle will be over within 2 years if 2 trips are assumed on each day. A cost of 14000€ per two years can be expected to replace the batteries. However, adding more batteries helps to cover more distance and reduce the number of charging cycles. It has been reported that buses for transportation are customised with battery capacity ranges from 60 – 500kWh [91]. To analyse the outcome, the battery capacity has been increased to 120kWh, 170kWh and 200kWh. From the results, it's clear that the battery helps to cover more distance through each charging and reduce the number of charging cycles, in 30 days from 51 to 23 charging cycles from standard battery capacity to increased capacity of 200 kWh.

While using a fuel cell, it improves life by 12% compared to the standard specifications. However, the cost-benefit ratio is much lesser than that of the electric vehicle, due to the high initial cost of fuel cell and fuel price. From the analysis, it can certainly tell that ultra-capacitor will be the most beneficial option when considering public transport. With ultra-capacitor, even though the range was limited to 15 – 25 km, the ultra-capacitor last to 1.5 million charging cycles within least favourable conditions and it will last for at least 25 years. From the simulation, it shows to cover 1 trip, it is necessary to charge the ultra-capacitors 4 times. However, these advantages of energy sources come with some disadvantages. Figure 31 shows the change in curb mass and initial cost change for different energy sources in comparison with the test vehicle.

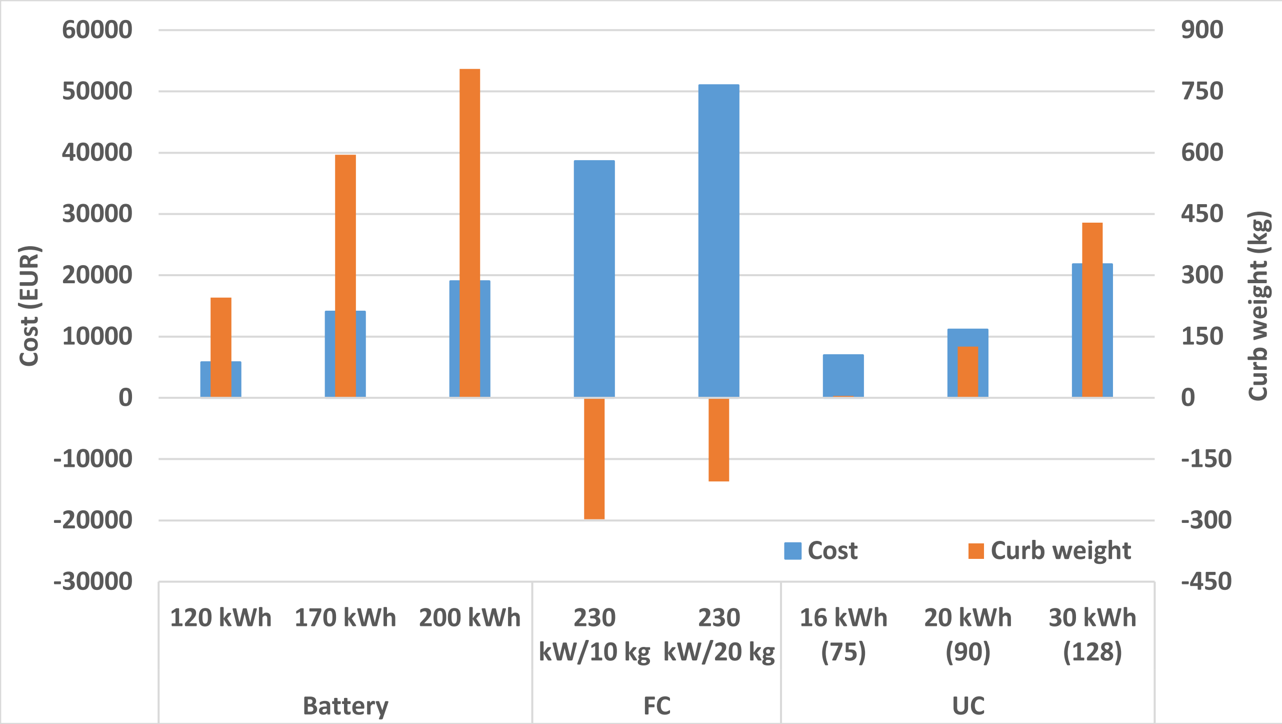

Figure 31: Change in curb mass and the initial cost of the bus for different energy sources (compared to the standard vehicle)

From the Figure 31, it can be observed that all other power sources are expensive compared to that of the electric vehicle. Doubling the battery capacity surely increases the initial cost, but it helps to cover more distance with less charging cycle and helps to runs the bus longer before battery replacing. However, it increases the vehicle mass and also the battery replacing cost will be around 30,000 € over a period of 3.5 years. While considering mass, evidently it can be observed that fuel cell as an energy source has an undue advantage on the curb mass. When using 10 kg of hydrogen, the range is about 98 kg. One of the noticeable advantages of the fuel cell is that to increase mileage, no additional arrangements are required other than the storage tank for more fuel. When 10kg hydrogen is stored more, the increase in weight is less than 120 kg and range doubles. This shows that fuel cell can be used as the primary energy source for vehicles like trucks and luxury coaches were long distances have to be covered without refuelling. However, high fuel cell cost results in a high initial cost of the vehicle. For UC, the expense is similar to 200 kWh battery, however, it has the highest cost-benefit ratio when comparing lifetime. The 30 kWh UC lasts for around 40 years and with quick charging, enables recharging within minutes during stops in bus stations, which is suitable for short-frequent trips.

Figure 32 shows the power consumption profile by the bus during the operation. From the profile, we can observe that during the whole trip, power consumption above 150 kW is less than 4%, with the regenerative braking limited to 25% of the motor power, i.e. 56 kW. The power consumption is highly volatile in between 50 kW and 150 kW. By considering this, the setpoint for the control system is set at 70 kW (blue line). Table 19 shows the performance of e.City Gold bus with multiple power sources.

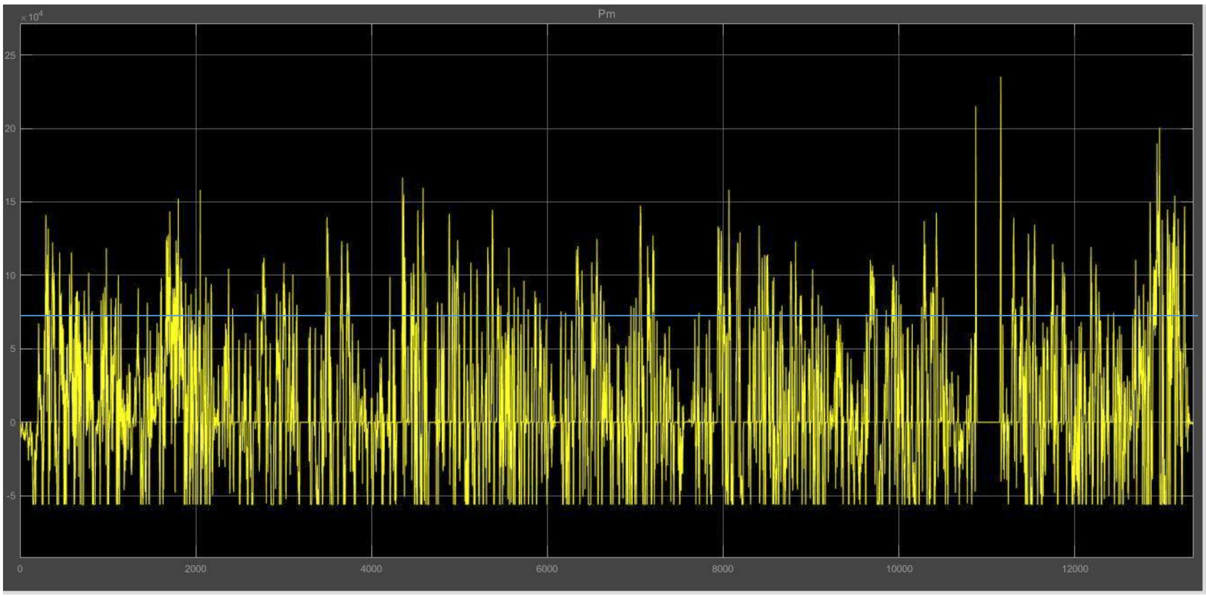

Figure 32: Power consumption profile of the bus during the real-world drive cycle

Table 19: Simulation results of performance of e.City Gold bus with combination of energy source

Primary Source (PS)	Secondary source (SS)	Energy consumption (Wh/km)	Range (km)	Cost (€)	Curb mass (kg)
Battery: 52 kWh	UC : 5.1 kWh	978	58	5184	73
Fuel cell: 135 kW	Battery : 16 kWh	2702	129	24617	- 330
Fuel cell: 135 kW	UC : 5.1 kWh	2717	124	32612	- 40

Comparing the previous results with passenger vehicle and results from the bus, we can observe that combining battery with ultra-capacitor won't bring any benefits in range or energy consumption, apart from the battery life extension for vehicles. While with the fuel cell, both studies show it is better to combine with a battery than ultra-capacitor, which helps to improve the performance of former than the latter with economic benefits.

4.3. TOTAL OWNERSHIP COST ANALYSIS

The goal of this study is to investigate the effectiveness of electric vehicles in the transportation sector and the cost efficiency of electric vehicles compared to conventional vehicles. TOC portraits the cost efficiency of a vehicle throughout its lifetime. All costs that occur during the expected vehicle's lifespan are included: purchase cost, registration tax, vehicle road tax, maintenance, tires and technical control cost, and fuel or electricity cost. Results are shown per vehicle segment and illustrate the share of all cost components. The total ownership cost (TOC) of the electric vehicle, fuel cell vehicle and gasoline vehicles are compared.

The average distance travelled per year by a passenger vehicle is assumed to be 12500 km, 220-250 km per week [71]. Over 12 years, the total distance covered is 150,000 km which is within the battery life warranty period. Due to this battery replacement cost is not considered. Also, the government incentives for electric vehicles are narrowed to the limited number of vehicles and it cannot be made a promise that the vehicle purchase always ends up with incentives. So government incentives are also avoided for the study.

For conventional vehicles, the maintenance cost includes oil replacement over 5000 km; brake check-up, vehicle tune-ups, transmission maintenance, air filter changing and tire changing at 50000 km; belt and hose changes over 100,000 km, while for electric and fuel cell vehicle brake check-up and tire changing is carried out at 50,000 km. Figure 33 shows the maintenance cost for the various vehicle per unit km.

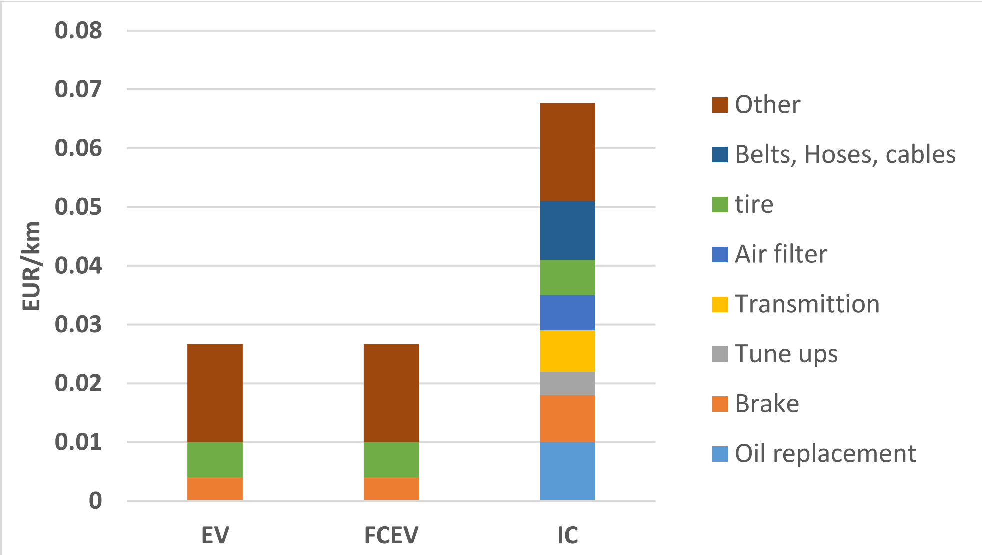

Figure 33: Maintenance cost per unit km

As mentioned in section 3.3, for hatchback vehicle, the average ISV is approximately 800 €, and for SUV its 1200 € during the registration process. IUC for a hatchback gasoline vehicle is around 130 €/year and for SUV its 160 €/year [77]. Both these taxes are calculated for the lifetime of the vehicle. However, electric vehicle and fuel cell vehicles are exempted from both ISV and IUC taxes. Figure 34 shows the TOC of different vehicles of different powertrains.

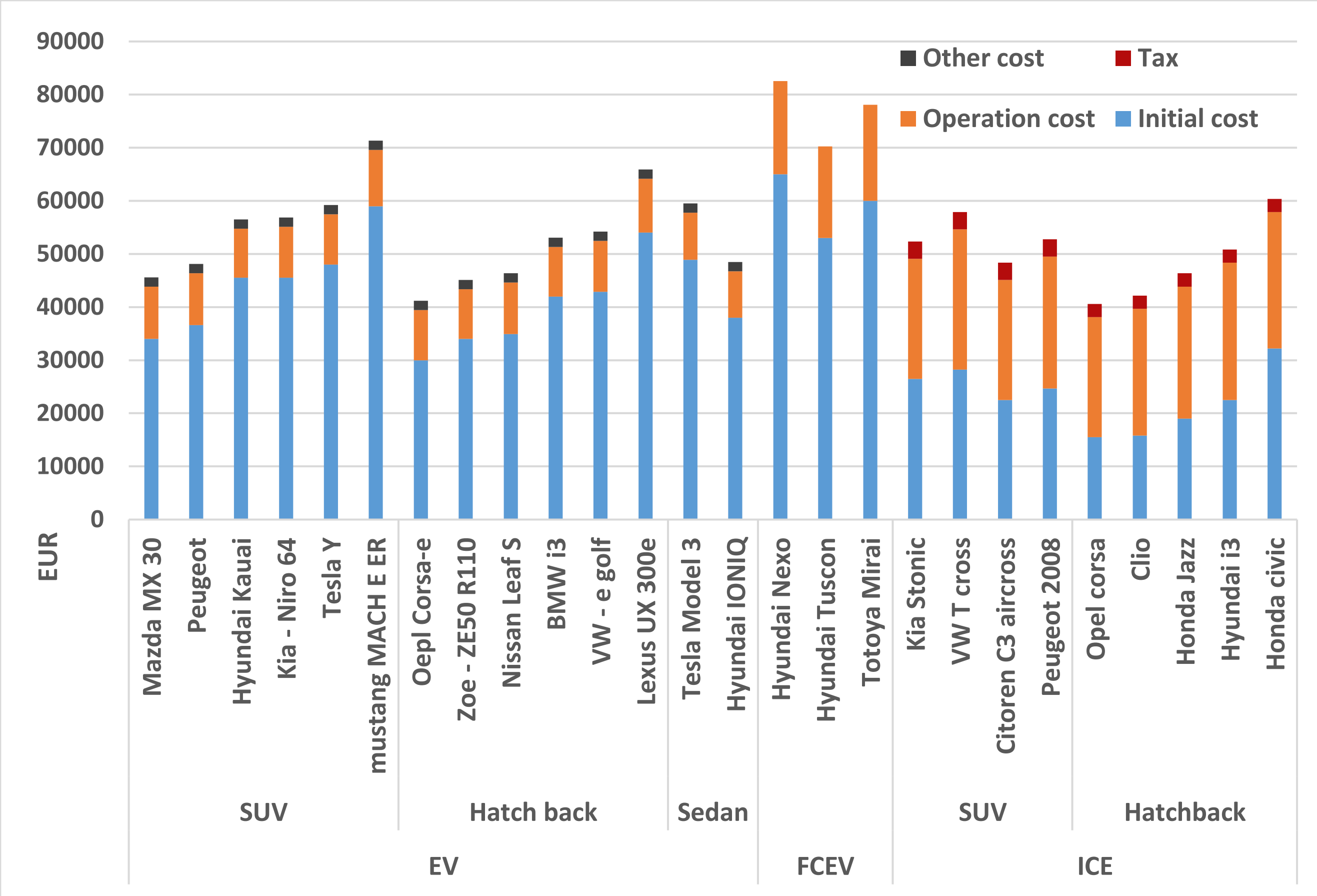

Figure 34: TOC of different vehicles available in the market for a period of 12 years

From the results, it can be observed that conventional vehicles are the least expensive to buy. However, half of the TOC over the period is spent on operational and maintenance cost. While for electric vehicles the initial cost is high which is almost 70% of the TOC is, the operational cost is between 20 – 25%. In the case of fuel cell vehicle, it can be observed that both the initial and operational cost are high, which make it least preferable by the customers. Figure 35 shows the average price range of vehicles from different segments.

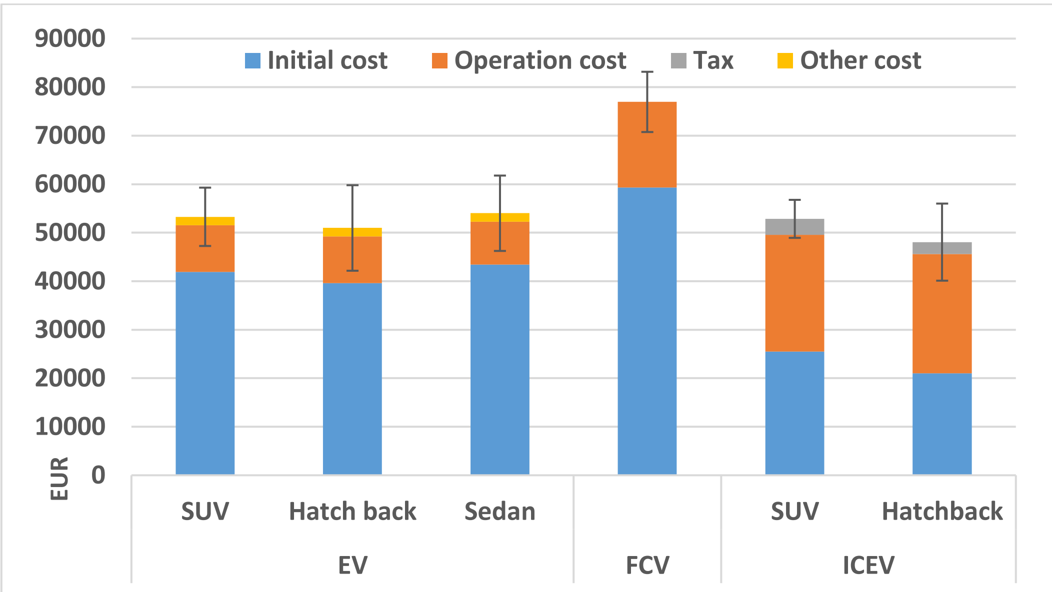

Figure 35: Average price distribution between various vehicle segments

From Figure 35 we can observe that fuel cell vehicle is the most expensive option in the light-duty vehicle models. As mentioned before, the main reason for this is due to the higher initial fuel cell cost, high fuel price and lack of refuelling stations. The studies showed that the higher price on the fuel cell unit is due to the lack of mass production. With 1000 units production cost 175 €/unit and it can be reduced to 45 €/unit with a production of 500,000 unit [92]. Also, studies point out with more investment in renewable energy, green hydrogen cost will be reduced by 40%-50% in 2030 [75]. More countries in the EU such as Germany, Portugal, and Denmark are now focusing on developing the hydrogen economy. Assuming the conditions are favourable, it will increase the production of fuel cell units, which forces to open up more hydrogen refuelling stations. This shows that soon the electric passenger fleet will be competing against fuel cell vehicles and the latter has a higher probability to survive the automotive industry.

5. CONCLUSIONS AND FUTURE WORK

This aim of this research work was to study the energy and cost-effectiveness of powertrains powered by battery, fuel cell and ultra-capacitor for different vehicle segments. To achieve this, a vehicle model was developed in Matlab using Simulink toolbar. The developed model was validated through different vehicle models that's available in the market. The simulation results showed an absolute error less than 4% (combined for battery, fuel cell and ultra-capacitor module) for light duty vehicles and 2% for heavy duty vehicles. This shows that the model is reliable, flexible and its accuracy is above 96%.

This study shows that the increase in battery capacity will help to cover more range. When the battery capacity is tripled from 24kWh to 72kWh, the range of the vehicle increases by 294%. Theoretically, the increase should be 300%, but, due to more battery packs, vehicle mass also increases which has a negative influence and reduces range by 6%. The study related to energy density shows that higher the energy density, lower will be the energy consumption and higher the range. Combining these two inferences, using high energy density battery, along with high battery capacity will helps to exploit both their benefits and increase the expected range to an admirable point. The study on the average speed of vehicle shows that the EV moving with average speed between 30-40km/h has the least energy consumption and highest range. But in real-world, maintaining between the former values can be a little difficult, but maintaining the speed between 20-50kmph results in satisfying range with a difference of 10%. On the other hand, the results on aggressive driving shows that EV range can be reduced by 4% based on the driving pattern. However, reducing the average speed of the vehicle along with less aggressive driving can help to increase the range by 10% – 20%.

Furthermore, the results on the influence of atmospheric temperature on range show the optimal atmospheric temperature to obtain maximum range is between 20°C-30°C, and range can be reduced to 25% – 35% in colder regions where the temperature is below -20°C. During lower temperature; the air density, the rolling resistance force, and the auxiliary power requirement are high. This clearly explains the reduction of range of same model vehicle in different regions around the world. It is hard to mitigate this problem manually, however, we can reduce the effect by idling vehicle for a couple of minutes, which heats up the vehicle and reduces the effect on the range during cold conditions.

The analysis of the vehicle performance with energy storage system shows that the battery vehicles have the least energy consumption, while FCEV showed the highest range and ultra-capacitor vehicle showed the possible longer life. When ultra-capacitor is combined with the battery, the life of the battery is extended by 10%. Considering fuel cell as secondary source and combining it with battery (battery or ultra-capacitors as primary source) will increase the primary cost because of the higher market price won’t be beneficial. While, considering fuel cell as a primary source, combining battery or ultra-capacitor helps to cover more distance with reduced energy consumption.

With the fuel cell, combining more energy source won't benefit in the operation life, however, the powertrain can be benefited in terms of cost by the reduction of the number of fuel cells in the stack. Ultra-capacitors show positive results with other powertrains, nevertheless, it cannot be used as the primary energy source due to the high cost for per kW storage. This limits the amount of ultra-capacitor that can be incorporated with the powertrain and this negatively affects the range.

For light duty vehicles, from real-world-tested results and comparing with simulation results, it can be seen that electric powertrain is much more efficient than that of conventional vehicle. BEV only consumes 23% of total energy compared to the energy used by conventional vehicle, while fuel cell energy consumption is higher with 65%. The advantage of regenerative braking is prominently seen in this study. When it comes to charging or refuelling, it is to be noted that the BEV has undergone 3 full charging cycle, while fuel cell EV covered the distance without any refuelling. The total ownership cost analysis indicates that battery electric vehicle is preferred due to moderate initial cost and lower operational and maintenance cost. While fuel cell vehicle is currently the most expensive option due to higher initial and operational cost. However, if the condition favours to the production and increases to more than 100,000 per year, the fuel cell vehicles will be competing actively against battery electric vehicles in the future for both light-duty and heavy-duty vehicles. This proves that real-world mobility patterns may influence the shift in vehicle technology since autonomy is still a variable highly valued by the consumer, which in this case would favour a fuel-cell EV in the future.

For buses, the results were entirely different than that of passenger cars. Batteries are less favourable as the primary sources in buses due to higher charging duration. Long-time gaps are required between trips which are not favourable for the considered model. While fuel cell vehicles only requires fewer minutes to refuel and to increase the range, they have to add more storage space for the hydrogen, where the curb mass change is negligible. This makes fuel cell preferable in buses, coaches and trucks which is intended to cover long-distance trips. For short-frequent trips, ultra-capacitor is recommended because of its ability to deliver high power in a short time. Even though the low energy storage capacity of UC forces frequent charging, the fast charging property of ultra-capacitor makes it possible during stops. While the combination of energy sources didn’t show any improvement than the former results on buses.

In the future, additional works can be performed by upgrading the developed model.

- The methodology adapted can be improved in the developed model. The assumptions made in the input variables (auxiliary power consumption, the efficiency of the electronic devices and components, transformation processes…) can be improved.
- Additional minor improvements make the model adaptable for different types of light and medium-duty vehicles.
- At present, to test the performance of dynamic powertrain, only longitudinal car dynamics has been used with longitudinal tyre motion, but in the future, the car model can be equipped with the ability of lateral motion to test other kinds of driving tests such as turning through a corner.
- At present, the motor is modelled based on mathematical equations, while it can be updated with complex modelling of the motor, to help to predict the energy consumption and efficiency of the motor more precisely.
- A delegated and vibrant control system can be developed, which helps to determine the set point for multiple energy sources more accurately based on the driving pattern and can be customised for individual customers.
- Developing electrochemistry based 1-D mathematical model for the Li-ion battery and employing control volume method to solve the simultaneous coupled partial differential equations to capture the realistic charging and discharging behaviour of the battery under normal operation conditions helps to optimize the battery pack more efficiently. Also considering the thermal management of the battery would improve the representativeness of the model.
- The present generic model is very good at predicting battery behaviour in normal operating conditions and on different temperature conditions. The electrochemistry based 1-D mathematical model with proper thermal model improves the performance prediction and is an advantage over this generic model.
- Electro chemical-based modelling of fuel cell helps to optimise the fuel cell stack and volume based on the vehicle segment, which helps to optimise the whole vehicle system.
- Like the developed model for light-duty and heavy-duty vehicle, advanced modelling updates helps to accommodate flights and ships, which can be simulated and carry out study for customised situations.

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