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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MODELLING AND OPTIMIZATION OF DRIVING PERFORMANCES OF HYBRID ELECTRIC VEHICLES

Dilara ALBAYRAK SERİN

Supervisor
Assist. Prof. Dr. M. Alper ÖZPINAR

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ACCEPTANCE AND APPROVAL PAGE

On 05/02/2018 Dilara Albayrak Serin successfully defended the thesis, entitled "Modelling and Optimization of Driving Performances of Hybrid Electric Vehicles", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury members whose signatures are listed below. This thesis is accepted as a Master's Thesis by Istanbul Commerce University, Graduate School of Natural and Applied Sciences.

Approved by:

Supervisor	**Assist. Prof. Dr. M. Alper ÖZPINAR** Istanbul Commerce University
Jury Member	**Assoc. Prof. Dr. Ali ÇINAR** Kocaeli University
Jury Member	**Assist. Prof. Dr. Muhammet CEYLAN** Istanbul Commerce University

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Assoc. Prof. Dr. Necip Şimşek
Head of Graduate School of Natural and Applied Sciences

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Date
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Name and Surname
Dilara Albayrak Serin

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ABSTRACT

M.Sc. Thesis

MODELLING AND OPTIMIZATION OF DRIVING PERFORMANCES OF HYBRID ELECTRIC VEHICLES

Dilara ALBAYRAK SERİN

Istanbul Commerce University
Graduate School Of Natural and Applied Sciences
Department of Mechatronics Engineering

Supervisor: Assist. Prof. Dr. M. Alper ÖZPINAR

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Throughout the history electric vehicles and hybrid electric vehicles have come to spotlight of researchers but interest in these concepts decreased from time to time. With the desire to decrease fuel consumption and emissions studies on hybrid electric vehicles have risen throughout the years. The aim of this thesis study is to find alternative ways and to improve driving performance of a hybrid electric vehicle by improving the fuel efficiency and decreasing emissions. Through this research, finding an optimum point for a better driving performance of a hybrid vehicle is aimed. For this goal, a mid-size family sedan type of hybrid electric vehicle is modelled with help of MATLAB/Simulink and the modelled vehicle is tested with a simulation from Istanbul to Ankara, 450 kilometers. The properties of vehicle route are retrieved from Google Earth and the road is simulated in MATLAB. Both simulation and optimization processes are held. Acquired minimization is up to 44.29% in fuel consumption and 37.34% in total trip cost when compared to the simulation results before optimization.

Keywords: Driving performance, fuel consumption, hybrid electric vehicles, optimization, simulation.

ÖZET

Yüksek Lisans Tezi

HİBRİT ELEKTRİKLİ ARAÇLARDA SÜRÜŞ PERFORMANSININ MODELLENMESİ VE OPTİMİZASYONU

Dilara ALBAYRAK SERİN

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Yakıt sarfiyatını ve zararlı gaz salınımını azaltmak amacı ile hibrit araçlar üzerinde gerçekleştirilen çalışmalar yıllar içerisinde artış göstermiştir. Bu çalışmanın amacı da bir hibrit elektrikli aracın sürüş performansını artırmak ve bu esnada yakıt verimliliğini artırmak ve emisyon salınımını azaltmaktır. Bu araştırma esnasında orta büyüklüğe sahip sedan tipi, aile kullanımına uygun bir binek araç modellenmiştir. Modelleme sürecinde MATLAB ve Simulink kullanılmıştır. Aracın performans değerlerinin ölçümü ve iyileştirilebilmesi için araç İstanbul-Ankara arası ücretli yol olan TEM otobanını temsil eden bir simulasyon verileri üzerinde test edilmiştir. Aracın test edildiği rota olan 450 kilometre üzerindeki yol özellikleri Google Earth üzerinden çekilmiş ve benzetim ile araç bu simulasyon üzerinde koşturulmuştur. Bu çalışma kapsamında hem simulasyon hem de optimizasyon basamakları gerçekleştirilmiştir. Çalışmanın sonucu olarak yakıt sarfiyatında %44.29, bir sürüşte harcanan tutarda ise %37.34 azalmaya gidilmiştir.

Anahtar Kelimeler: Hibrit elektikli araçlar, optimizasyon, simulasyon, sürüş performansı, yakıt tüketimi.

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Last but not least, I would like to show my gratitude and my love to my precious family for their love, kindness and endless belief in me. I would not be half the person I am today if it weren’t for any of them.

Dilara ALBAYRAK SERİN
İSTANBUL, 2018

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SYMBOLS AND ABBREVIATIONS LIST

Al-Air	Aluminum Air
CO_2	Carbon Dioxide
CC	Constant Current
CV	Constant Voltage
CVT	Continuously Variable Transmissions
DC	Direct Current
ECE	Economic Commission for Europe
ECMS	Equivalent Consumption Minimization Strategy
EESS	Electrical Energy Storage Systems
EM	Electric Motor
EMF	Electromotive Force
EPA	Environment Protection Agency
ESS	Energy Storage System
EV	Electric Vehicle
FTP	Federal Test Procedure
HEV	Hybrid Electric Vehicle
HWFET	Highway Fuel Economy Test
ICE	Internal Combustion Engine
IMA	Integrated Motor Assist
IWM	In Wheel Motors
Ki	Integral Gain Coefficient
Kp	Proportional Gain Coefficient
Li-air	Lithium air
$LiFePO_4$	Lithium Iron Phosphate
Li-Ion	Lithium Ion
Li-Po / Li-Polymer	Lithium Polymer
Li-S	Lithium–Sulfur
MDP	Markov Decision Process
Pb-acid	Lead Acid
PI	Proportional-Integral
PNGV	Partnership For A New Generation Of Vehicles
REX	Range Extender
Na-NiCl2	Sodium Nickel Chloride
Na-S	Sodium Sulphur
NEDC	New European Driving Cycle
Ni-Cd	Nickel Cadmium
Ni-Zn	Nickel Zinc
Ni-MH	Nickel Metal Hydride
SCS	Supervisory Control Systems
SOC	State Of Charge
SUV	Sport Utility Vehicle
UDDS	Urban Dynamometer Driving Schedule
VRLA	Valve Regulated Lead Acid Battery
ZEV	Zero Emission Vehicles
Zn-Air	Zinc-Air Battery

1. INTRODUCTION

Throughout the history electric vehicles and hybrid electric vehicles have come to spotlight of researchers but interest in these concepts lowered from time to time. The rekindling of interests in EVs started at the outbreak of the energy crisis and oil shortage in the 1970's. With increase in oil prices and higher standarts on reducing production of harmful gasses to provide a greener environment new challenges for automotive industry started to emerge in 21st century. Through researches it is seen that, these goals could only be satisfied via reaching zero emission vehicles (ZEVs). However, battery technology to support this plan is not yet developed. Also the development of the required infrastructure is neither easy nor economically feasible. So to answer this problem, hybrid electric vehicles (HEVs) are introduced as a transitional solution. Since these type of vehicles use electricity as their power source, aim of reaching lower levels of emissions is also satisfied. (Chau and Wong, 2002) and (Özden, 2013).

As stated above, the best way to protect environment in terms of transportation is to have vehicles with zero emissions but since battery technology is not yet developed sufficiently to solely support a vehicle on a long distance, an internal combustion engine is necessary. Therefore hybrid technology is the best possible solution to decrease fuel consumption and harmful emissions until the improvement of pure electric vehicle batteries. Tremblay et al. (2007) state that the near future technologies related to hybrid electric vehicles (HEV) are the most promising alternatives to cope with the reduction of greenhouse gasses in the car industry.

It is a well-known fact that transportation has a huge effect on pollution hence authorities in this field set some regulations and rules to deduct the value of created emissions. According to Boyalı and Güvenç (2010), the proposed emission limits for near future can no longer be satisfied by Internal Combustion Engines (ICE) despite the good advancements in engine technologies.

The National Highway Transportation Safety Administration and the Environmental Protection Agency (EPA) have estimated that the standards formed throughout the years will save consumers over $1.9 trillion at the pump, reduce oil consumption by

14.3 billion barrels, and eliminate 7.3 billion metric tons of greenhouse gasses pollution by 2027 (Environmental and Energy Study Institute, 2015).

Boyalı and Güvenç (2010) add that there are many possible ways to adapt zero emission energy sources to road vehicles. For instance, with adequate technology vehicles can be powered by both hydrogen and pure electricity. However, in practice there are some obstacles for usage of hydrogen since it is hard to be stored and produced. For pure electric vehicles range and charging are problems. So the best solution is to use less of carbon intensive fuels or increasing average efficiency of ICE by using secondary power source in the vehicle.

With the help of researches and recent regulatory actions taken by governments to protect the environment, purchase and usage of hybrid electric vehicles (HEVs) have risen throughout the years (Figure 1.1). As the result of such actions the harmful gas emissions is aimed to be decreased and fuel economy is aimed to be improved (Figure 1.2).

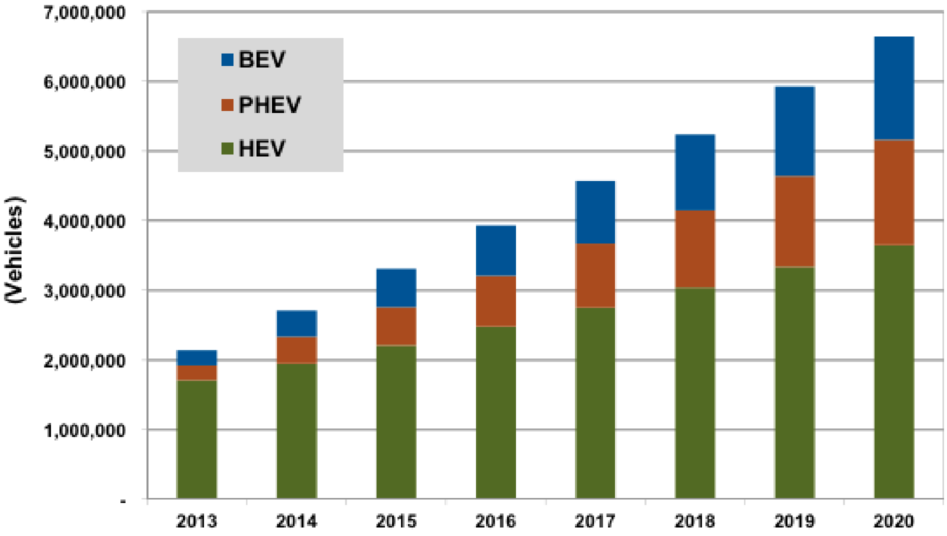


Figure 1.1. Increase in Purchase of HEVs and EVs (Marcacci, 2013)

According to U.S. Energy Information Administration (2014), for hybrid electric vehicles (HEVs), fuel efficiency will extend up to 71 miles per gallons by the year 2025. When this value is transferred to the units used in Turkey, the amount corresponds to 30 kilometers per liter and this can be seen as an acceptable improvement since today range of HEVs is only 50 miles per gallons (21.25 kilometers per kilometers). When 30 kilometers per liter aim is reached in 2025, the vehicle cost will remain just over $30.000 and the electric propulsion system will be much more efficient.

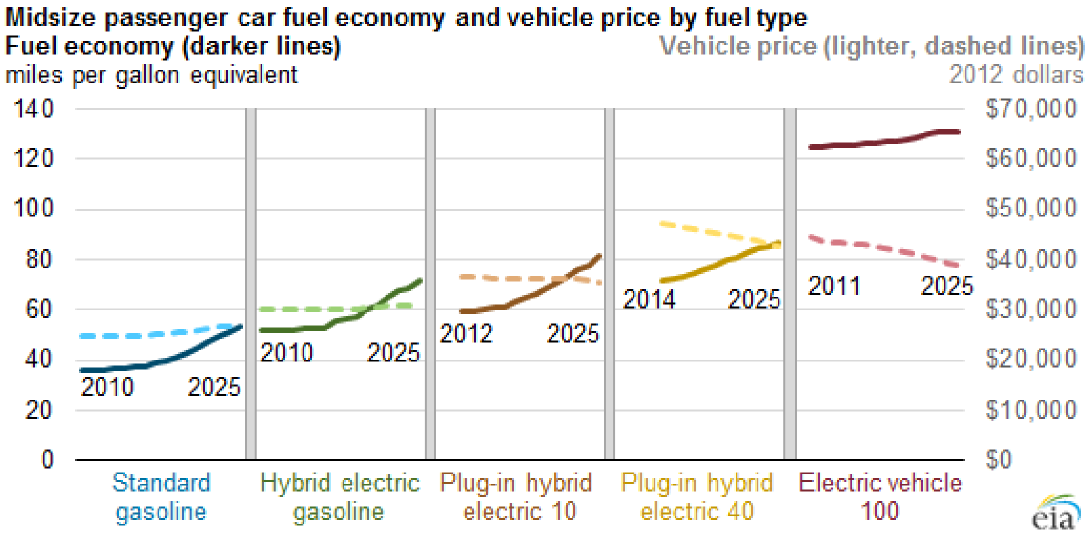


Figure 1.2. Fuel Economy in Different Vehicle Types (U.S. Energy Information Administration, 2014)

From regulatory reasons to environmental means, there are several reasons to own a hybrid electric vehicle. Total cost of a HEV ownership (Figure 1.3) can be counted as another motivation to support improvement in HEV technology. It is important to mention that cost includes: Initial price of vehicle: Base price of vehicle, battery, and net additional cost of components to electrify the vehicle. Periodic Costs: Ten years cost of fueling, maintenance, insurance, and financing (assume finance total initial price of vehicle at 7.5% interest) (Deutsche Bank Securities Inc, 2009). Period of Amortization in Hybrid Electric Vehicles can be seen in Figure 1.4.

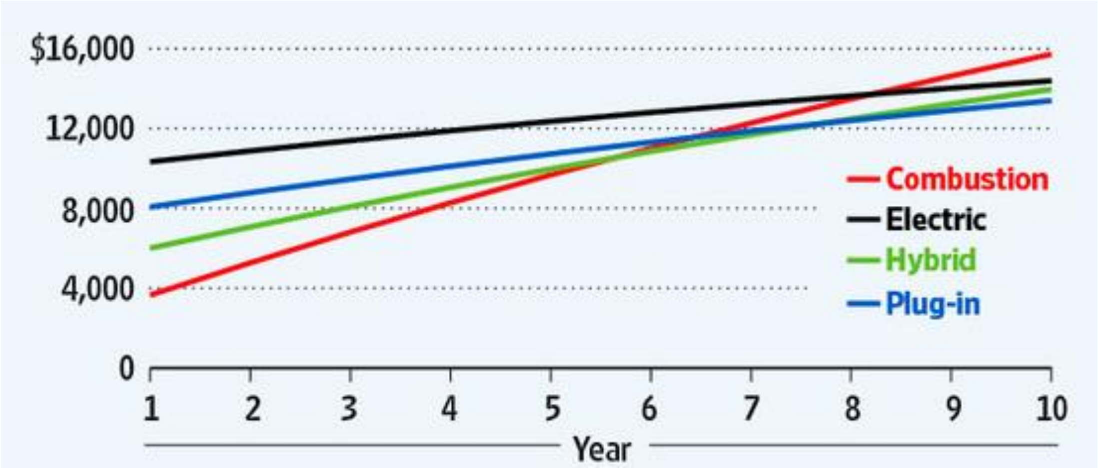


Figure 1.3. Total Cost of a Vehicle Ownership According to Vehicle Type (Hobbs, 2014)

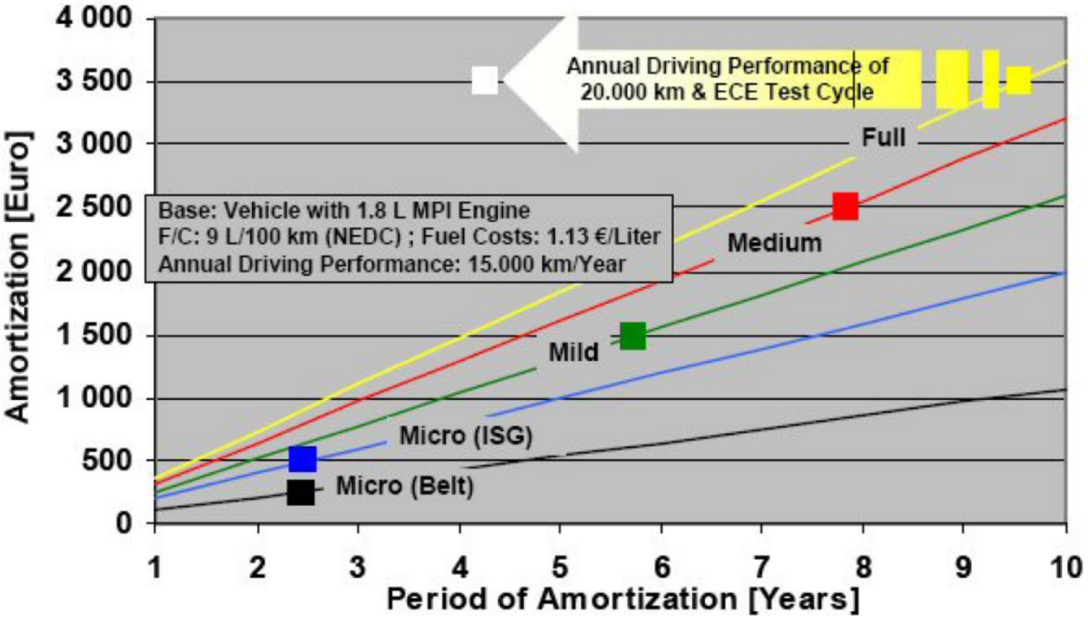


Figure 1.4. Period of Amortization in Hybrid Electric Vehicles (Gökçe, 2005)

Moreover in Figure 1.5 it can be easily seen that transferring into hybrid technology is a big step towards decreasing the CO_2 emissions.

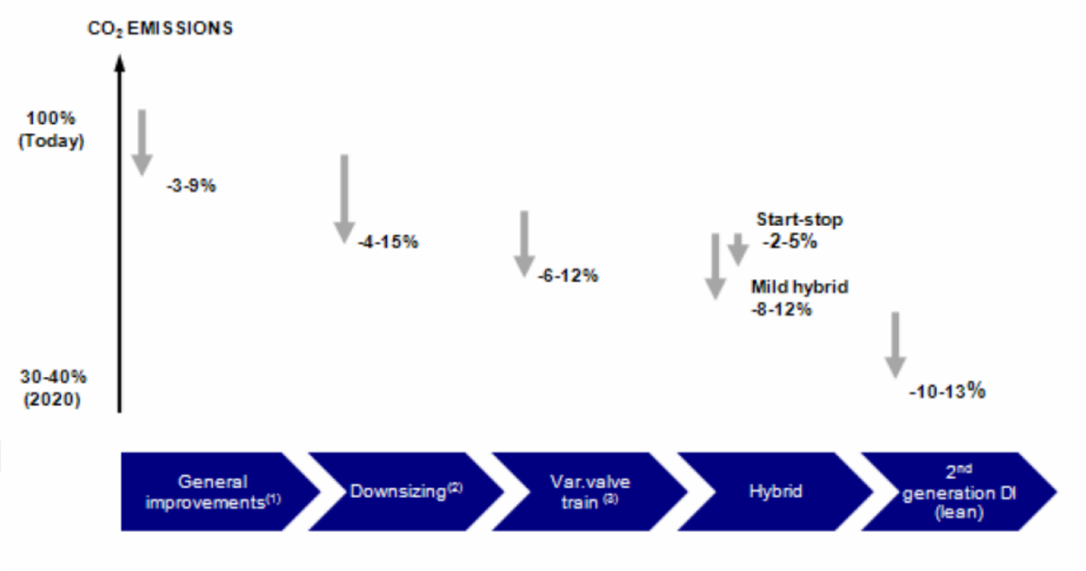


Figure 1.5. Possible Ways to Improve CO_2 emissions of a Vehicle (Deutsche Bank Securities Inc, 2009)

Nonetheless, it cannot be unseen that the industry along with its participants will shift towards the extended use of electric propulsion. For that reason, the U.S. has clearly set a new direction with collaboration with EPA in order to decrease greenhouse gases up to 40%-50% by 2025, compared to 2016, and 80% by 2050. Japan also has taken some serious actions in order to enhance less fuel usage over the last 10 years. In order to reach better fuel efficiency levels, the country has also rolled out tax policies to encourage purchase of more fuel efficient vehicles. (Deutsche Bank Securities Inc, 2009). According to Society of Motor Manufacturers and Traders Limited (2015), hybrid vehicles in United Kingdom saw a significant increase in 2014 and remain dominating market.

Additionally when the legislative point of view is considered it is seen that European Union countries approach to fuel consumption and production of polluting gas emissions very seriously hence there are several regulations and directives to coordinate these concepts. (Enang and Bannister, 2017).

When all these improvements around the World and advantages of HEV are considered the importance of following this concept and performing researches about HEV technology in our country can be seen. Hence, in this master’s thesis HEV technology will be discussed and modelling and optimization of driving performances of hybrid electric vehicles will be analyzed in order to enhance the benefits of the HEVs for the future researches and studies.

2. LITERATURE REVIEW AND CURRENT STUDIES

With the desire to decrease fuel consumption and emissions studies on hybrid electric vehicles have risen throughout the years. The reason of this thesis study is to find alternative ways to improve driving performance of a hybrid electric vehicle by improving the fuel efficiency and decreasing emissions. So to support efforts about this subject, a comparative and detailed research about this field is carried out by examining previous works and studies.

According to Boyalı (2008), in literature and applications there are several ways to provide energy efficiency and decreased exhaust emissions. Such as implementing an engine start/stop function during heavy traffic, using regenerative braking and power management.

Hybrid electric vehicle control systems aim to decrease overall fuel consumption and emissions while maintaining drivability of the vehicle. The strategy developed by Park and Park (2012) takes the equivalent fuel consumption as a quantitive criterion to determine the operating points of the ICE and EM simultaneously. The writers suggest a practical method to obtain an optimal value by employing a direct search method and evaluating cost using the simulation model of the vehicle.

Patil et al. (2016) suggest that, by providing more and more electric energy for vehicle propulsion will lead to minimization in fuel consumption. On the other hand, writers emphasize that using more electric energy will eventually result in faster battery degradation and a shorter battery life. In literature many researchers focus on this trade-off between fuel efficient usage of vehicle and battery employement. In their study, Patil et al. (2016) aim to find an application focused target battery life via benefit from supervisory control.

According to Lot and Evangelou (2013), in order to increase fuel efficiency and decrease harmful emission gasses energy management is needed and it can be achieved via main relative control objective method. With this application, maintaining or enhancing vehicle performance can be reached. In this paper, supervisory control systems (SCSs) are benefitted in order to decide the best way for splitting energy since there are more than one energy sources in HEVs. In this research usage on a given vehicle mission is tested on a global based SCS via indirect optimal control.

Fontaras et al. (2008) analyze hybrid electric vehicles with European and real world driving cycles and find that under urban driving conditions, fuel consumption of HEVs are 40-60% lower than conventional vehicles. Also it is shown that, the vehicle fuel consumption is affected by battery conditions. For instance capacity of the battery can fluctuate according to the operating temperature hence the alterations in the battery temperature can affect the performance of the hybrid electric vehicle, overall. Researchers of this study show that as vehicle hybridization level increases, the effect of ambient temperature on fuel consumption becomes more important. Higher temperatures tend to increase the battery capacity and thus improve the penetration potential of the electrical system, which leads to better fuel economy.

Sabri et al. (2015) support that fuel efficiency in hybrid electic vehicles can be enhanced by answering torque demand from a more efficient in wheel motor (IWM) rather than internal combustion engines. To elaborate, the writers suggest implementing electric motors in wheels of hybrid electric vehicle. It is adviced that by benefitting from highly efficient IWMs and excluding heavy and chassis mounted EMs will lead to both lighter weighed vehicles and more fuel efficiency can be reached. IWMs are more helpful for energy storage problems since they are in smaller sizes and leave extra space to install energy storage systems (ESSs) for longer vehicle operations.

According to Lin et al. (2015), to reach high levels of fuel efficiency and performance levels, energy management in hybrid electric vehicles is inevitable. This paper proposes a way to answer energy employment via a Markov Decision Process (MDP) method. By implementing this method on battery pack model and model of driving cycles stochastic data coming from driving cycles is aimed to be retrieved. With this step, capturing recovery effects of battery pack is intended. The structure is tested both on real life and simulated driving cycles. As a result of this study, it is seen that the presented policy for splitting power in hybrid electric vehicles leads to enhancement in fuel economy better when compared to rule based methods.

Li et al. (2015) propose an optimization control strategy of the energy management mode and the shift schedule has been suggested to improve the energy economy of the hybrid electric vehicle on the premise of the dynamic performance. Via dynamic programming of the optimal control strategy, the operating points of the engine and the electric motor have been acquired. In this paper, writers choose working with dynamic programming since the minimization of the energy consumption economy without considering dynamic constraints of the gear would result in frequent gear shifting, which is unfavorable to the transmission and the driver.

According to Syed at al. (2007), fuel efficiency improvement without harming driving performance of a hybrid electric vehicle is possible. For this statement researhers propose usage of an advisory system based on fuzzy logic. The system in the study is formed by two fuzzy logic controllers (one is for following upper limit of acceleration pedal, other is for following upper limit of brake pedal). The controller used for accelerator follows the use of the pedal and uses the gathered data to calculate the error in fuel economy and error in rate of change in fuel economy. At the end of the calculations the advisory system proposes an upper limit position for both pedals in order to enhance the efficient use of fuel. It is mentioned that through improved controller 22% fuel economy improvement [which is close to maximum fuel economy improvement possible with this system] is achieved.

Supina and Awad (2004) state that by optimizing target battery power when the engine is running and find that there is opportunity for a 1%-2% improvement in fuel economy by changing the battery usage. This is an improvement in fuel economy that can be gained by changing the control strategy, without the increase in cost or weight associated with hardware design changes. The fuel economy improved, these changes in battery power have increased the average efficiency of the entire system. Thus, in certain regions, the optimizer increased the charging power when it would increase the system efficiency, and it decreased the battery power at the points were the impact to system efficiency was minimized.

Zhang et al. (2016) study SOC sustainability and enhance the fuel economy via modelling the vehicle and simulating. An adaptive equivalent consumption minimization strategy (ECMS) is proposed to adjust the equivalent factor using Fuzzy PI controller to impose charge sustainability. It is found that using Fuzzy PI is more robust when compared with ECMS. Hence a better fuel economy is achieved with this study.

Lukic and Emadi (2004) chooseto carry out their study on simulation of a real life vehicle which is a Chevrolet Lumina. In this paper, operation of internal combustion engine only at its efficient zone is aimed. The vehicle is tested at FTP driving cycle. For each simulation, to keep the unity, the highest and the lowest levels of state of charge is determined and simulations are done accordingly. Here in this paper, finding the optimum way for charge sustaining control in order to acquire the best fuel efficiency level. Also, it is shown that hybridization improves vehicle fuel economy and dynamic performances up to a critical optimum point.

Yan et al. (2014) use Newtons’s Law in order to propose a mathematical model for electric energy usage in hybrid electric vehicles. The aim of this paper is to find an optimization algorithm which provides energy saving under various driving conditions. In the study, tests are carried out for different driving profiles and the optimal velocity value for the best energy saving is determined. For these scenarios, practical guidance is provided to control the energy consumption.

Mion (2017) proposes a real time power management control strategy which allows to minimize fuel consumption of a hybrid electric vehicle. Battery depletion led to the addition of a new cost functional to the fuel consumption term in order to constrain the current state-of-charge. The proposed approach provides a directly implementable control design path, which is highly desirable because of its potential for a fully integrated optimal design and control process.

According to Markel et al. (2002), balancing state of charge is a crutial concept in hybrid electric vehicle area. If alteration in state for charge (SOC) is quite big, the vehicle fuel consumption can be interpreted as very high or very low but when in fact it is not the real case.

Schouten et al. (2003) study on a parallel hybrid electric vehicle and aim to find the best fuel economy. For the research, the vehicle is modelled on MATLAB/Simulink with the help of Analysis Toolkit. Among other modelled components, power controller is modelled in the simulation step. With the help of power controller needed enery to provide propulsion is determined. Moreover power controller provides data that how much power is needed to charge the battery. The necessary power for wheel propulsion is divided between internal combustion engine and electric motor. When there is need for battery charging, negative feedback will be applied to electric motor and only internal combustion engine will give power to vehicle while it is charging the battery, simultaneously. To select the efficient operation zones of both EM and ICE, their efficiency maps are used.

Hou and Guo (2008) use MATLAB/Simulink to simulate three different types of hybrid electric vehicles. Simulated vehicles alter according to their hybrid powertrain structures, controlling strategies and cycles they are tested. In this paper, researchers go backwards from energy request in powertrain to energy splitting mechanism to provide the demanded amount.

According to Kazemi et al. (2017), management ofenergy split is the mst crutial concept in optimization of hybrid electric vehicle powertrain performance. Writers propose this since power control greatly affects fuel efficiency and harmful gas produced by hybrid electric vehicles.

To provide another point of view, this concept can be evaluated from industrial perspective. In other words, fuel efficiency and energy optimization of hybrid electric vehicles are also popular and important subjects in automotive industry. Vehicle manufacturers plan and implement several research and development projects to acquire improvements in fuel consumption and energy requirement. In 2007 new HEV sales contributed to fuel savings about 56 million gallons of gasoline (or 1.3 million barrels of oil which stands for 15% of petroleum consumed by light duty vehicles in a single day) (Bennion and Thornton, 2009).

In Table 2.1.a and Table 2.1.b comparison of conventional and hybrid electric vehicles in terms of engine size and EPA fuel economy can be analyzed.

Table 2.1.a. Conventional and Hybrid Electric Vehicle Comparison (U.S. News, 2017)

Properties	**Toyota Camry 2010**	**Toyota Camry Hybrid 2010**	**Honda Civic 2011**	**Honda Civic Hybrid 2011**	**Ford Escape 2012**	**Ford Escape Hybrid 2012**
Engine (L)	2.5	2.4	1.8	1.3	2.5	2.5
EPA Fuel Economy (lt/100 km)	7.35	6.91	6.91	5.47	9.40	7.58
Fuel Tank Size (L)	70	65	50	46	62	57

Table 2.1.b. Conventional and Hybrid Electric Vehicle Comparison (U.S. News, 2017)

Properties	**Volkswagen Jetta 2014**	**Volkswagen Jetta Hybrid 2014**
Engine (L)	2.0	1.4
EPA Fuel Economy (lt/100 km)	8.11	4.9
Fuel Tank Size (L)	55	45

According to Shelton (2015), United States-based auto companies are leading the industry in electrified vehicle and this can be verified by analyzing the number of obtained patents by automotive companies. Most of the patents are about electric vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles. In Table 2.2 the four most innovative companies in the EV segment and their related patent numbers can be seen.

Table 2.2. Patent Number Comparison (Shelton, 2015) and (Tesla Motors, Inc., 2016)

	Ford	**General Motors**	**Honda**	**Tesla**	**Toyota**
Patent Numbers	459	370	272	204	201

It is also mentioned that in terms of electric vehicle related patents, Japan is in second place. Moreover, in Figure 2.1 comparison of potential fuel saving methods carried via industrial applications and fuel saving opportunities on hybrid electric vehicles is represented.

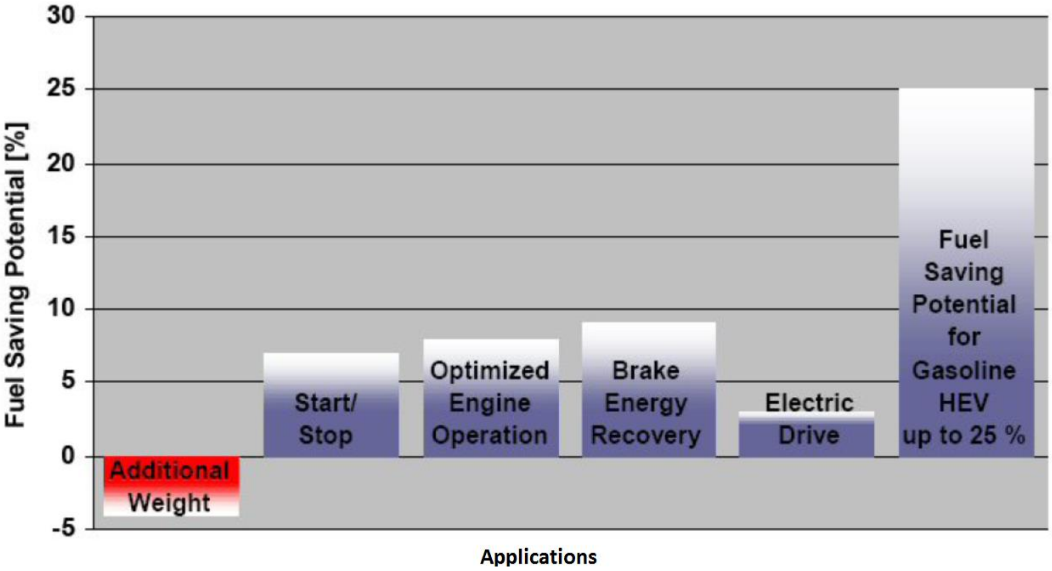


Figure 2.1. Fuel Saving Potentials vs. Hybrid Functions (Gökçe and Üstün, 2015)

From Turkey’s point of view, several applications on HEV can be exemplified. For instance, in 2008 Otokar produced the prototype of their first hybrid electric bus, Doruk 160 LE Hibra (Görgüç, 2007).

Additionally, with collaboration of Siemens, Temsa produced their hybrid bus named Hybrid Avenue in 2010 (Buldurgan, 2010). According to Karabağ (2007), Karsan has a plan of producing both hybrid busses and hybrid automobile. Other than HEV research and development processes on busses in Turkey, our country also aims to change conventional cabs running on road with the hybrid ones.

According to Gözütok (2017), with the economic support from Denizbank, 600 cabs will be altered with HEV ones by the end of 2017. In the five year plan, a whole of 17.925 cabs with conventional powertrains will be transformed into HEVs.

3. HYBRID ELECTRIC VEHICLES (HEVs)

With the increase in fuel cost and rise in standards for providing a cleaner and greener environment, need for finding new ways to energize the vehicles emerged. When limited range in electric vehicles and difficulty of employing hydrogen as a power source, hydrogen powered vehicles are not the solid solution industry seeks for. So when other options are narrowed down, hybrid electric vehicles can be seen as the most reliable way without harming the environment. (Park and Park, 2012). As stated by Wei et al. (2016), one of the best answers to green and clean way to energize vehicles is to use hybrid powertrains.

According to Guardiola et al. (2014), hybrid electric vehicle concept is a general term used for describing vehicles with powertrains formed by an internal combustion engine and one or multiple electric motors. Chau and Wong (2002) bring another perspective to this concept by explaining that hybrid electric vehicles have drawn attention due to their advantages coming from usage of highly efficient electric machines.

Electric vehicles and hybrid electric vehicles togerther differ from conventional vehicles with usage of electric motors, power electronics components, continuously variable transmissions (CVTs) and related controlling methods. With hybrid electric vehicles and electric vehicles technologies using Li-Ion batteries and supercapacitors is also possible. Despite using such new generation technologies, hybrid electric vehicles still can benefit from conventional internal combustion engines along with other mechanical and hydraulic subsystems. (Gao and Mi, 2007).

Moreover, hybrid electric vehicles offer attractive fuel savings in many commercial applications with start/stop duty cycles such as delivery truck, shuttle bus and city bus (Patil, et al., 2016). To understand the improvement within this field, background of HEVs should be well analyzed and studied.

3.1. History of Hybrid Electric Vehicles

According to Csiarretta and Guzeella (2007), although hybrid electric vehicles have existed since 1900, interest in these vehicles has grown substantially only in the last 15-20 years. It is added that Ferdinand Porsche’s first hybrid vehicle, produced by the Austrian company Jacob Lohner & Co. in 1899. The powertrain was a series hybrid, with an engine-generator providing the electricity to drive four wheel-mounted electric motors. This series hybrid electric vehicle is given in Figure 3.1.

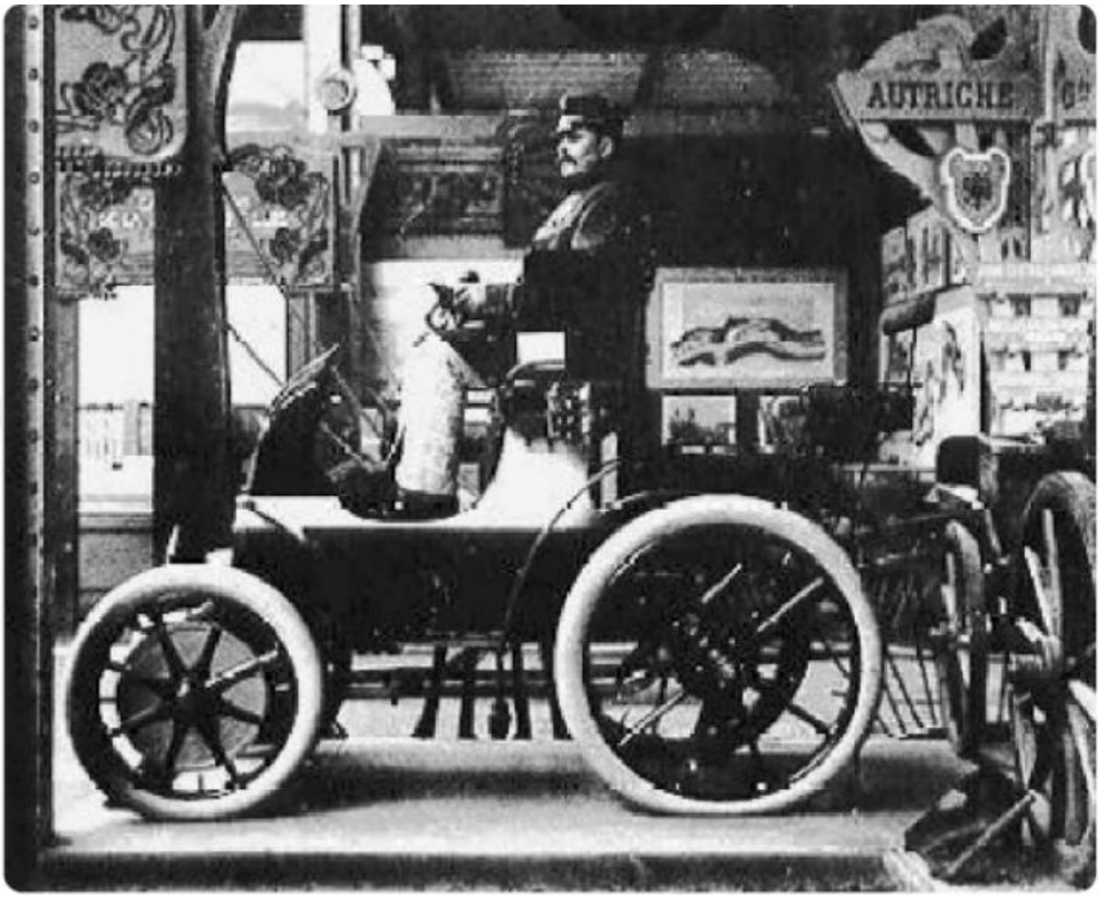


Figure 3.1. Ferdinand Porsche's First Hybrid Electric Vehicle (Csiarretta and Guzeella, 2007)

In the first half of the 20th century, various electric vehicles and cars with hybrid powertrains were produced. Another hybrid electric vehicle made in 1903 by the Krieger Company, used a gasoline engine along with a battery pack. In 1905, an American engineer named H. Piper applied for patent of a petrol electric hybrid vehicle. The main idea behind this design was to use an electric motor to support an internal combustion engine, enabling it to achieve 25 mph (Chan, 2007).

According to Youngs (2012), due to mass production of inexpensive vehicles with internal combustion engines by Ford by the year 1905 had substantially harm the research and development process of hybrid electric vehicles. Since power electronics did not become available until mid-1960, it was very hard to control the electric structure of the vehicle. It took scientists a very long time to weigh on hybrid electric vehicles again. According to Youngs (2012), the Arab oil embargo of the early 1970s encouraged further improvements in modern hybrid vehicles. Leading companies of automotive industry, including Toyota and entrepreneurs successfully developed and tested gas/electric hybrids in 1970s and 1980s.

Ehsani et al. (2005) continue that in 1975, along with his colleagues Dr. Victor Wouk, converted a Buick Skylark into a parallel hybrid version. The used engine was a Mazda engine, coupled to a manual transmission.

In 1976, the first prototype of Toyota hybrid electric vehicle is tested on real life. (Youngs, 2012). According to Ehsani et al. (2005), the biggest support and improvement actions on hybrid electric vehicle area have come from Japanese automotive companies and scientists. In 1997, Toyota released the Prius in Japan. Two years later, the U.S. has its first sale of a hybrid electric vehicle, the Honda Insight. After release of these models, minds of people on car powertrain is also altered. Usage of battery along with internal combustion engine is seen as an applicable and usable way of energizing vehicles during everyday use. (Chan, 2007).

3.2. Types of Hybrid Electric Vehicles According to Drivetrains

According to Çimen (2010), HEV can be categorized based on drivetrain configurations and hybrid electric vehicles have three main types which are series hybrid, parallel hybrid, and series-parallel hybrid drivetrains. In this section all these subcategories will be analyzed and advantages and disadvantages of each configuration will be discussed.

3.2.1. Series hybrid drivetrain

According to Wallén (2004), a series hybrid vehicle has an internal combustion engine (ICE) in series with a generator and the electric motor (EM). The main idea behind this configuration is to have the ICE running at an optimal point and store the energy in the battery via the generator. In other words by this, the ICE is kept operating only within its efficiency intervals. Chau and Wong (2002), state that the series hybrid is the simplest kind of hybrid electric vehicles. It is an engine-assisted electric vehicle which aims to extend the driving range to be comparable with that of the pure internal combustion engine vehicle.

To elaborate it can be interpreted that, a series hybrid vehicle can be seen as an electric vehicle only supported with an ICE to keep it on the road longer. Karabasoglu and Michalek (2013) explain series hybrid where the engine turns the generator which generates electricity to be used by the electric motor to turn the wheels. To be clear it should be emphasized that in series hybrid drivetrains the ICE does not directly drive the wheels instead electric motor provides power to the wheels. A schematic figure of a series hybrid electric vehicle can be seen in Figure 3.2.

Johanyak (2015) states that generally a series hybrid electric vehicle is built up from six main components which are fuel tank, internal combustion engine, generator, battery, electric motor and gear. As Wallén (2004) explains the main duty of ICE is to charge the battery. When the state of charge (SOC) drops below the previously determined limit value, ICE starts to operate and re-charge the battery.

When compared to other topologies, series hybrid has the lowest power efficiency. It is important to emphasize that the size of the ICE used in this topology is rather small. So to provide necessary power to the whole vehicle weight of e-powertrain parts such as battery is heavy.

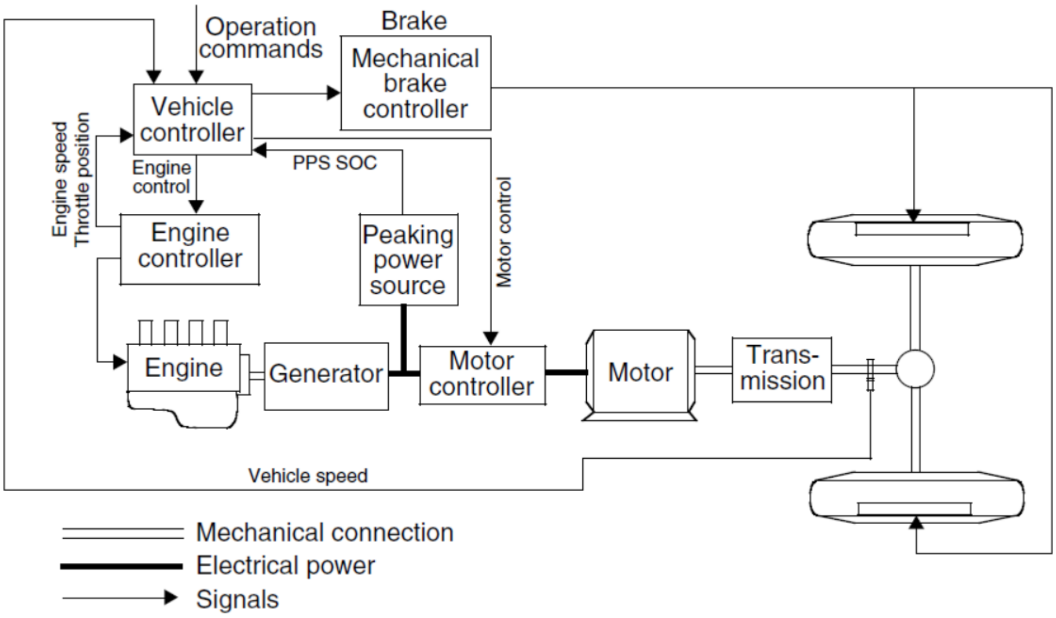


Figure 3.2. A schematic figure of a series HEV (Ehsani et al., 2005)

The advantage in series hybrid configurations, is that the ICE works at optimal conditions of speed and torque hence consumption of fuel is low and driving efficiency is high hence the produced emissions are lower when compared to other configurations. As an example to series hybrid configuration, Fisker Karma (Figure 3.3) can be given.

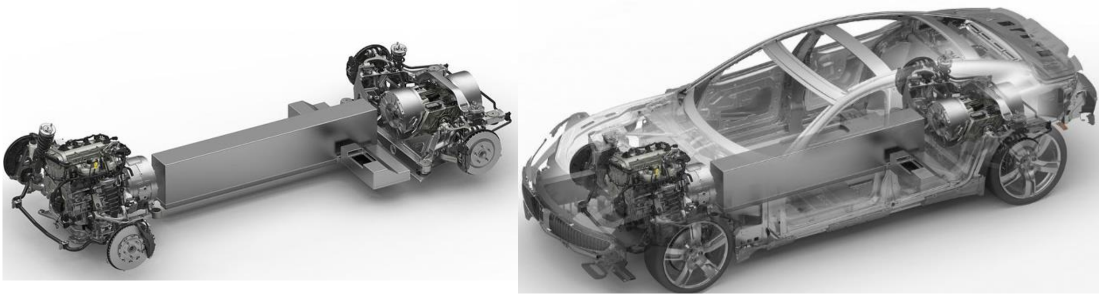


Figure 3.3. Fisker Karma Powertrain Configuration (Cobb, 2014)

To sum up it can be said that, a series hybrid powertrain is supported by an internal combustion engine providing electricity to a battery pack or an electric motor. The vehicle is solely powered by an electric motor. The internal combustion engine is not coupled directly to the wheels and can run in its most efficient operating region (Hou and Guo, 2008). Series hybrid configuration is much more suitable for busses since there is more space for placing batteries with required sizes and their operating speeds are less than automobiles.

3.2.2. Parallel hybrid drivetrain

Patil et al., (2016), state that in a parallel hybrid powertrains, there are two separate ways to drive wheels. The first option is to purely launch the vehicle and provide propulsion via electric motor. Second way is to use internal combustion engine rather at its efficient zone at high torque demands. (Karabasoglu and Michalek, 2013). One of the most important points in this configuration is that when necessary a parallel hybrid electric vehicle can either be driven via the ICE or electric motor or by both components working simultaneously (Wallén, 2004).

In this type of hybrid vehicles, the traction power is provided by union of the internal combustion engine and the electric machines. A generator or a motor-generator can be benefitted to keep the electrical energy storage system (EESS) in a determined state of charge (SOC) range (Koprubasi, 2008). As Wallén (2004) states, a parallel hybrid electric vehicle can have a continuously variable transmission (CVT) thus it becomes possible to choose the most efficient operating point for ICE in order to acquire lower fuel consumption and so on. The parallel hybrid configuration can be seen in Figure 3.4.

Boyalı (2008) emphasizes that parallel hybrid configuration has a larger ICE and more complex power management when compared to series hybrid configuration. Moreover when compared to series hybrid structure, via regenerative braking energy can be saved in this configuration. Parallel hybrid configuration can be seen as the most efficient one of the hybrid electric vehicle topologies.

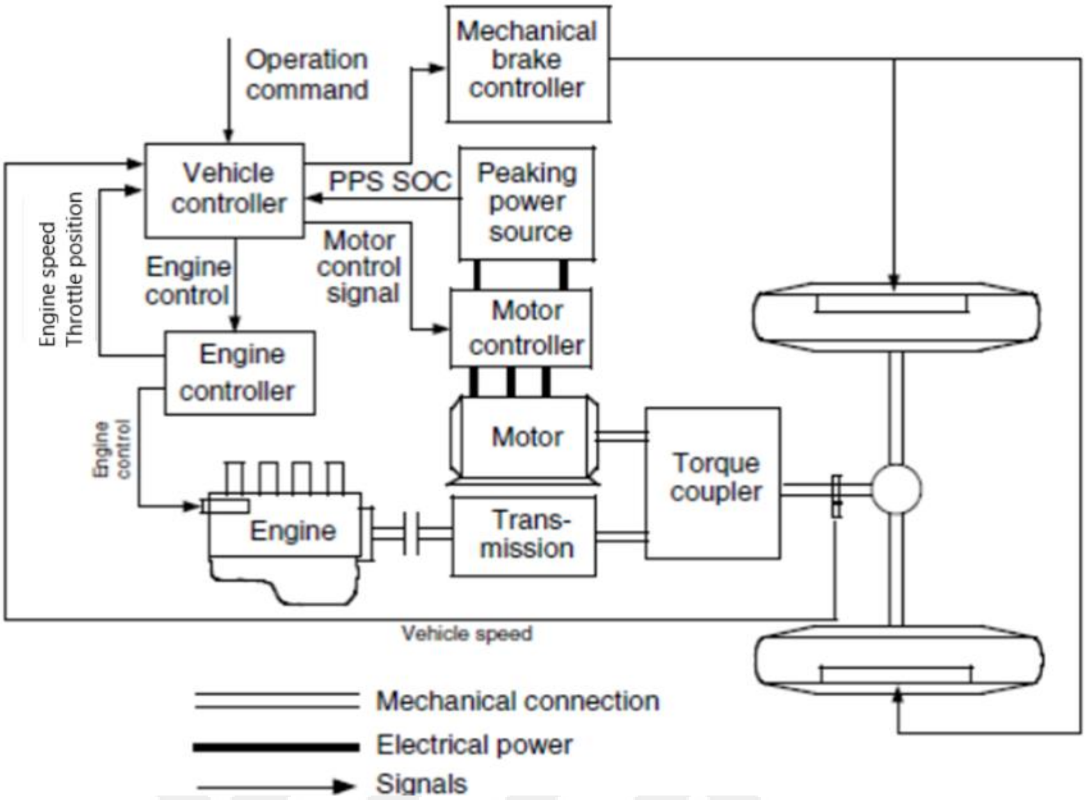


Figure 3.4. A schematic figure of a parallel HEV (Ehsani et al., 2005)

According to Özden (2013), when compared to series hybrid structure, parallel drivetrain has the benefit for needing only one extra motor, a smaller electric motor than the one used in series HEV and also smaller engine could be used which results in weight deduction and more free space within the vehicle. Ford’s Escape SUV (Figure 3.5) model which is first produced in 2005 is an example for parallel hybrid electric vehicle configuration.

Figure 3.5. Ford Escape Parallel HEV Configuration (West, 2008)

Different from the series hybrid drivetrain, the parallel hybrid drivetrain has properties that yield both the internal combustion engine and traction motor to provide their mechanical power directly to the driven wheels. The advantages of parallel powertrain structure over series are no need for a generator, smaller traction motor, and multiconversion of the power from the engine to the wheels is not necessary. So that, the cumulative efficiency can be higher (Ehsani et al., 2005).

3.2.3. Series-parallel hybrid drivetrain

The series-parallel hybrid electric vehicle is a blend of the series and the parallel hybrid topologies. There is a supplemental mechanical link between the generator and the electric motor when compared to the series hybrid topology and an extra generator compared to the parallel hybrid topology. With this design it is possible to gather the benefits of both the series and the parallel topologies, but when compared others the series-parallel hybrid is more complicated and more expensive (Wallén, 2004).

In literature series-parallel hybrid drivetrain configuration is also named as split configuration. Karabasoglu and Michalek (2013) state that split structure uses a planetary gear device to operate both in series and in parallel and provide the greatest flexibility to both manufacturer and user.

Series-parallel hybrid structure provides a flexibility to control unit which employs the power split algorithm and makes it possible to run the vehicle in very low and very high speeds as a series hybrid vehicle and to run the vehicle as a parallel hybrid electric vehicle within the efficient speed intervals to make the best use of ICE. Thereby vehicle efficiency can be driven to higher levels (Çimen, 2010). Series-parallel hybrid structure provides lower fuel consumption and lower emission production (Uçarol, 2003). The series-parallel HEV schematic can be seen in Figure 3.6. and an example for this topology is given in Figure 3.7.

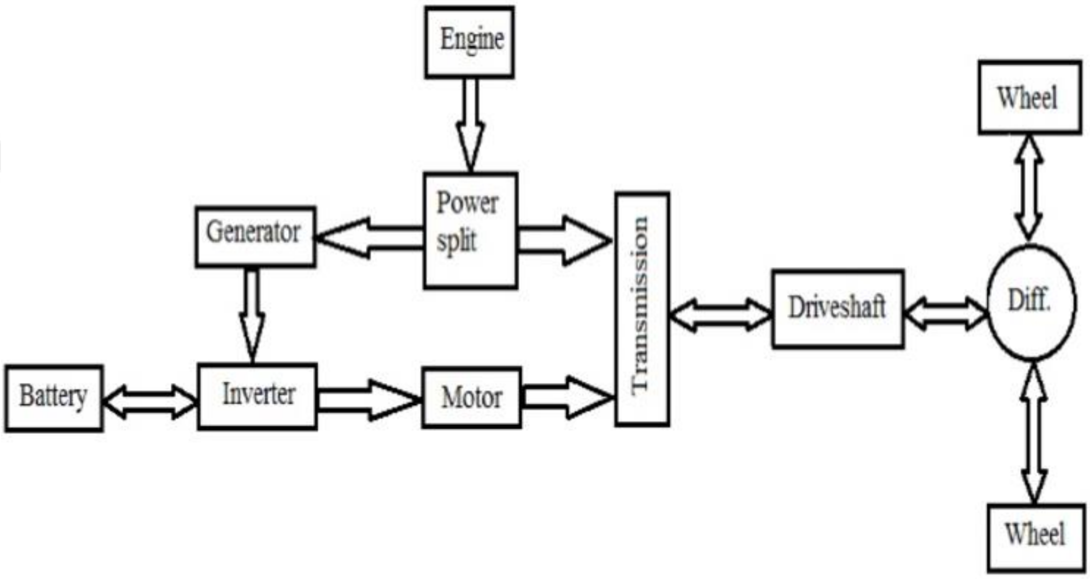


Figure 3.6. A schematic figure of a series-parallel HEV (Karthik, 2016)

Figure 3.7. Toyota Prius with Series-Parallel HEV Drivetrain (Hobbs, 2014)

3.3. Types of Hybrid Electric Vehicles According to Hybridization Levels

According to Çimen (2010), hybrid electric vehicles can also be categorized according to their ratio of electric energy to overall energy and according to the place of electric energy within the powertrain system. HEVs are divided into three sub-categories due to their hybridization levels as micro hybrid electric vehicles, mild hybrid electric vehicles, and full hybrid electric vehicles.

3.3.1. Micro hybrid electric vehicles

The first one these sub-divisions is micro hybrid electric vehicles. Çimen (2010) states that all auxiliary load is provided from the EM which is acting as a generator. Wang (2012) states that micro hybrids are also be named as stop-start cars. This definition means that once the vehicle is stopped, the ICE turns off. For instance, the driver stops the vehicle when the light turns to red and simultaneously the ICE stops working and this situation leads to a cleaner and cheaper usage of vehicles. The writer adds that micro hybrid electric vehicles can have better fuel economy up to 5-10%.

Micro-hybrids, which use a small battery to provide varying degrees of efficiency-boosting features, will dominate the automotive market, gaining 42% of the overall light-duty vehicle market.

Micro-hybrids will grow nearly eight-fold to 39 million vehicles in 2017 and create a $6.9 billion market for energy storage devices (Gundry, 2012). European automakers are the most active in making micro hybrids, and examples of micro hybrid models include Daimler’s Smart For Two, BMW 320d and Volkswagen’s Passat Blue Motion (Wang, 2012). Efficiency of micro hybrid electric vehicles can be increased via small alterations (Çimen, 2010). In Figure 3. 8 an example to micro hybrid electric vehicle can be seen.

Figure 3.8. Citroen C3 Micro Hybrid Electric Vehicle (Ingram, 2013)

3.3.2. Mild hybrid electric vehicles

In mild hybrid electric vehicles, electric motor provides additional traction force to the traction force supplied by the ICE (Çimen, 2010). A mild hybrid electric vehicle with enough charge is able to stop and restart its internal combustion engine various times. In a mild hybrid electric vehicle, the internal combustion engine is always operating, if the car is not stopped or the driving speed is not under 8km/h.

It is seen that in this type of topology, electric motor has a limited operating area and it doesn’t need much power and therefore a large battery pack to store great amount of electric power is not needed. These all help to reduce the size, weight and cost of the drivetrain (Fung, 2014). Vehicles with mild hybridization level can be exemplified with Honda Insight and Honda Civic IMA (Integrated Motor Assist) (Koot, 2006). In Figure 3.9 an example to mild hybrid electric vehicle can be seen.

Figure 3.9. BMW 7 Series Hybrid Mild Hybrid Electric Vehicle (Boeriu, 2010)

3.3.3. Full hybrid electric vehicles

Full hybrid electric vehicles go a step further than mild HEVs since their electric motors are powerful enough to power a car on their own. A full hybrid's drivetrain operates in three basic conditions: internal combustion engine and electric propulsion combined, electric motor or motors only, or solely powered by the internal combustion engine.

Regenerative braking, as well as eliminating extra or excess energy during acceleration or driving, is sufficient enough to keep the batteries charged hence there is no need for vehicle to be plugged into the grid (Fung, 2014). To have these drivetrain options yield usage of internal combustion engine within the efficiency cycle of the ICE (Çimen, 2010).

From all these information it can be interpreted that the driver can switch between electric vehicle (EV) mode to internal combustion engine mode to make the best of driving performance and fuel economy. For instance, utilizing electric motor more often while driving the vehicle in city and switching to the ICE while cruising between cities. When compared to micro and mild hybrid levels, full hybrid vehicles are the most fuel efficient ones (Cobb, 2014). For this type of hydrization, Toyota Prius, BMW ActiveHybrid 3, Porsche Cayenne Hybrid can be given as examples (Fung, 2014). To sum the concept of hybridization levels of hybrid electric vehicles Table 1 is provided (Çimen, 2010) and (German, 2015). In Figure 3.10 an example to full hybrid electric vehicle can be seen.

Figure 3.10. Chevrolet Tahoe Hybrid Full Hybrid Electric Vehicle (Edmunds, 2013)

Table 3.1. Functions of HEVs According to Their Hybridization Levels (Çimen, 2010) (German, 2015)

Functions	**Type of Hybrid Electric Vehicle**		
	Micro HEV	**Mild HEV**	**Full HEV**
Idle Stop/Start	✓	✓	✓
Electric Torque Assistance (fill and boost)	☒	✓	✓
Energy Recovery (Regenerative Braking)	✓	✓	✓
Electric Driving (EV Mode)	☒	☒	✓
Battery Charging (During Driving)	☒	☒	✓

3.4. Key Systems and Components of Hybrid Electric Vehicles

3.4.1. Internal combustion engine

Internal combustion engine in hybrid vehicle technology acts as energy source assist hence when compared to the ICE in conventional vehicles, ICE in hybrid electric vehicle is smaller (Gökçe, 2005).

It is a known fact that two main types of internal combustion engines are used in automotive industry. These types are spark ignition engines and diesel engines. Diesel engines have higher efficiency than spark ignition engines but these efficiency values are not adequate for catching today’s clean energy expectations. Thermal efficiency ratios of an internal combustion engine can be seen in Figure 3.11.

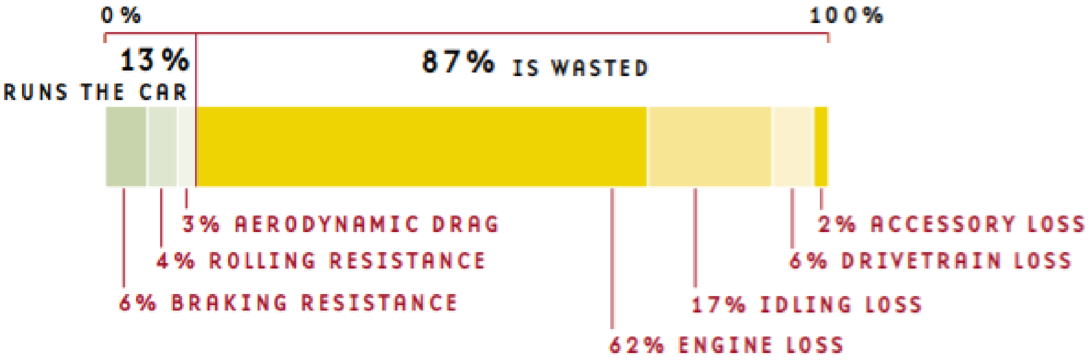


Figure 3.11. Internal Combustion Engine Efficiency Ratio (The Energy Foundation, 2003)

As seen in the Figure 3.11, 87% of a gallon of gasoline is wasted and 62% of this wasted value is purely engine loss. Hence adopting a healthier and cleaner way to energize vehicles is crucial. There are several studies on bio-fuels and hydrogen usage for providing fuel for vehicles without harming the environment. Unfortunately, for now all these technologies are in research and development phase and hybridization of a vehicle via electrification is the best thing the industry have (Gökçe, 2005).

To elaborate the advantages of hybridization via electrification, it should be mentioned that internal combustion engines are the most efficient in a narrow operating range. Acceleration and deceleration take engines out of their efficiency zone and lead to higher fuel consumption and emission production. By hybridizing a vehicle, electric motor can fill in for the ICE when the engine is out of its efficiency zone (The Energy Foundation, 2003).

3.4.2. Electric propulsion system

Electric propulsion system is composed of several items. Electric motors, generators (brushless DC motors), power electronic circuits are the most used components in electric propulsion systems of vehicles. The efficiency of a brushless DC machine can reach up to 80%, efficiency of power electronic circuit, in high voltage can go up to 90%. So it can be interpreted that, the overall efficiency of this system will always be higher than the efficiency of the ICE (Gökçe, 2005).

According to Tuncay and Üstün (2004), a drive system should have:

- Fast torque response
- High power at high speeds
- High reliability and robustness
- Regenerative braking
- Reasonable cost

and all these necessities can be provided via usage of electric propulsion system and improving hybrid electric vehicles. Electric motors can be seen as the heart of the electric propulsion systems. Motor driver, which is consisted of electric motor, power electronics switching components and electronic control units, is the core of the vehicle propulsion system. There are several expectations from an electric propulsion system. These expectations can be summarized as below:

- High efficiency
- High security
- Low maintenance cost
- Low noise
- Long driving range
- Low energy saving
- Driving comfort
- High driving performance (Uçarol, 2003).

Role of an electric motor alters from series hybrid electric vehicle to parallel hybrid electric vehicle. In other words, in series hybrid topology, electric motor provides traction force while starting and driving the vehicle. In this type of hybrid electric vehicles, ICE is connected to the generator so that its output is directly converted into electricity by the generator. On the contrary, in parallel hybrid topology, internal combustion engine plays an active role in the propulsion of the vehicle since it is directly connected to the wheels. So, parallel hybrid electric vehicles can be driven only by ICE only by EM or by both of them.

Generator acts as an additional energy support to the vehicle by converting output of ICE into electricity and either feed it to electric motor or to batteries to charge them.

3.4.3. Batteries

According to Tuncay and Üstün (2004), future of electric vehicles and hybrid electric vehicles rely on improvements on battery technology. Batteries to be capable of automotive usage should have high energy density (Wh/kg), power density (W/kg), long lifespan and low unit cost.

Patil et al. (2016) state that Li-ion based electrochemical batteries used for energy storage on hybrid electric vehicles are expensive and their energy and power capabilities degrade over time. With an optimal control strategy to reduce wear on the battery is possible. Writers suggest managing battery degradation simultaneously minimizing engine fuel consumption.

There are several types of electrochemical batteries used for energy storage on hybrid electric vehicles. Valve regulated lead acid (VRLA), nickel cadmium (Ni-Cd), nickel zinc (Ni-Zn), nickel metal hydride (Ni-MH), zinc-air (Zn-Air), aluminum air (Al-Air), sodium sulphur (Na-S), sodium nickel chloride (Na-NiCl2), lithium polymer (Li-Polymer) and lithium ion (Li-Ion) type batteries can be given as examples (Tuncay and Üstün, 2004).

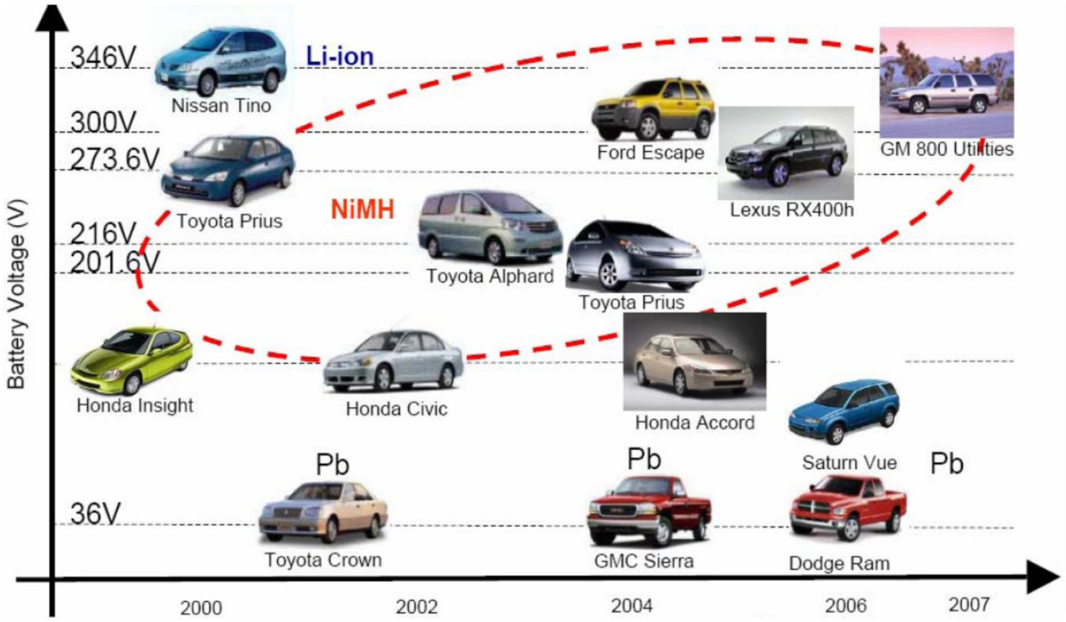


Figure 3.12. Battery Types of HEVs in the Market (Tuncay and Üstün, 2004)

As mentioned above, there are several battery technologies – even though some are in research process - used in electrified vehicle technologies. These technologies can be analyzed in Table 3.2 below.

Table 3.2. Major Types of Battery Chemistries (Muratoğlu and Alkaya, 2016)

Types of Battery	Nominal Voltage [V]	Energy Density [Wh/kg]	Life Cycle	Memory Effect	Working Temperature [C]
Pb-acid	2	35	1000	No	-15,+50
NiCd	1.2	50-80	2000	Yes	-20, +50
NiMH	1.2	70-95	Up to 3000	Few	-20, +60
Zebra	2.6	90-120	1200	No	+245, +350
Li-Ion	3.6	118-250	2000	No	-20, +60
LiPo	3.7	130-225	1200	No	-20, +60
LiFePO$_4$	3.2	120	2000	No	-45, +70
Zn-air	1.65	460	200	No	-10, +55
Li-S	2.5	350-650	300	No	-60, +60
Li-air	2.9	1300-2000	100	No	-10, +70

3.4.4. Ultracapacitors

Ultracapacitors can be described as an innovative energy storage technology which offers high power density, almost instant charging and very long lifetime. Ultracapacitors store energy in an electric field rather than in a chemical reaction as in batteries this way ultracapacitors can be charged and discharged much faster than batteries. Ultracapacitors can be named as supercapacitors, as well. Supercapacitors can be charged and discharged over million cycles and work up to 100% efficiency thanks to their low internal resistance. The benefits of ultracapacitors can be listed as below:

- Very long lifetime (more than 1 million charge cycles)
- A wide operating temperature range
- More efficient than batteries (Up to 30%)
- No harmful chemicals
- Low maintenance requirements (Skeleton Technologies, 2016).

In automotive industry, ultracapacitors are used in hybrid implementations with batteries in order to increase energy storage density (Çimen, 2010). While the benefits of Li-ion over NiMH and lead–acid in both specific energy and power are obvious, the potential of super-capacitors in very high power usages cannot be disregarded (Young et al., 2013).

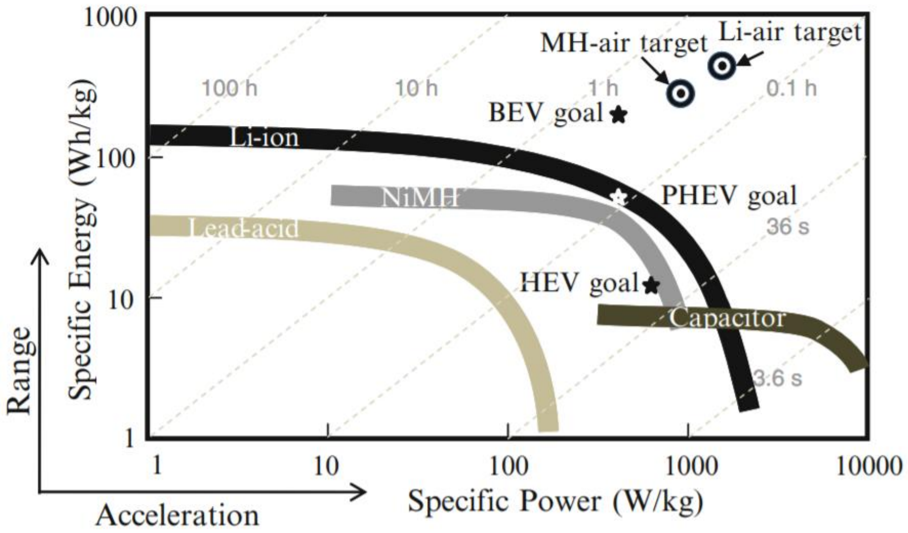


Figure 3.13. Specific Power Values of Battery Types and Ultracapacitors (Young et al., 2013)

To sum it can be expressed that, an ultracapacitor provides and absorbs the current peaks so that battery and electric motor can work in a healthier environment.

3.4.5. Range extenders

According to Patent No. US5264764 A (1993), a hybrid electric vehicle having a range extender provides a bargain between an internal combustion powered vehicle and a pure electric vehicle. A REX in a hybrid electric vehicle formed by a small internal combustion engine which navigates an alternator to produce electrical energy. This electrical energy accompany the electrical energy produced by a battery or a system of batteries in order to power the electric motor powering the drive system of the vehicle. In such way vehicle performance is improved and the vehicle range is extended while keeping emissions minimal.

The concept of a hybrid electric vehicle with REX is inspired by the limitations in present battery systems for providing extended range (greater than 150 km) in case of electric vehicle use. The inclusion of an Internal Combustion Engine (ICE)-alternator alliance for in situ battery recharge could potentially enlarge the vehicle driving range. This forms a series combination of range extender hybrid electric vehicle where the initial drivetrain power is given to the electric motor drive system directly by the battery pack and the engine-alternator collaboration plays the role of mainly charging the battery (Powell and Pilutti, 1994). Representation and placement of a range extender in a hybrid electric vehicle can be seen in Figure 3.14.

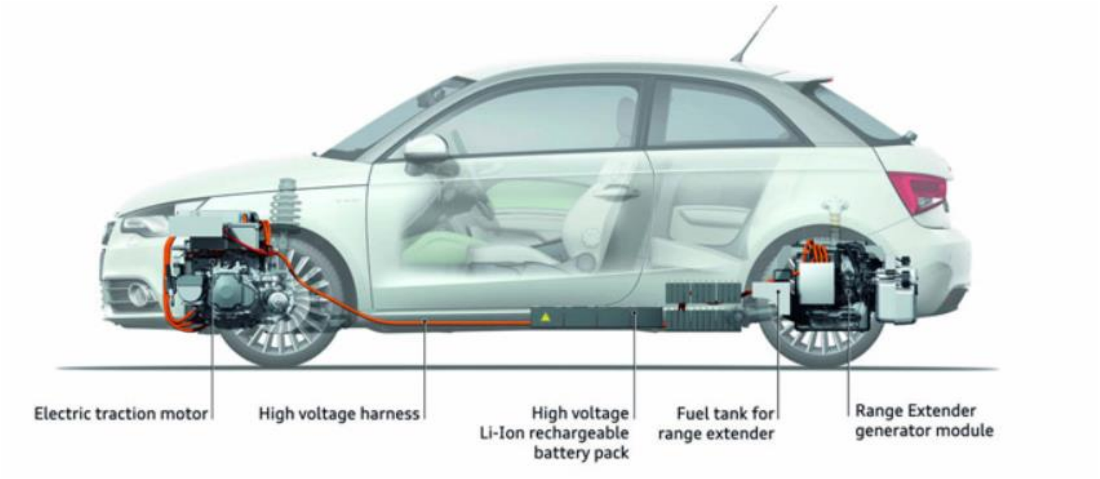


Figure 3.14. Range Extended Electric Vehicle (Ike, 2010)

The range extended electric vehicles seem to hit a sweet spot in the variety that ranges from very mildly hybrid electric vehicles to fully electric vehicles. Range extended electric vehicles have all the benefits of electric cars without the limited range tension but with the small disadvantage of carrying a mostly unused internal combustion engine (Ike, 2010).

4. MATERIAL AND METHOD

4.1. Vehicle and System Modeling

To model the vehicle and implement necessary steps, a model is created on MATLAB/ Simulink. The selected model is a mid-size family sedan which contains a battery, an electric motor, REX and a vehicle controller. To model the vehicle, necessary parameters and magnitudes are selected. The route, which the vehicle is following, is between Istanbul and Ankara. This distance corresponds to 450 km and it is assumed that, vehicle is only using toll road, TEM and the maximum permissible velocity in this route is 120 km/h (Turkish General Directorate of Highways, 2017). In the following sub-sections of this study, modelled components and necessary concepts will be introduced.

4.2. Vehicle Dynamics

There are several entities that affect the dynamics of a vehicle such as load model, battery used in the vehicle, the route it is following and electric motor used in the vehicle. All these concepts will be introduced in following sub-sections.

4.2.1. Load modeling of the vehicle:

While modelling the vehicle, only longitudinal forces are considered. For acquiring simplicity of the model, lateral forces are not included in this model. The route, vehicle is following is assumed to be open and the weather is accepted as dry and sunny. Road grade is considered during calculations. When forces applied on the vehicle are analyzed, they are identified as wheel rolling resistance, drag resistance, gravitational force due to road slope and acceleration force. The formula used for calculation of each force can be seen in following page. Definitions of scientific parameters can be seen in Table 4.1.

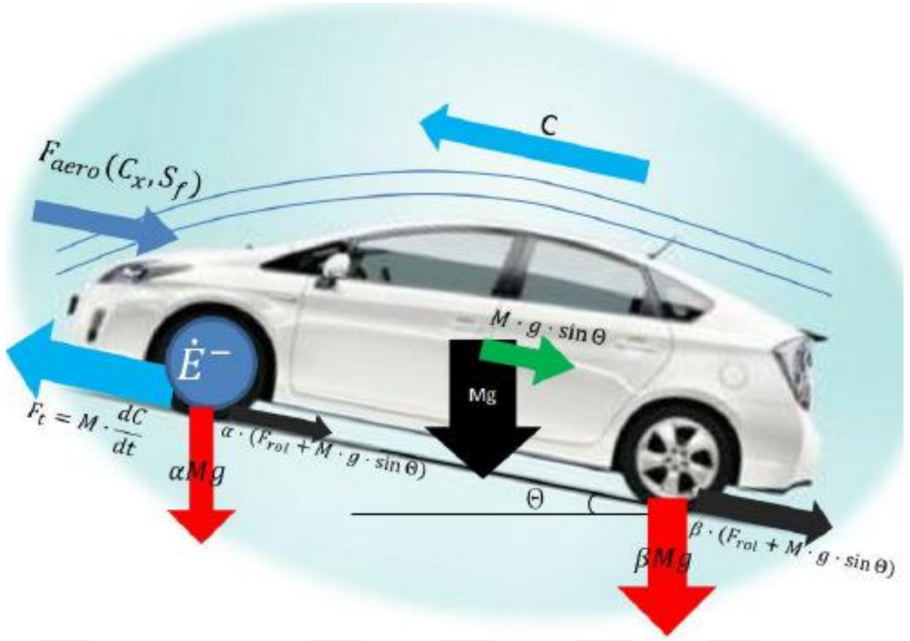


Figure 4.1. Representation of Forces Acting on a Vehicle (Iglesias and Favrat, 2013)

Wheel rolling resistance: $F_{rr} = c_{rr}.m.g.cos\Theta$ (4.1)

Air drag resistance: $F_{aero} = 0.5.c_d.\delta.Af.V^2$ (4.2)

Gravitational force due to the slope: $F_{slope} = m.g.sin\Theta$ (4.3)

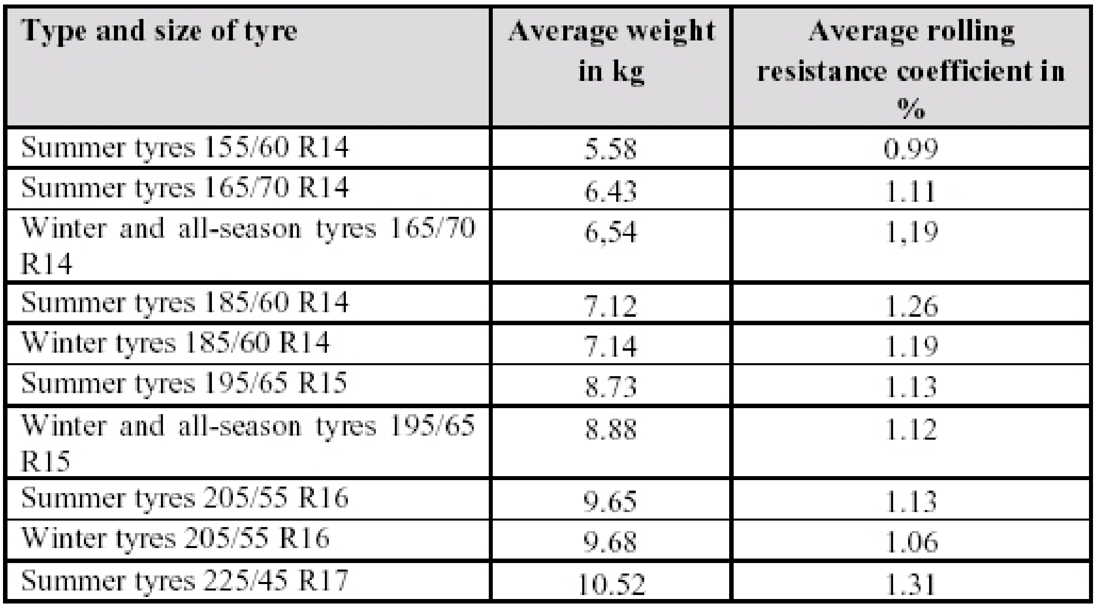
Mechanical Force: F_{mech}= *Load due to Mechanical Friction * Number of Wheels* (4.4)

Table 4.1. Vehicle Body Parameters

Abbreviation	**Definition**	**Value [unit]**
Crr	Wheel rolling resistance	0.01
m	Total mass of the vehicle	1650 [kg]
g	Gravity	9.81 m/s^2
Ɵ	Slope of the road	- [rad]
Cd	Air drag coefficient	0.3
δ	Air density	1.293[kg/m^3]
Af	Frontal area of the vehicle	2.33 [m^2]
V	Vehicle speed	- [m/s]
η_T	Transmission efficiency	0.85
R_T	Tire efficient radius	0.3 [m]

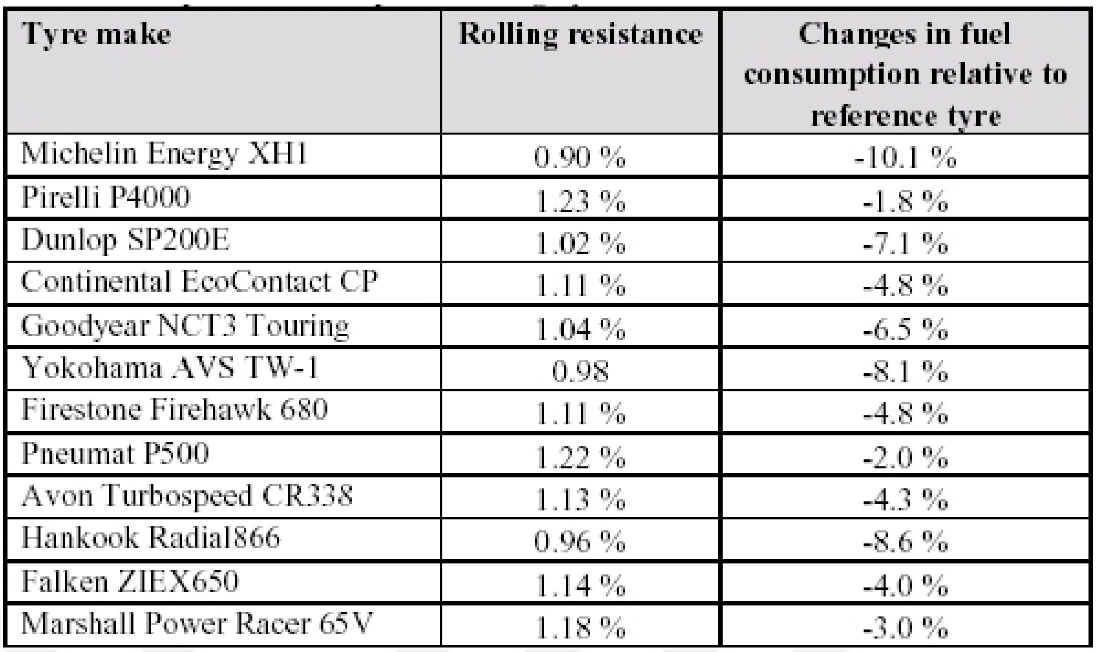
In Figure 4.1., the representation of the loads acting on the vehicle is given. Forces acting on the vehicle are represented and are fed to the system. Load model of the vehicle is given in Figure 4.6. Variables and parametres used for this application are transferred to the block diagram via a parameter file. Brief explanations of the given variables can be seen below.

Wheel rolling resistance: According to Ehsani et al. (2005), rolling resistance is a coefficient caused by the tire deformation on the road. Baldissera and Delprete (2016), state that rolling resistance plays a non-negligible role in the efficiency of human powered vehicles, whether they are designed for daily commuting or to set speed records. Writers add that with the increase in number of wheels, tire rolling resistance increases simultaneously. Tires have a very important effect on the fuel economy of a vehicle. In other words, an alteration in the tire rolling resistance coefficient by 0.001 result in an average fuel consumption change in 2.2 cc/km on the EPA urban cycle and 1.5 cc/km on the highway cycle. (Thompson and Reineman, 1981). In HEV applications mostly tires with R15, R16 and R17 are used and Crr value alters from tire to tire. Tires with different labels and different rolling coefficients can be seen in Figure 4.2.



Type and size of tyre	Average weight in kg	Average rolling resistance coefficient in %
Summer tyres 155/60 R14	5.58	0.99
Summer tyres 165/70 R14	6.43	1.11
Winter and all-season tyres 165/70 R14	6,54	1,19
Summer tyres 185/60 R14	7.12	1.26
Winter tyres 185/60 R14	7.14	1.19
Summer tyres 195/65 R15	8.73	1.13
Winter and all-season tyres 195/65 R15	8.88	1.12
Summer tyres 205/55 R16	9.65	1.13
Winter tyres 205/55 R16	9.68	1.06
Summer tyres 225/45 R17	10.52	1.31

Figure 4.2. Rolling Resistance and Weight Given as Averages for Groups of Tires of the Same Size from Different Manufacturer (Vejdirektoratet, 2004)



Tyre make	Rolling resistance	Changes in fuel consumption relative to reference tyre
Michelin Energy XH1	0.90 %	-10.1 %
Pirelli P4000	1.23 %	-1.8 %
Dunlop SP200E	1.02 %	-7.1 %
Continental EcoContact CP	1.11 %	-4.8 %
Goodyear NCT3 Touring	1.04 %	-6.5 %
Yokohama AVS TW-1	0.98	-8.1 %
Firestone Firehawk 680	1.11 %	-4.8 %
Pneumat P500	1.22 %	-2.0 %
Avon Turbospeed CR338	1.13 %	-4.3 %
Hankook Radial866	0.96 %	-8.6 %
Falken ZIEX650	1.14 %	-4.0 %
Marshall Power Racer 65V	1.18 %	-3.0 %

Figure 4.3. Changes in Average Fuel Consumption with Different Makes of Summer Tires of the Size 195/65 R15, When Driving Through the New European Driving Cycle (Vejdirektoratet, 2004)

Total mass of the vehicle: This indicates to the whole body weight of a vehicle when all necessary components and sub systems are mounted. The conventional and the parallel hybrid electric vehicles appear to be the most sensitive to a change in vehicle mass and it is known that with a lower mass, the engine is turned on less often, increasing the percentage in electric vehicle (EV) mode and leading to less fuel consumption and greener cruise opportunity.

Moreover with a deduction in vehicle mass, less battery power is needed to recover the stored energy (Pageritet al., 2006).

Slope of the road: This phenomenon can also be named as road gradient. According to Wood et al. (2014), grade penalties between the midsize HEV and BEV models were approximately the same. Approximately 1% to 3% average energy consumption penalty is created as a result of road.

Frontal area of the vehicle and air drag coefficient: With the increase in aerodynamic drag, horsepower used during cruise also increases. These alterations lead to consumption of fuel more and more. Most of the drag (90%, or more) results from pressure differences upon shape of the vehicle so to overcome large air drag and improve aerodynamic properties of the vehicle shape alterations can be carried out (Browand, 2015).

Aerodynamic force increases with the square of speed, hence drag concept is crucial for cruise in higher speeds. Reducing the drag coefficient of the design, automatically increases the performance of the vehicle such as fuel consumption.

Change of drag coefficient in vehicle design in years can be seen in Figure 4.4 and change of drag coefficient in different designs can be seen in Figure 4.5.

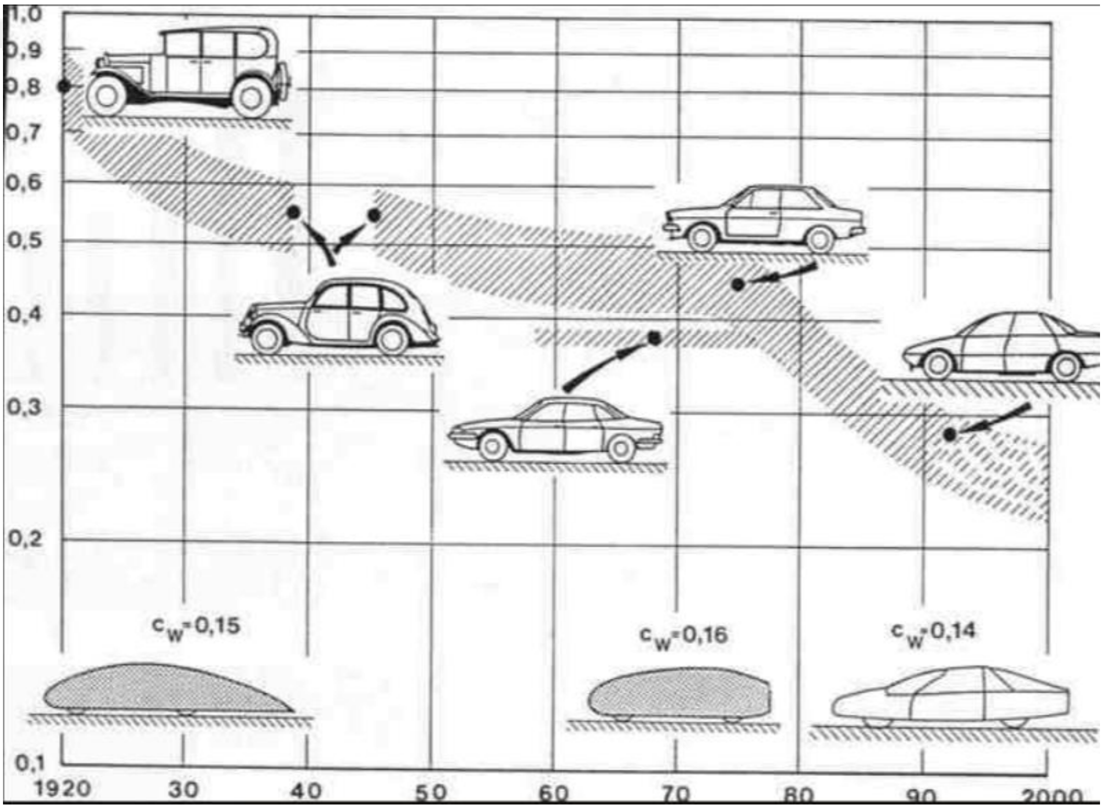


Figure 4.4. Change of Drag Coefficient in Vehicle Design in Years (Rivas, 2017)

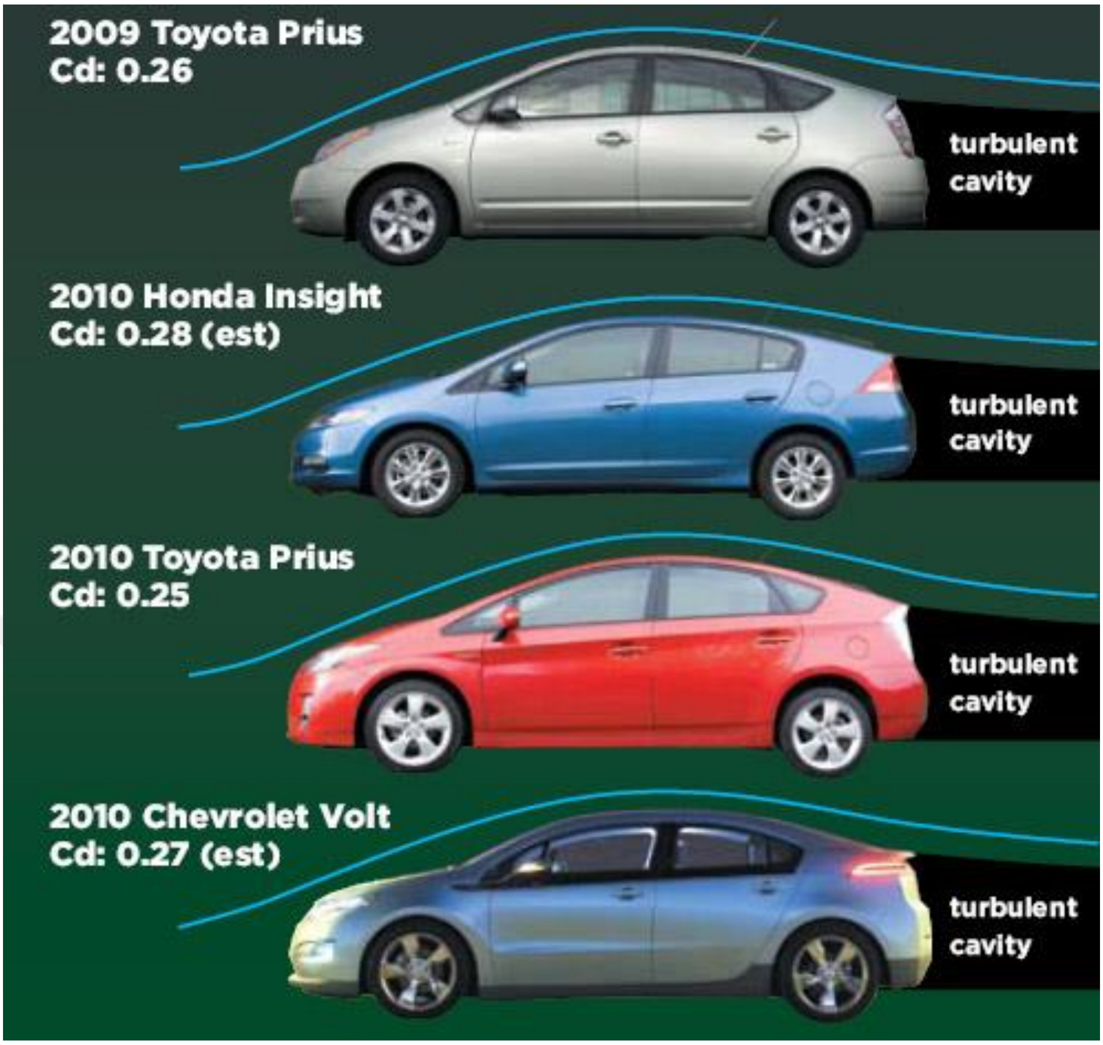


Figure 4.5. Change of Drag Coefficient in Different Designs (Haase, 2009)

Vehicle speed: This concept stands for the instantaneous vehicle speed which has the biggest affect on emission and fuel economy factors, followed by emission and fuel consumption rates. (Tong et al., 2011).

Tire efficient radius: This parameter can lead to improved steering, fuel efficiency, riding comfort, and braking performance of tires (Yamagishi et al., 1987).

To sum all the forces acting on the vehicle, the total load on the vehicle is represented with F_T. F_T is calculated as:

$$F_T = F_{rr} + F_{aero} + F_{slope} + F_{mech} \tag{4.5.}$$

Total power dissipated by the total load is shown as P_T. P_T is calculated as:

$$P_T = F_T * V \tag{4.6.}$$

V in formula 4.6 corresponds to the vehicle speed.

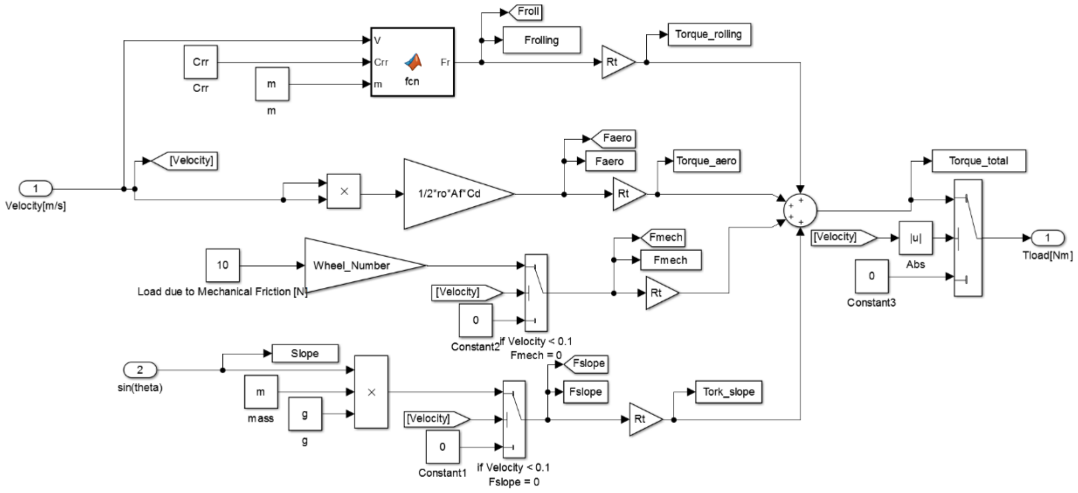


Figure 4.6. Load Model of the Vehicle

4.2.2. Battery model

Battery adapted to this vehicle model is Panasonic NCR 18650B with Li-Ion chemistry. At the present, Li-ion chemistries are being greatly studied and improved aiming to significantly enhance energy and power capabilities as well as working voltage such Panasonic, Tesla, LG Chem, and Samsung SDI (Chemali et al., 2016).

To elaborate it can be said that, Tesla Model S battery packs are formed by Lithium Ion 18650B batteries (Boucher, 2016). Tesla’s current custom 18650 battery cells produced by Panasonic are presumed to have an energy density of ~250 Wh/kg and the price is changing (Lambert, 2016).

Battery model is formed by 96 cells in series and 29 series in parallel, the nominal voltage is 345 V_{DC}. Each cell has 3.60 V nominal voltage and 3200 mAh capacity.

Battery specifications can be seen in Table 4.2. Charge characteristics (Figure 4.7) and discharge characteristics (Figure 4.8.a and Figure 4.8.b) of the battery are presented in following. Battery model block diagram is presented in Figure 4.9.

Table 4.2. Battery Specifications (Sanyo Energy Corporation, 2012)

Rated capacity	Min. 3200 mAh
Capacity	Min. 3250 mAh Typ. 3350 mAh
Nominal voltage	3.6 V
Charging	CC-CV, Std. 1625 mA, 4.20 V, 4.0 hours
Weight (max.)	48.5 g
Temperature	Charge: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density	Volumetric: 676 Wh/Liters Gravimetric: 243 Wh/kilograms

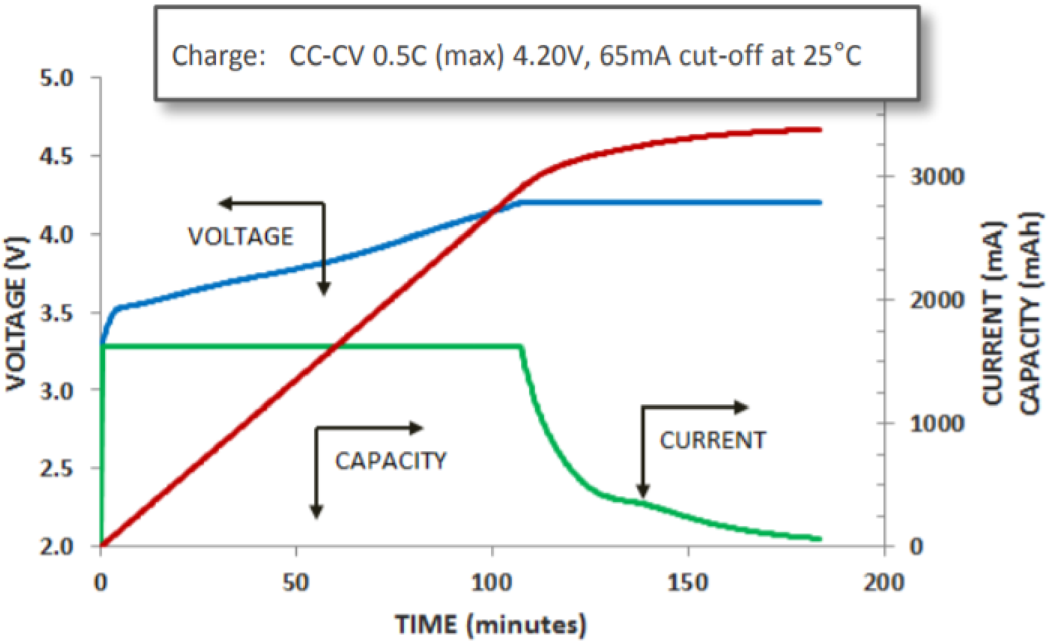


Figure 4.7. Charge Characteristics of the Battery (Sanyo Energy Corporation, 2012)

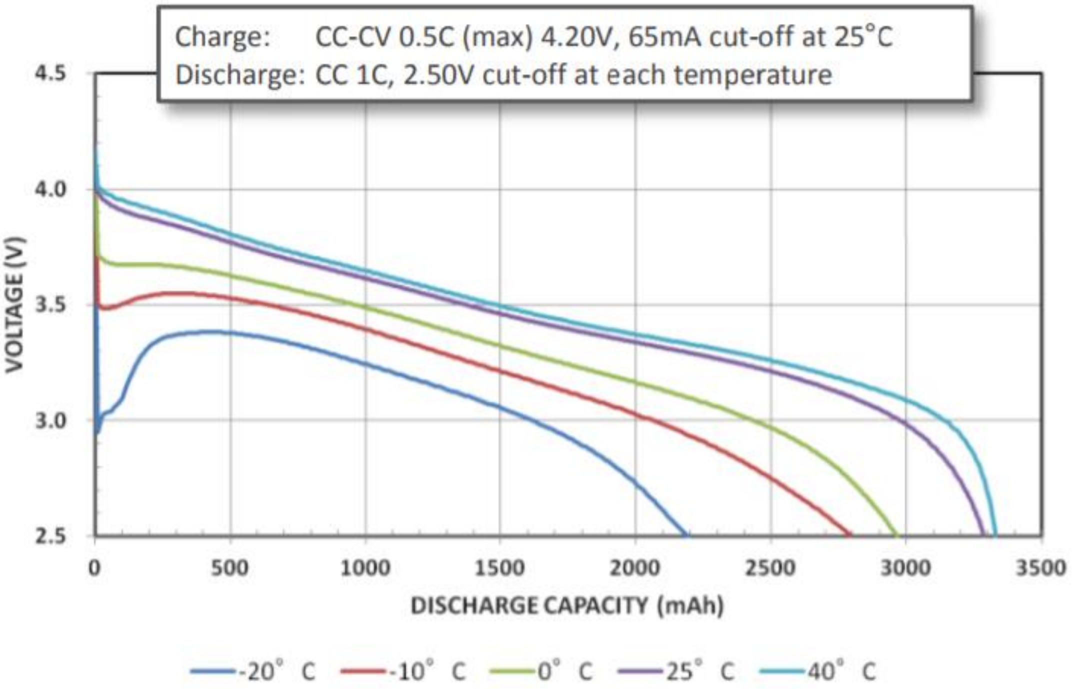


Figure 4.8.a. Discharge Characteristics of the Battery (by temperature) (Sanyo Energy Corporation, 2012)

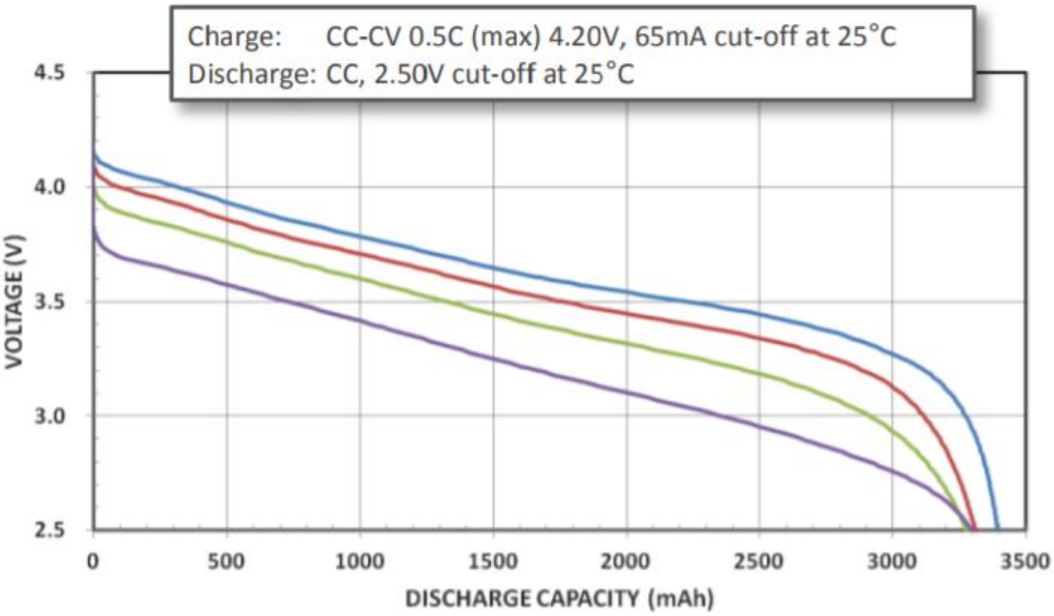


Figure 4.8.b. Discharge Characteristics of the Battery (by rate of discharge) (Sanyo Energy Corporation, 2012)

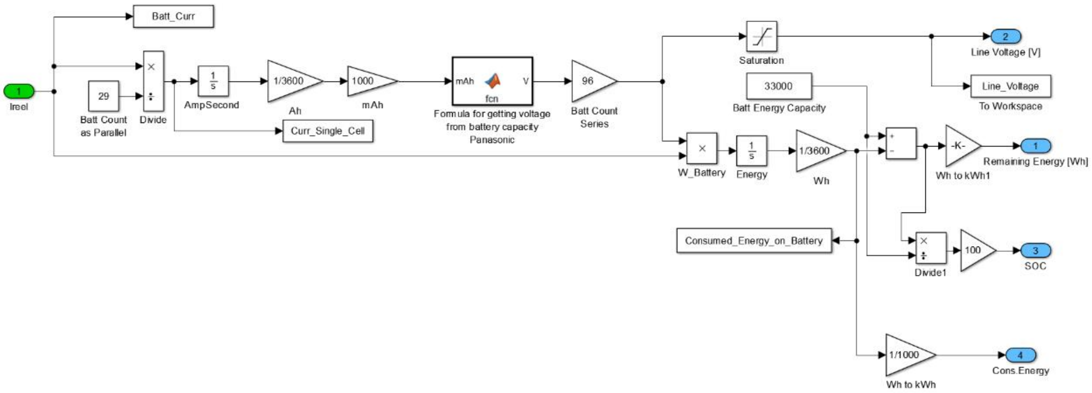


Figure 4.9. Battery Model Block Diagram

4.2.3. ICE and range extender model

Since this study does not primarily focus on internal combustion engine, a detailed model is not created.

Through literature review, speed and rpm values of the used engine are taken as given in Table 4.3 and the torque-speed characteristics of the engine are given in Figure 4.10.

Table 4.3. Torque vs. Speed Values of the Used Engine (W20 Engine, 2014)

Speed [rpm]	**Torque [Nm]**
1043	22
1545	31
2020	35
2527	34
3034	35
3523	34
4012	34
4506	38
5003	30

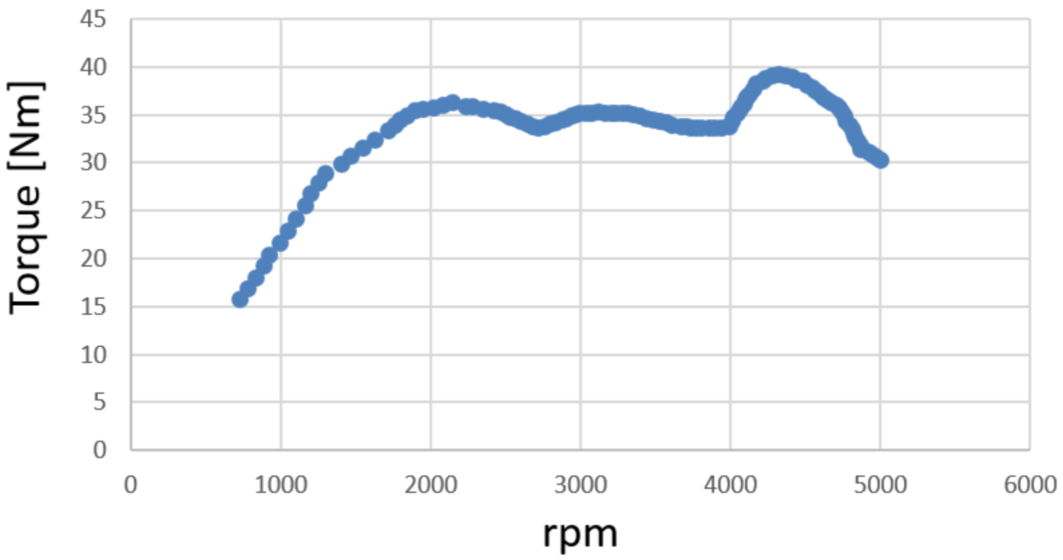


Figure 4.10. Torque-Speed Characteristics of the Engine (W20 Engine, 2014)

As explained earlier in this study, range extender is a component composed of an internal combustion engine and a fuel tank, an electric motor and an inverter. From another point of view, REX can be seen as a generator in this model. Range extender (REX) is used to enhance the distance which a hybrid electric vehicle can travel when only supported by the electric energy. Below the range extender model used for this study can be seen in Figure 4.11.

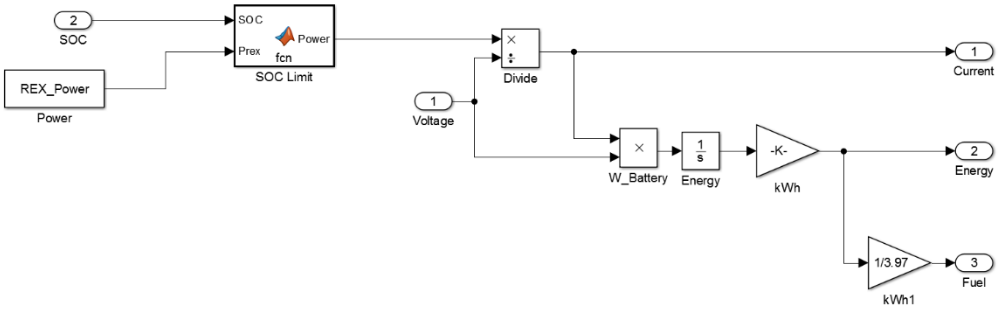


Figure 4.11. Range Extender Block Diagram

Here in the model, 3.97 kWh stands for the electric energy that can be produced by this REX design with 1 liter fuel. In other words, by dividing the energy in 3.97, the consumed fuel by the range extender is found.

When SOC of battery is more than or equal to 80%, battery voltage is very close to its upper limit and if REX gets activated and re-charges battery, its voltage value will go higher to a critical value for the battery since it can be degraded. Hence it is so designed that, the REX will be activated once the SOC drops lower than 80%.

4.2.4. Road model

The distance which modelled vehicle is expected to travel is between Istanbul and Ankara through toll road, TEM. This distance corresponds to 450 km. To model the grade of the road, height of the road at every kilometer section is necessary. These values are retrieved from Google Earth by sampling (Google Earth, 2017). For 450 km distance, height values from 453 different sections are gathered and altitude alteration through vehicle route is presented in Figure 4.12.a and the image retrieved from Google Earth is given in Figure 4.12.b. This sampling corresponds to height measurement in every 993 meters of the route.

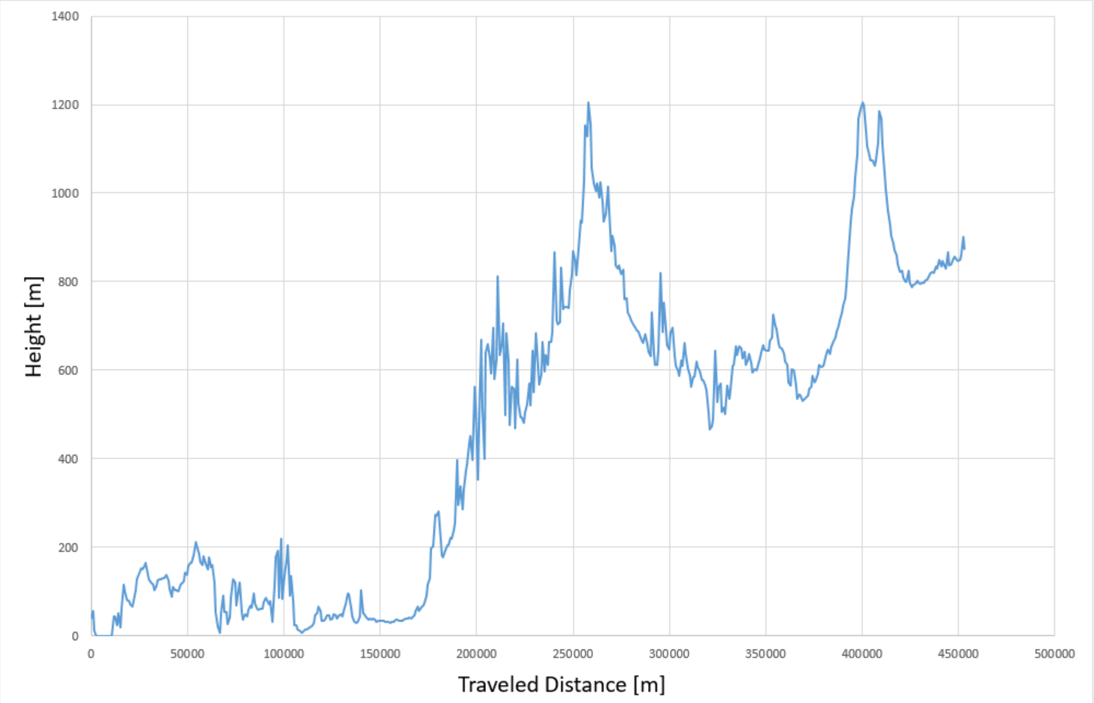


Figure 4.12.a. Height Alteration throughout the Vehicle Route

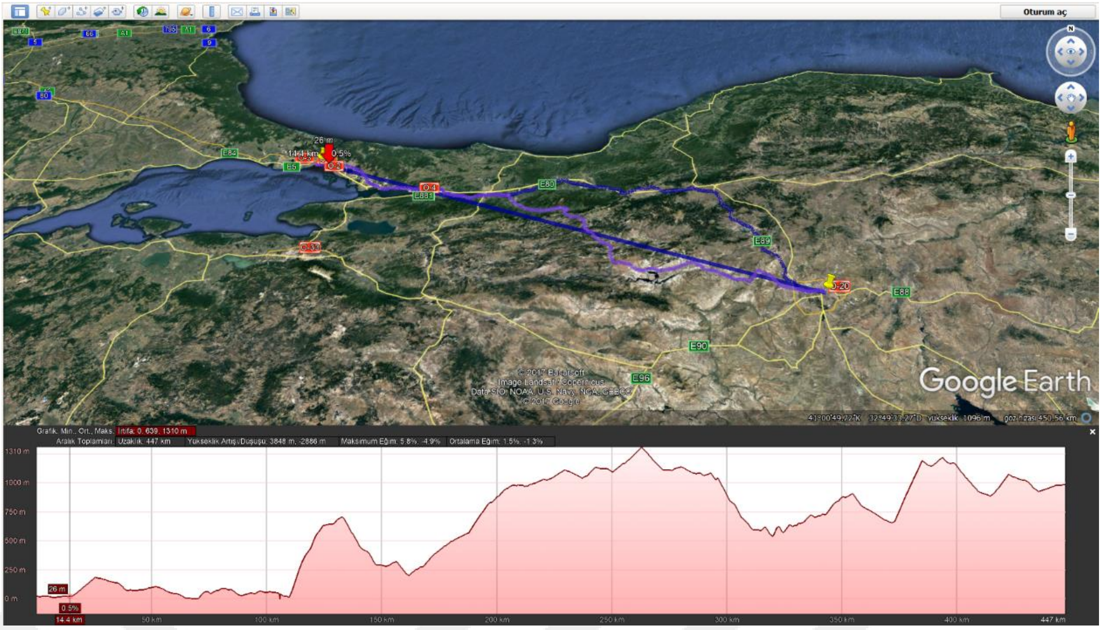


Figure 4.12.b. Height Alteration from Google Earth throughout Route (Google Earth, 2017)

Since altitude value of every kilometer is known, corresponding road grade could be calculated approximately for that distance. To embed these values into the model, a Simulink block named look up table is used. Block diagram of the road model can be seen in Figure 4.13.

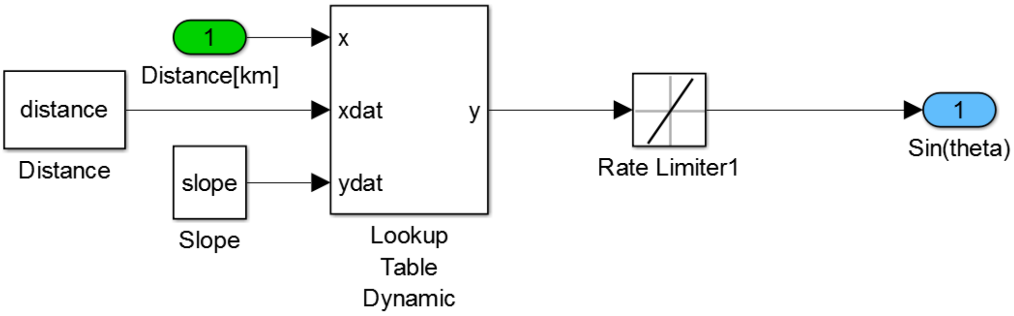


Figure 4.13 Road Model

4.2.5. Motor model

The vehicle modelled for this study is a series hybrid electric vehicle. To elaborate this it can be mentioned that, during start and low speeds it is only electric motor which provides propulsion to the vehicle.

Motor model is formed via taking values of a brushless DC electric motor into account. Parameters of the electric motor are embedded in parameters m file and used in model respectively. Model of electric motor can be seen in Figure 4.14.

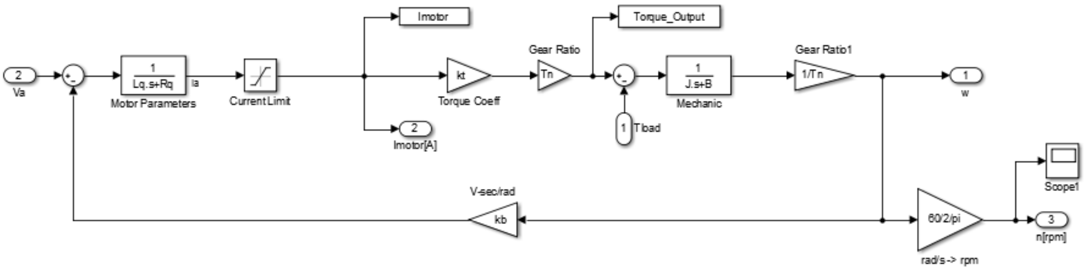


Figure 4.14. Electric Motor Simulink Model

4.2.6. Velocity controller

Velocity controller is a logical construction to lead the vehicle through its miscellaneous operating conditions and a dynamic control strategy related with each operating mode to indicate the vehicle demands (Phillips et al., 2000).

In other words a controller can be explained as a component which determines the way of supplying propulsion to vehicle according to the driving conditions as in driving the vehicle only by the ICE, or only by the electric motor or using them simultaneously and this yields less fuel consumption and better usage of electric power during cruise.

For this study, a PI controller is used for velocity controlling. As a design parameter, the vehicle is wanted to accelerate from 0 km/h to 100 km/h in 10 seconds. To fit this constraint, necessary Kp and Ki values are calculated with parameter estimation toolbox in the MATLAB. Simulink model of velocity controller is given in Figure 4.15. and representative images from parameter estimation process can be seen in Figure 4.16. By using this controller, vehicle can be driven at constant speed.

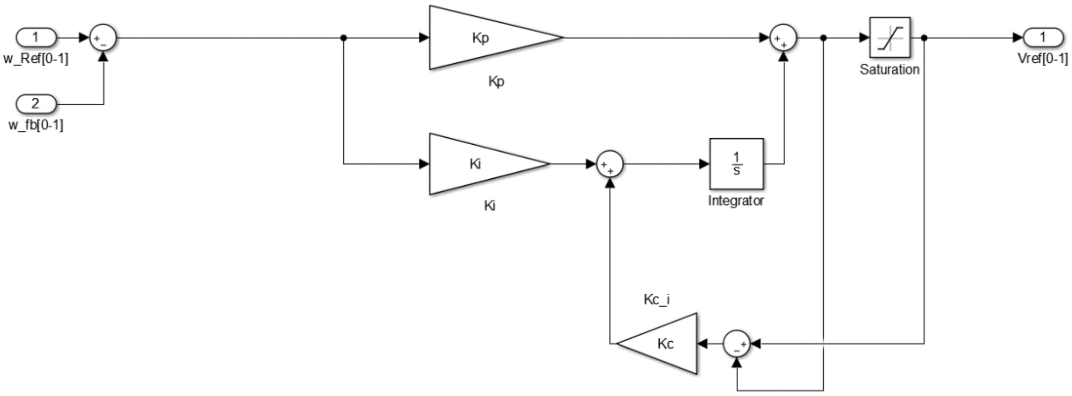


Figure 4.15. Simulink Model of Speed Controller

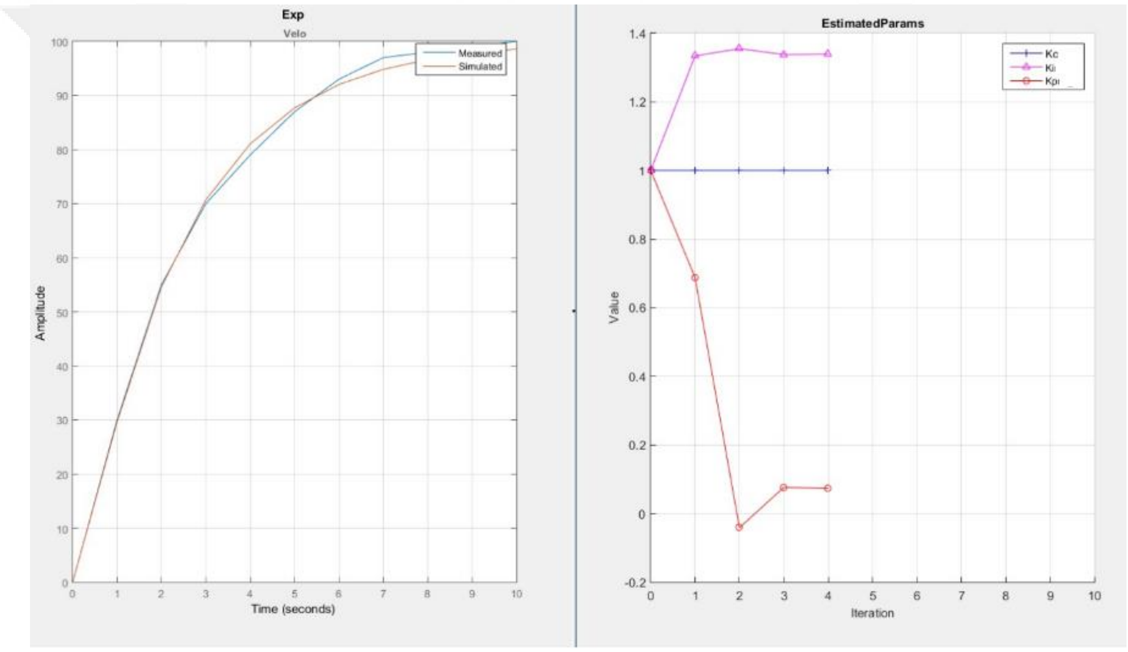


Figure 4.16. Parameter Estimation Process for Velocity Controller

In Figure 4.16. estimation process and alteration in parameters in that phase can be seen. Value of each parameter in each iteration step can be analyzed.

5. RESEARCH FINDINGS AND DISCUSSION

For the analysis of the model, a simulation is created with the help of MATLAB/Simulink and an optimization process is implemented. In this chapter findings from simulation and optimization processes will be presented. After going over research findings, these results will be discussed with the help of findings from literature.

5.1. Simulation

Table 5.1. Parameters Used in Simulation

Parameters	Value	Unit
Battery Capacity	33	kWh
Depth of Discharge	85	%
Battery Nominal Voltage	345	V
Transmission Gear Ratio	9	-
Fuel Tank Capacity	30	liters
Fuel Price	5.5	TL/liters
Electricity Price	0.2	TL/kWh
Mass	1650	kg
Coefficient of Rolling Resistance	0.015	-
Drag Coefficient	0.3	-
Frontal Area	2.33	m^2
Air Density	1.293	kg/m^3
Tire Radius	0.3	m
Gravity	9.81	m/s^2
Number of Wheels	4	-
Kp	0.07	-
Ki	1.3396	-
Kc	1	-

The series hybrid electric vehicle is modelled on MATLAB with the help of Simulink. The parameters used in this model are fed into system via a parameter file formatted as a m file. The vehicle model is run in Istanbul-Ankara route over toll road, TEM. This corresponds to 450 kilometers. Road height data for every 993 meters is acquired via Google Earth application (Google Earth, 2017).

During modelling and simulation processes, the vehicle assumed as starting from Istanbul and heading to Ankara without stopping in a road with no traffic juntions or heavy traffic. Developed energy management system switched propulsion between battery, range extender and electric motor during cruise.

For the simulation, it is assumed that the vehicle has 115 km/h average velocity. The maximum velocity capability of the vehicle is calculated as 131.76 km/h based on gear ratio and maximum electric motor speed. This amount of maximum value is acceptable for a mid-size family sedan HEV since the admissible maximum velocity value in paid route, TEM is 120 km/h (Turkish General Directorate of Highways, 2017). To show the working principles of the simulation, finished simulation for 115 km/h velocity can be seen in Figure 5.1. and 5.2. All tests are carried out with a full battery. Battery capacity is assumed as 33kWh and DOD is 85%.

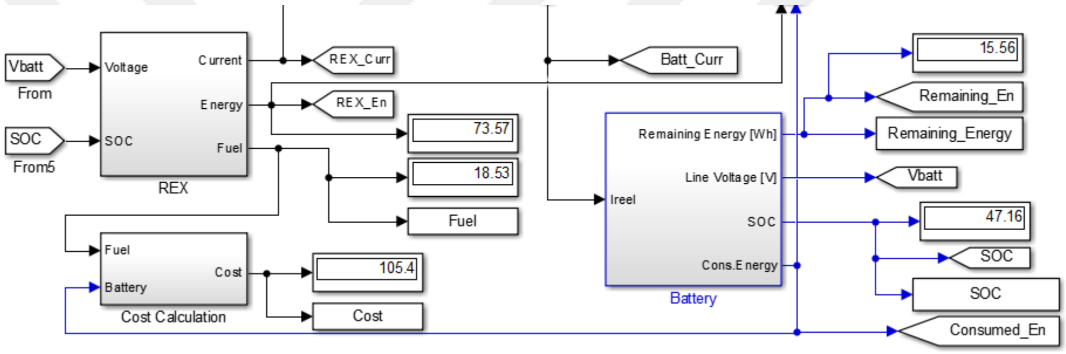


Figure 5.1. Simulation Results Showing Fuel Consumption of REX and Cost of this Cruise

As can be seen in Figure 5.1 during the trip, REX starts to operate and supports vehicle in terms of electrical energy as a generator. From the figure it can be seen that, to provide 73.57 kWh energy to the vehicle, range extender consumes 18.53 liters of fuel. And this cruise costs 105.4 Turkish Liras to the driver. If the driver used a conventional vehicle with an average of 7.0 liters/100 km fuel consumption. He/She would have consumed 31.5 liters of fuel and paid approximately 170 Turkish Liras. Again in the figure, remaining SOC can be seen as 47.16% and the remaining energy in the battery is 15.56 kWh.

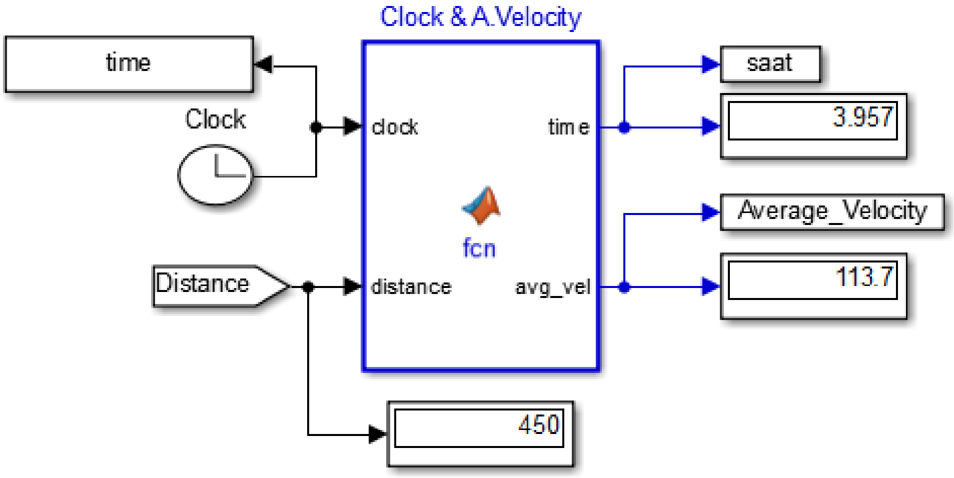


Figure 5.2. Average Velocity and Duration of Trip

As represented in Figure 5.2 average velocity of 115 km/h is demanded from the vehicle but 113.7 km/h is achieved during the trip and the vehicle finished the Istanbul-Ankara route in 3 hours 57 miuntes. Alteration in loads acting on vehicle during the cruise is given as a graph in Figure 5.3 and cumulative energy spent during the trip due to each load can be analyzed in Figure 5.4.

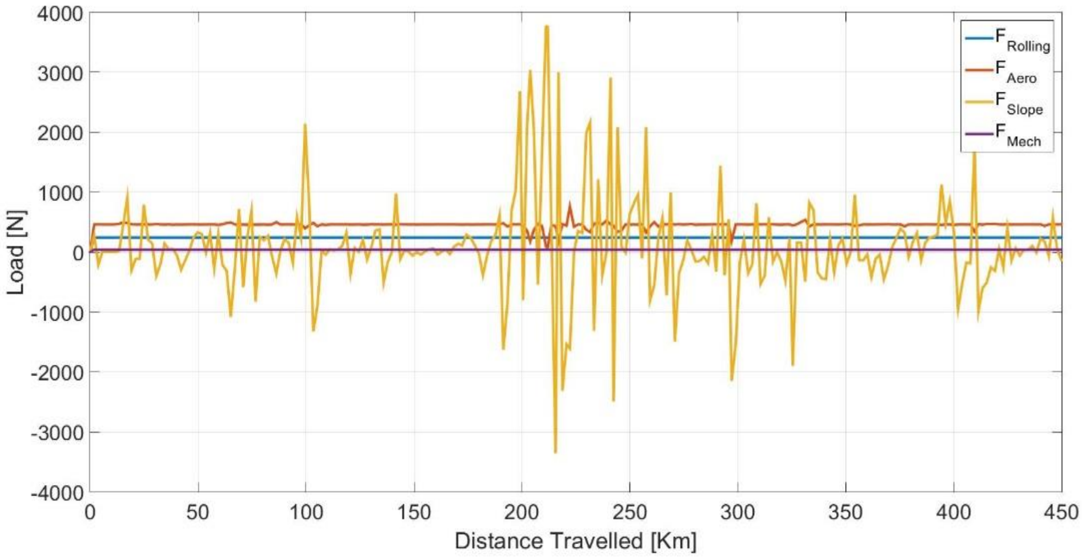


Figure 5.3. Alteration in Each Load with Respect to Covered Distance

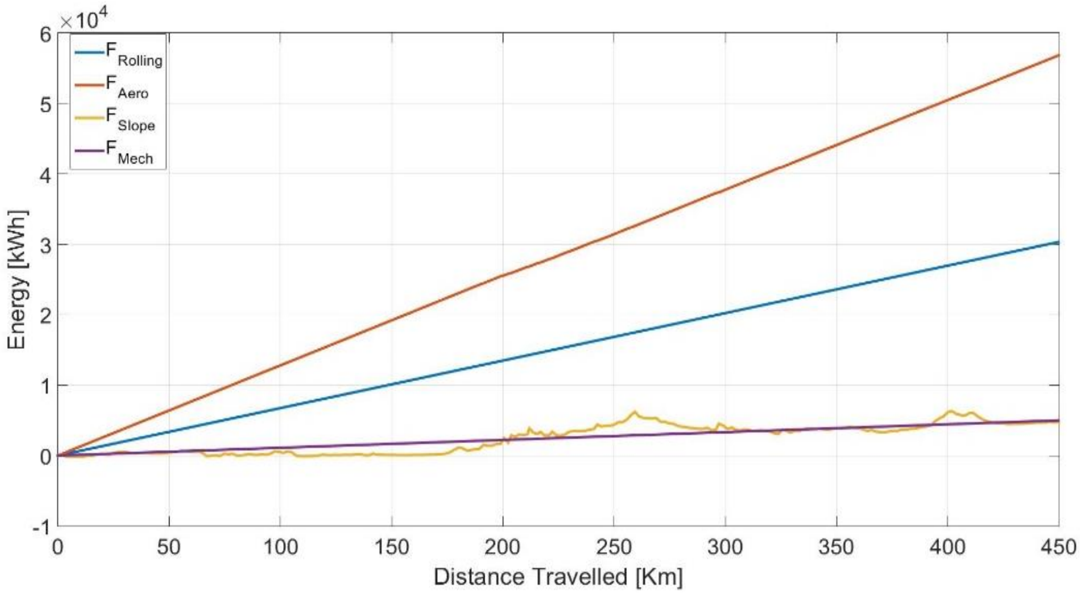


Figure 5.4. Cumulative Energy Spent During the Trip Due to Each Load with Respect to Covered Distance

In Figure 5.5 change in state of charge with respect to covered distance can be seen. As represented in the graph, at some points percentage of SOC increases. This rise is due to the help of REX and ICE. In other words, in this study simulation is so designed that REX is not activated until percentage of SOC drops below 80 and when this constraint is satisfied, REX starts to operate and help the battery to charge so at some points in the graph SOC increases.

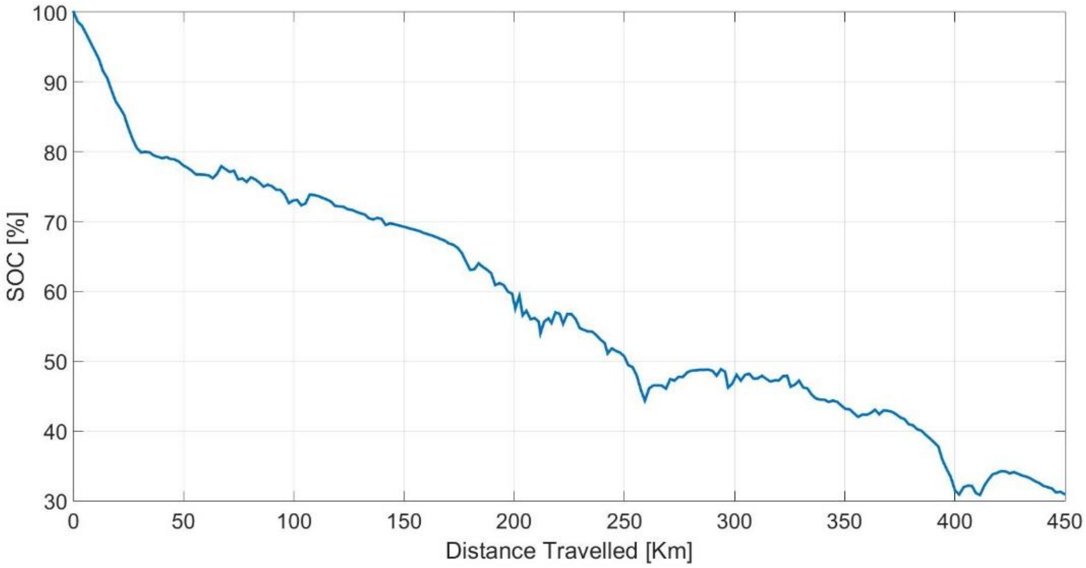


Figure 5.5. Alteration in SOC with Respect to Covered Distance

For 115 km/h a comparison for energy provided by REX, consumed during the trip and remaining energy in battery is retrieved. The related graph can be observed in Figure 5.6.

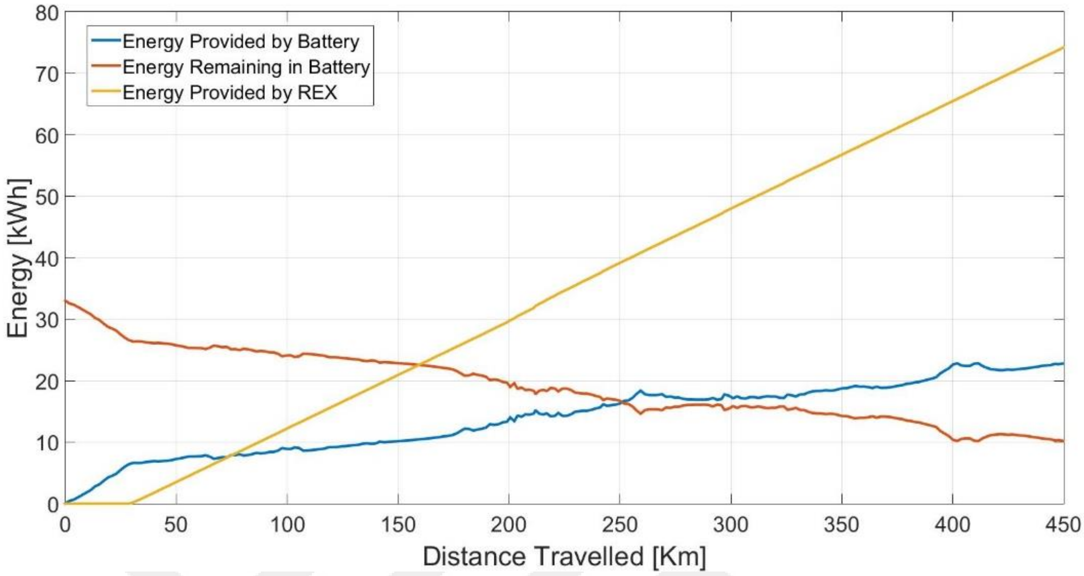


Figure 5.6. Energy Comparison for 115 km/h

Simulation is carried out for different velocity values in order to see the change in fuel consumption by REX and alteration in trip cost. Related outcomes can be analyzed in Table 5.2, in the following.

Table 5.2. REX Fuel Consumption and Total Travel Cost Comparison for Different Velocity Values

Velocity[km/h]	**Fuel Usage [lt]**	**Cost of Travel[TL]**
75	14.36	80.30
80	15.21	84.97
85	16.11	89.94
90	17.06	95.16
95	18.07	100.70
100	19.12	106.50
105	20.23	112.60
110	21.38	118.90
115	22.42	124.80
120	23.82	132.30

As can be seen in Table 5.2, when the velocity is increased, fuel usage also increases in each iteration along with rise in trip cost. This outcome is plausible since with increase in velocity, values of loads acting on vehicle increases and to provide propulsion to vehicle at given speed vehicle consumes more and more energy. Consumed energy when the velocity is altered is given in Figure 5.7.

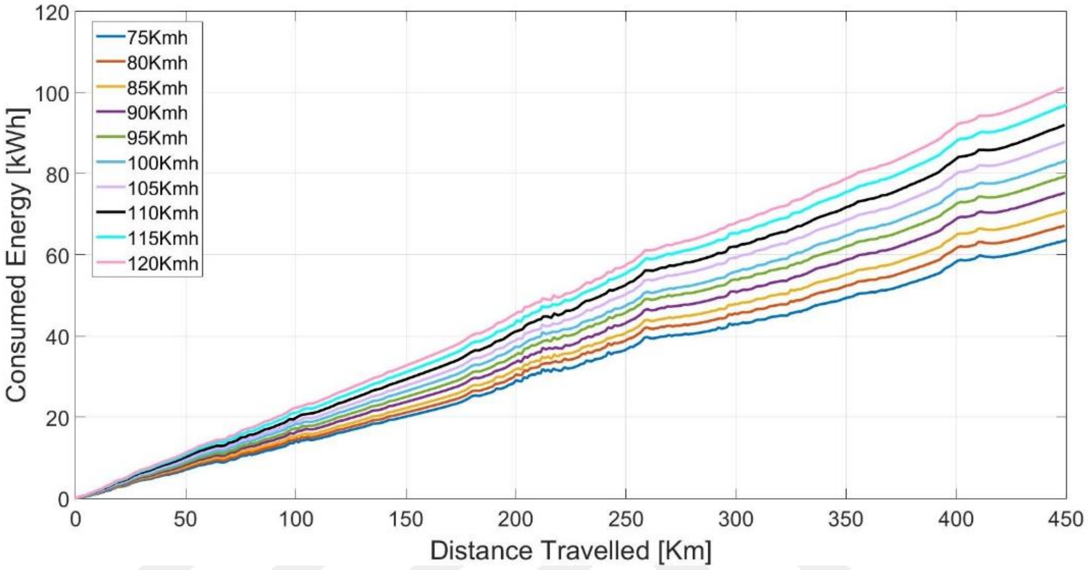


Figure 5.7. Cumulative Consumed Energy in Case of Different Velocities

Comparison for energy provided by REX, provided by battery and remained in battery is also done for select velocity values from this table. In each simulation REX started to operate when SOC dropped below 80%. Related graphs can be observed in Figure 5.8, Figure 5.9 and Figure 5.10.

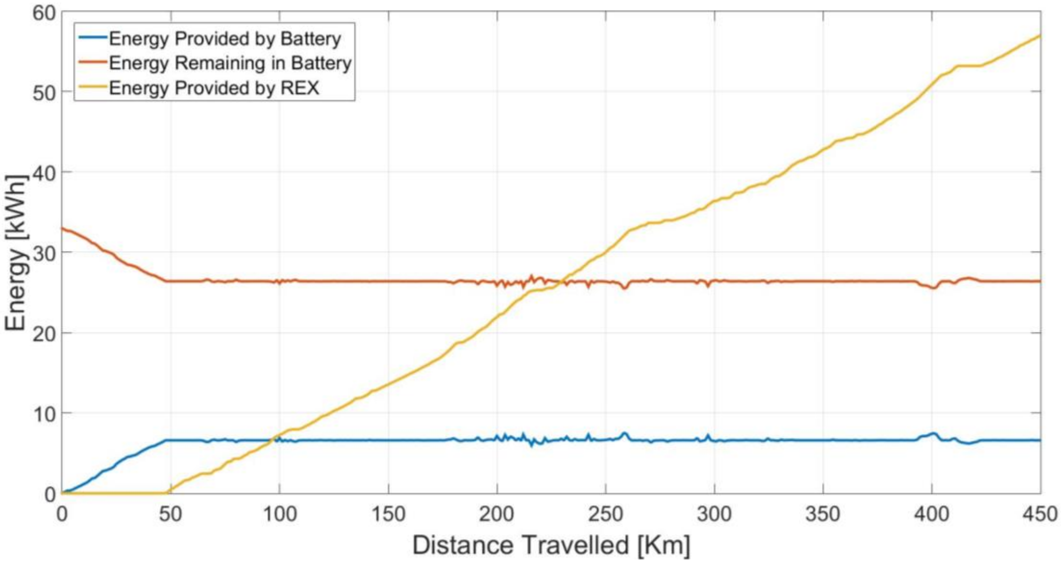


Figure 5.8. Cumulative Energy Usage for 75 km/h

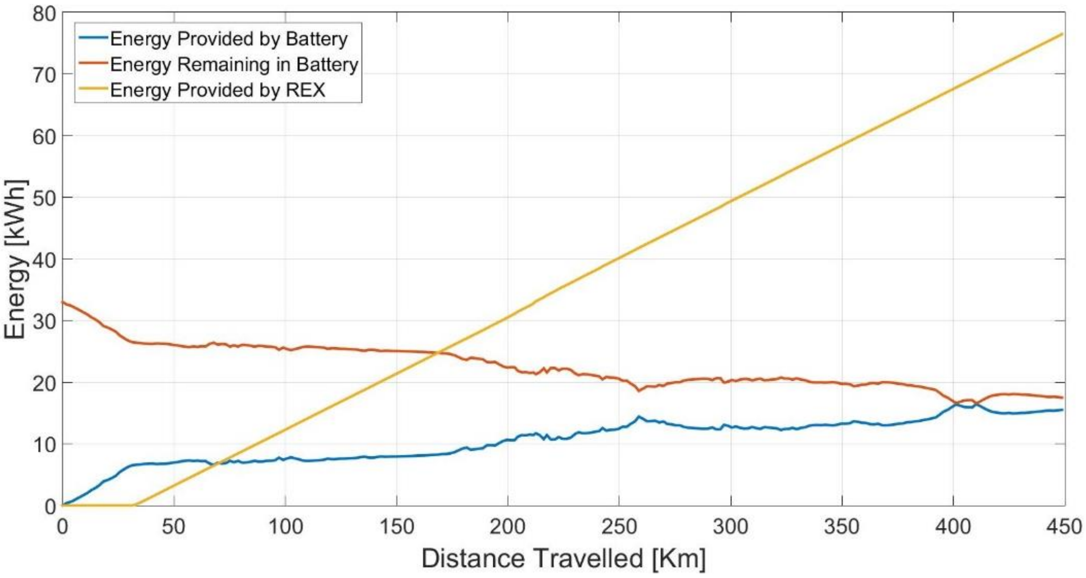


Figure 5.9. Cumulative Energy Usage for 110 km/h

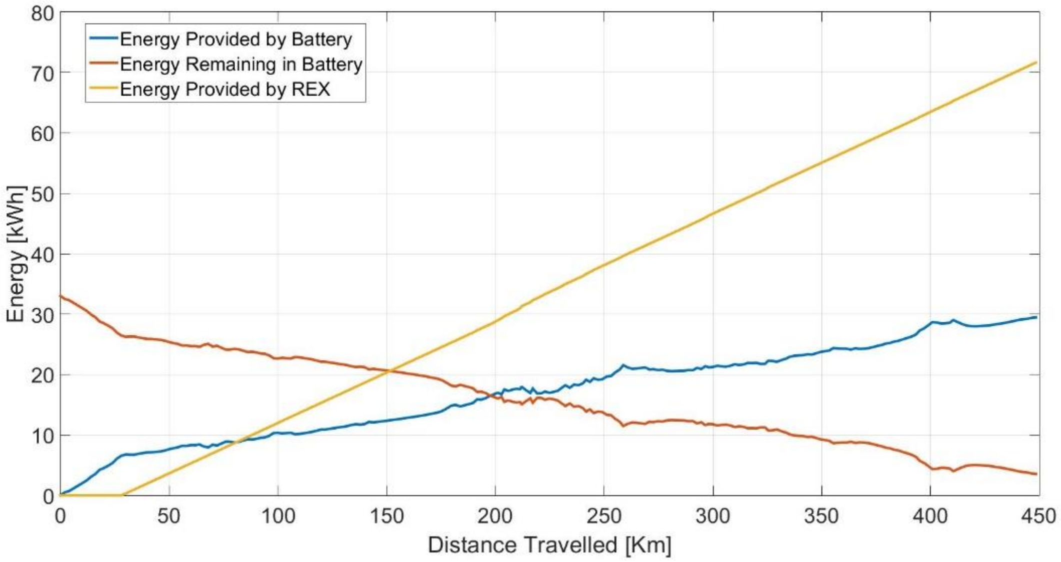


Figure 5.10. Cumulative Energy Usage for 120 km/h

When Figure 5.8, Figure 5.9 and Figure 5.10 are observed while comparing these results with outcome for 115 km/h, it can be interpreted that, with increase in velocity energy remaining in battery decreases in a more distinct way. Since these runs are done prior to the optimization, through the cruise, even though there is still energy in the battery, mostly REX powers the vehicle.

5.2. Optimization

The step after simulation is optimization in this research. In this phase optimizing the fuel consumption is the main aim. For optimization process, it is assumed that there are three different driver profiles. The first one is a student who is moving to Ankara from Istanbul for his/her university education. This driver is quite inexperienced in case of long distance and intercity driving and is carrying some of his/her belongings hence he or she wants to drive with 75 km/h cautiously, fuel consumption and duration of trip is not his or her main concern here. Second driver is father of two and driving with his whole family along with the family dog. He is looking for a tolerable trip in which children will not be afraid of the velocity yet they will not waste much time on the road so set velocity for this family is 100 km/h. Third driver is a young man who is travelling with his three friends, wants to reach final destination, Ankara as fast as he can, though he does not want to get a speeding ticket so set velocity for this driver is 120 km/h. For optimizing each driver profile case studies are held and will be presented throughout this chapter. Design criterion in this process is that, once the SOC becomes smaller or equal to 10%, the optimization will be completed. At optimization phase, both keeping the number of iterations low and having initial value of REX power set according to vehicle velocity are taken into account. That is to say, with the increase in velocity, need for energy also increases. So to answer that much of energy demand, initial value for power of REX is determined according to velocity. At the beginning of each test run, SOC is 100%.

Case 1

Case 1 is composed of the first driver who wants to drive with 75 km/h in a cautious way. Results of each iteration step is presented in Table 5.3.

Table 5.3. Iteration for Velocity of 75 Km/h

Iteration No	REX Power [W]	REX Energy [kWh]	Battery Usage [%]	Fuel Usage [lt]	Cost of Travel[TL]
0	15000	57	20%	14.5649	81.43
1	10000	53.3	33%	13.4241	75.9874
2	8000	43	64%	10.8158	63.7183
3	6000	32.3	97%	8.1118	51.0221

As can be seen in Table 5.3, REX starts to operate with 15000 W power. Throughout the iterations, it is found that for the first driver to travel with 75 km/h, the optimal point for REX to operate is with 6000 W so that the vehicle will get most of its propulsion from the battery and battery will be used up to 97%. Using battery this much will reduce the fuel consumption and cost of travel. If the trip is not optimized, the first driver would have paid 81.43 Turkish Liras for going from Istanbul to Ankara but with the optimization, the battery is used in convenient points and REX is not activated without necessity and the first driver could travel just for 51.0221 Turkish Liras. This corresponds to approximately 37.34% trip cost and 44.29% fuel consumption reduction. Change in total trip cost and SOC is given in Figure 5.11.

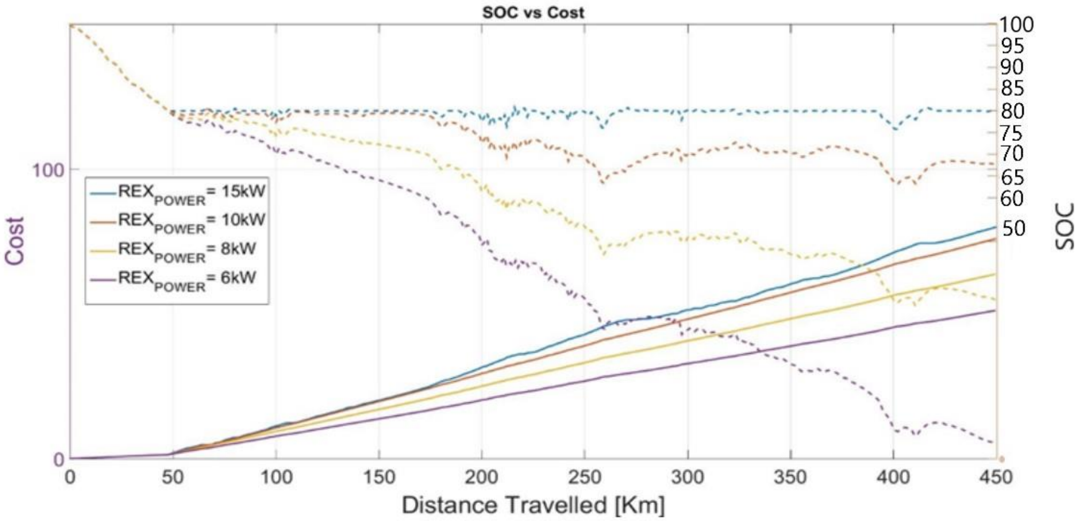


Figure 5.11. Change in Total Trip Cost and SOC with respect to Covered Distance When Velocity is 75 km/h

Case 2

Case 2 is composed of second driver who is travelling with his whole family along with the family dog. Set velocity value for this trip is 100 km/h. To reach the optimal point for this case, a number of iterations is carried out. Results of each iteration step is presented in Table 5.4., in the following page.

Table 5.4. Iteration for Velocity of 100 Km/h

Iteration No	REX Power [W]	REX Energy [kWh]	Battery Usage [%]	Fuel Usage [lt]	Cost of Travel[TL]
0	20000	75.9	20%	19.4146	108.10
1	15000	62.6	66%	15.6584	90.4731
2	13000	54.4	90%	13.5706	80.5835

As shown in Table 5.4, REX starts to operate with 20000 W power at the beginning of the optimization process, after a set of iterations it comes to the optimal point that REX operates with 13000 W power and the battery is used up to 90%. At the beginning of the optimization process the fuel usage is 19.4146 liters and this value s decreased to 13.5706 which corresponds to 30.10% reduction in fuel consumption. From cost of travel perspective, it is seen that at the beginning the cost is 108.10 Turkish Liras and then lowered to 80.5835 Turkish Liras. This reduction corresponds to 25.45% reduction in total cost of this trip. Change in total trip cost and SOC is given in Figure 5.12.

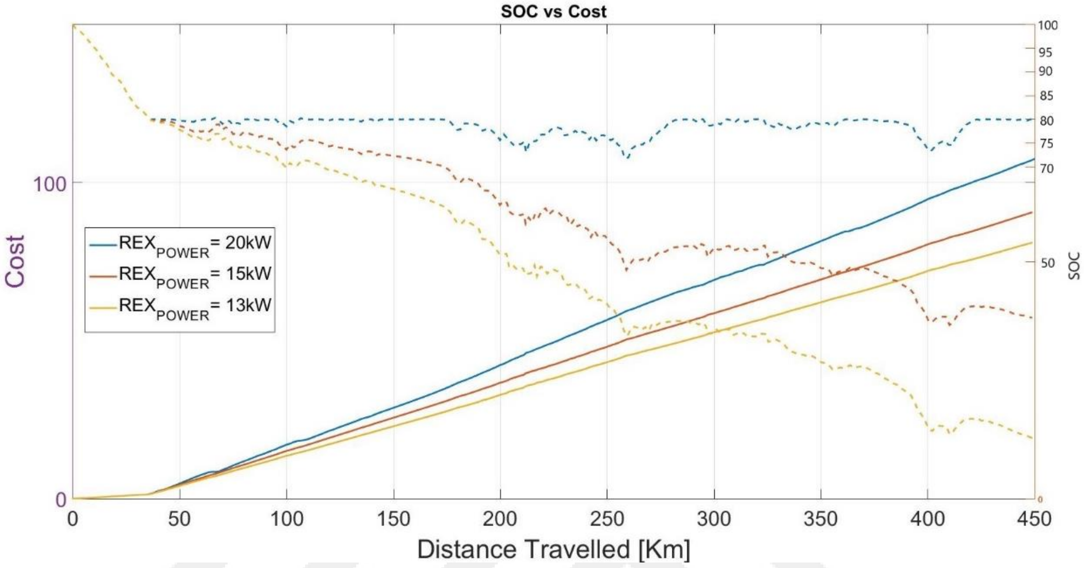


Figure 5.12. Change in Total Trip Cost and SOC with respect to Covered Distance When Velocity is 100 km/h

Case 3

Case 3 contains a young man who is travelling with his three friends, wants to reach Ankara as fast as he can without getting a speeding ticket so set velocity for this driver is 120 km/h. Results of each iteration step is presented in Table 5.5.

Table 5.5. Iteration for Velocity of 120 Km/h

Iteration No	REX Power [W]	REX Energy [kWh]	Battery Usage [%]	Fuel Usage [lt]	Cost of Travel[TL]
0	30000	94.5	20%	23.9314	132.94
1	25000	88.7	42%	22.083	124.2097
2	23000	82	63%	20.3672	116.1921
3	21000	75.2	85%	18.6019	107.9199
4	20000	71.8	96%	17.7161	103.7456

As shown in Table 5.5, REX starts to operate with 30000 W power at the beginning and with the optimization steps, it comes to optimal point which is 20000 W at 120 km/h velocity. With this process, battery is used up to 96% and fuel consumption is reduced from 23.9314 liters to 17.7161 liters. This corresponds to 25.97% reduction in fuel consumption.

When it comes to cost of travel, it can also be observed that, at the beginning the total trip cost is 132.94 Turkish Liras and when the iteration is completed it is seen that the cost of trip at the optimal point is 103.7456 Turkish Liras. This reduction corresponds to 21.96% reduction in total cost. Change in total trip cost and SOC is given in Figure 5.13 in the following page.

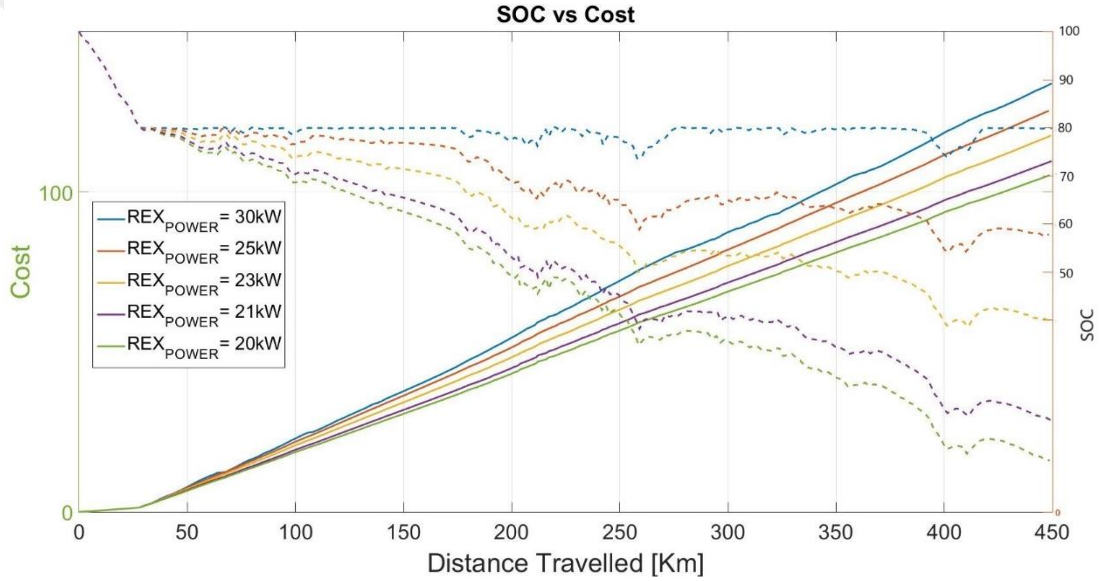


Figure 5.13. Change in Total Trip Cost and SOC with respect to Covered Distance When Velocity is 120 km/h

Table 5.6. Fuel Consumption and Travel Cost Comparison for Different Velocity Values After Optimization

Velocity[km/h]	Fuel Usage [lt]	Cost of Travel[TL]
75	8.1118	51.0221
80	8.9267	55.492
85	9.6369	59.4673
90	10.3385	63.4842
95	12.0331	72.3134
100	13.5706	80.5835
105	13.9542	83.0811
110	15.2854	90.1753
115	16.5031	96.7813
120	17.7161	103.7456

For discussion part, outputs retrieved from this study are compared to researches from literature. Detailes of compared studies can ben seen in below.

The first study from literature is done by Supina and Awad in 2004 on fuel consumption optimization. Researchers model a Toyota Prius and try to optimize the employement of the high voltage battery. In order to reach this aim two levels of optimization were carried out, the battery power utilization over the whole drive cycle is optimized and the system working at each point in the drive cycle is optimized. During this study, model is tested via EPA cycle simulation. As a result of this research researchers gained 1%-2% decrease in fuel consumption.

Second study is done by Park and Park in 2012 on development of equivalent fuel consumption minimization strategy for HEVs. For this study, writers model a power-split HEV with an electric continuously variable transmission. The aim of this research is to find the optimal target driving cycle by using model-based parameter optimization method. The model is tested via UDDS cycle simulation and 13.8% increased fuel mileage is achieved.

Third study is done by Mansour and Clodic in 2012 on optimizing the energy management in Toyota hybrid system. For this aim, researchers propose an energy management system based on dynamic programming that a prior knowledge of the route is required in order to determine the split ratio. The modelled vehicle is tested via using NEDC cycle simulation. At the end of the research, 5% reduction in fuel consumption is achieved.

Another study presented in literature comparison is done by Zhang et al. in 2016 and the study is on adaptive equivalent consumption minimization strategy. The aim in this paper is to impose SOC charge-sustainability and to enhance the fuel economy. During this study, researchers design a fuzzy logic PI controller and model a single shaft parallel HEV. The model is tested on ECE cycle simulation and as the outcome t-of the study 3.5% improvement in fuel economy is achieved.

Study done by Johnson et al. in 2000 is on real time control strategy for fuel economy and emission optimization. During this research, a sample HEV is modelled. The model is tested on HWFET, FTP and NEDC cycle simulations and as the result of this paper it is found that, fuel economy is highest at HWFET as much as 50%. By this outcome it is interpreted that performance of a HEV is highly dependent on drive cycle since fuel economy in this research varies by 29% when drive cycle is altered.

Additionaly in 2016, Tang and Rizzoni provide a study on energy management strategy for battery life optimization on a HEV. The optimization problem is tried to be answered via dynamic prograaming. For this paper, a vehicle with its main components like battery, EM, ICE and continuously variable transmission are modelled. The optimization process is teste on two different driving cycles, federal urban driving schedule and US06. At the end of the research, optimal battery ans SOC intervals are determined.

In 2016, Farahat and Farahat study on optimization of HEVs through particle swarm optimization method. In this paper researchers aim to place components at the right size in order to reduce fuel consumption and increase vehicle performance. The modelled vehicle is tested in UDDS and HWFET driving cycles via simulation. At the end of the study, 57% fuel consumption and 68% emission improvement are achieved via UDDS cycle and 74% fuel consumption and 79% emission improvement are achieved via HWFET cycle.

Alternatively to the given studies, Bouwman et al. use traffic flow data for predictive energy management strategy in HEVs in 2017. Developed strategy works with real time traffic data and traffic light positions in order to reduce fuel consumption. The modelled vehicle is simulated on a real life drive cycle in Helmond, Netherlands. This route contains seventeen traffic lights. For uncertainty of traffic lights, researchers use

Monte Carlo approach. As the outcome of the study, 8-11% improvement in fuel consumption is achieved.

The last sample from literature on this subject is done by Li et al. in 2015. Researchers study on fuel consumption optimization via providing a control strategy. For this study a HEV is modelled. The modelled vehicle is run in NEDC and UDDS cycle simulations. As the outcomes of this research the optimum operating points of the engine and the motor have been acquired.

The outcomes of this thesis study can be summarized as following. For this study a series hybrid electric vehicle is modelled and tested on a simulation which corresponds to the route between Istanbul and Ankara. The approximate distance between these two cities is 450 kilometers. During this study, optimizing the usage of the high voltage battery and REX is aimed and case studies on three different scenarios are carried out. When the simulations are completed, it is seen that improvement in fuel consumption is achieved in all scenarios. For instance, in the first case study, cost of the trip is reduced by 37.34% and fuel consumption is decreased by 44.29%. Additionally, in second case cost of the trip is reduced by 24.45% and fuel consumption is decreased by 30.10%. In third scenario, cost of the trip is reduced by 21.96% and fuel consumption is decreased by 25.97%.

When these outcomes are compared to the presented studies from literature, it can be interpreted that the optimization process works in a convenient way and optimal points are achieved since at the end of iteration for each case an improvement in fuel consumption is acquired.

6. CONCLUSION AND IMPLICATIONS

The aim of this study is to find the optimum operating point for REX and battery in order to reduce fuel consumption in HEVs. For this study a series hybrid mid size family sedan is modelled, simulated and tried to be optimized. Throughout the research the loads acting on the vehicle, battery, electric motor, route, REX and velocity controller are modelled. For implementing the parameters of the controller a parameter optimization process is carried out.

Alteration in behavior of the vehicle when the velocity is changed is observed via simulation and related outcomes are presented. The step after simulation is optimization process which is formed via three case studies. The first one is a student who is moving to Ankara from Istanbul for his/her university education. This driver is quite inexperienced in case of long distance and intercity driving and is carrying some of his/her belongings hence he or she wants to drive with 75 km/h cautiously, fuel consumption and duration of trip is not his or her main concern here. Second driver is father of two and driving with his whole family along with the family dog. He is looking for a tolerable trip in which children will not be afraid of the velocity yet they will not waste much time on the road so set velocity for this family is 100 km/h. Third driver is a young man who is travelling with his three friends, wants to reach final destination, Ankara as fast as he can, though he does not want to get a speeding ticket so set velocity for this driver is 120 km/h. Via experimenting on all these cases, the optimal point to operate REX and battery for each case is found through a set of iterations. With operating REX and battery at optimum points, decrease in fuel consumption and trip cost is achieved. Related results are also mentioned in Table 6.1 in the following page.

Table 6.1. Results of the Optimization Process

	Case 1	Case 2	Case 3
Velocity [km/h]	75	100	120
Trip Cost Before Optimization [Turkish Liras]	81.43	108.10	132.94
Trip Cost After Optimization [Turkish Liras]	51.0221	80.5835	103.7456
Fuel Consumption Before Optimization[Liters]	14.5649	19.4146	23.9314
Fuel Consumption After Optimization [Liters]	8.1118	13.5706	17.7161
Reduction in Trip Cost [%]	37.34	25.45	21.96
Reduction in Fuel Consumption [%]	44.29	30.10	25.97

As seen in the Table 6.1 an improvement in terms of fuel consumption reduction and trip cost minimization is achieved. The acquired minimization is up to 44.29% in fuel consumption and 37.34% in total trip cost.

It is a known fact that until a breakthrough in battery chemistry, HEVs are the next best thing humankind can benefit to reduce carbon footprint and minimize fuel consumption. Hence it is inevitable that there will be several new upcoming studies and industrial projects on this subject. So that the aim behind this research is to implement a solid ground on this subject and proceed forward. In the following studies, this research can be elaborated in many ways. For instance along with the simulation, a sample HEV, which is similar to the modelled one, can be run between Istanbul and Ankara and simulation results can be compared to real world measurements. Moreover, a communication interface can be designed so that the driver can select the mode he or she wants to continue his trip as in economical, fast or moderate so that the vehicle can adapt to optimized values and provide such propulsion.

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CURRICULUM VITAE

Name and Surname : Dilara ALBAYRAK SERİN
Place and Date of Birth : ISTANBUL, 23/09/1991
Marital Status : Married
Foreign Languages : English(Advanced)
German(Pre-Intermediate)
Spanish(Beginner)
French(Beginner)
E-mail : dilaraalbayrak@ticaret.edu.tr

Educational Status

Bachelor's Degree : Sabancı University
Faculty of Engineering and Natural Sciences
Mechatronics Engineering, 2013
Master's Degree : Sakarya University
Graduate School Of Natural And Applied Sciences
Department of Industrial Engineering
Engineering Management, 2017

Work Experience

SGS : Automotive Homologation Expert
03.2014-11.2014
Hexagon Studio : Automotive Homologation Engineer
07.2015-12.2015
Istanbul Ticaret University Research Assistant
10.2016-ongoing

Publications

Albayrak Serin, D., Boyacı, A., Özpınar, A., Yarkan, S., (2017), An IEEE 802.11x Implementation for V2X Communications Towards IoT and Big Data, The First International Telecommunications Conference (ITelCon 2017), Istanbul, Turkey, December

Albayrak Serin, D., Yilmaz Yalçiner, A., (2017), Determination of Innovation and Self-Innovativeness Perceptions in Engineers, Fifth International Symposium On Innovative Technologies In Engineering (ISITES 2017), Baku, Azerbaijan, September