SIZING OF A SERIES HYBRID ELECTRIC VEHICLE

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

FUAT REMZICAN ARIKAN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

SEPTEMBER 2019

Approval of the thesis:

SIZING OF A SERIES HYBRID ELECTRIC VEHICLE

submitted by **FUAT REMZICAN ARIKAN** in partial fulfillment of the requirements for the degree of **Master of Science in Electrical and Electronics Engineering Department, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. İlkay Ulusoy
Head of Department, **Electrical and Electronics Eng.**

Prof. Dr. Hulusi Bülent Ertan
Supervisor, **Electrical and Electronics Eng., METU**

Examining Committee Members:

Assist. Prof. Dr. Ozan Keysan
Electrical and Electronics Eng., METU

Prof. Dr. Hulusi Bülent Ertan
Electrical and Electronics Eng., METU

Assoc. Prof. Dr. Murat Göl
Electrical and Electronics Eng., METU

Assist. Prof. Dr. Emine Bostancı
Electrical and Electronics Eng., METU

Prof. Dr. Güngör Bal
Electrical and Electronics Eng., Gazi University

Date: 27.09.2019

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Fuat Remzican Arıkan

Signature:

ABSTRACT

SIZING OF A SERIES HYBRID ELECTRIC VEHICLE

Arıkan, Fuat Remzican
Master of Science, Electrical and Electronics Engineering
Supervisor: Prof. Dr. Hulusi Bülent Ertan

September 2019, 133 pages

The main aim of this work is to investigate whether a cost competitive hybrid electric vehicle can be designed and under what conditions this can be achieved. For this purpose, first a light commercial vehicle is considered. Its model is developed in ADVISOR environment in Matlab and verified by comparing with the official tests of the vehicle, acceleration and NEDC fuel consumption, namely. Following that, electrical components are searched for rating, dimension, weight and cost through the literature and market in order to model the hybrid vehicle. A sizing approach which makes use of the energy and power requirements at the wheel of the conventional vehicle on NEDC cycle is proposed. Using the electrical component models, verified conventional vehicle model and the new sizing approach, a hybrid vehicle is modeled. Hybrid vehicle is found to consume 55% less than the conventional vehicle on NEDC cycle and it accelerates from 0 to 100 kph 36% slower than the conventional vehicle. Hybrid vehicle is heavier than conventional vehicle around 20% and its initial cost is 1.65 times the conventional vehicle. However, with 200 km per day usage, hybrid vehicle is found to overtake conventional vehicle in 2.8 years in terms of total vehicle costs. Running and initial costs of the vehicle are calculated depending on the component ratings to develop a mathematical model for optimization. After executing parameter sensitivity analysis for different cases, Genetic Algorithm optimization process has taken place using the hybrid vehicle model and the cost calculations, to achieve the purpose of developing a cost competitive hybrid electric vehicle from various aspects. Optimization results are found out to be 0.1% close to proposed sizing method results whereas conventional sizing method is 5% close. Proposed method resulted in lower initial cost and 10 years term running costs than the conventional sizing method.

Keywords: Hybrid Electric Vehicles, Series Hybrid Electric Vehicle Modeling, Advisor, Series Hybrid Electric Vehicle Component Sizing, Series Hybrid Electric Vehicle Cost

ÖZ

SERİ HİBRİT ELEKTRİKLİ ARACIN BOYUTLANDIRILMASI

Arıkan, Fuat Remzican
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği
Tez Danışmanı: Prof. Dr. Hulusi Bülent Ertan

Eylül 2019, 133 sayfa

Bu çalışmanın ana hedefi maliyet açısından rekabetçi bir hibrit aracın tasarlanabilirliğinin ve bu rekabetçiliğin hangi koşullarda sağlanabildiğinin araştırılmasıdır. Bu doğrultuda hafif ticari bir araç ele alınmıştır. Bu aracın benzetim modeli ADVISOR ortamında oluşturulup benzetim sonuçları aracın resmi hızlanma ve NEDC yakıt tüketimi testleri ile karşılaştırılarak doğrulanmıştır. Bunu müteakip, aracı modellemek amacıyla literatürde ve piyasada elektrikli araç komponentleri anma gücü, boyut, ağırlık ve maliyet açısından araştırılmıştır. Konvansiyonel aracın NEDC çevirimi üzerinde tekerlerindeki güç ve enerji ihtiyacı kullanılarak yeni bir boyutlandırma metodu geliştirilmiştir. Elektrikli araç komponent modelleri, doğrulanmış konvansiyonel araç modeli ve bu boyutlandırma metodu kullanılarak, hibrit araç modellenmiştir. Bu hibrit araç NEDC çevrimi üzerinde konvansiyonel dizel araçtan %55 daha az yakıt tüketmekte ve %36 daha yavaş 0-100 km/sa hızlanmasını tamamlamaktadır. Hibrit araç %20 daha ağır olup ilk maliyeti konvansiyonel aracın 1.65 katıdır. Ancak günlük 200 km kullanım ile hibrit aracın maliyet açısından konvansiyonel aracı 2.8 senede yakaladığı görülmektedir. Aracın işletme ve ilk maliyetleri elektriksel komponent kapasiteleri kullanılarak hesaplanıp optimizasyon için matematiksel bir model oluşturulmuştur. Farklı parametreler için duyarlılık analizi yapıldıktan sonra farklı maliyet açılarından rekabetçi bir araç oluşturmak amacıyla hibrit araç modeli ve maliyet hesapları kullanılarak Genetik Algoritma ile optimizasyon süreci başlatılmıştır. Optimizasyon sonuçları önerilen boyutlandırma metoduna %0.1 yakınlıkta çıkmış olup, literatürdeki boyutlandırma metodu %5 yakınlıktadır. Önerilen yöntem, ilk maliyet ve 10 yıllık işletme maliyeti açısından literatürde bulunan boyutlandırma yöntemlerinden daha düşüktür.

.

Anahtar Kelimeler: Hibrit Elektrikli Araçlar, Seri Hibrit Elektrikli Araç Modelleme, Advisor, Seri Hibrit Elektrikli Araç Boyutlandırması, Seri Hibrit Elektrikli Araç Maliyeti

To my family,

ACKNOWLEDGEMENTS

I would like to thank to my supervisor Prof. Dr. H. Bülent Ertan for his guidance and advises throughout my thesis.

I dedicate this thesis to the memory of my father Ö. Remzi Arıkan, who is no longer with us but continues to inspire us by his uncommon understanding and intelligence on everything.

I am also grateful to my family, especially to my mom R. Canan Arıkan and to my uncle M. Hakan Binokay for their endless support and deep understanding throughout my entire education life.

Lastly, I would like to thank to my precious love Hande for her great support starting from writing the thesis up until the end of my thesis presentation.

TABLE OF CONTENTS

CHAPTERS

APPENDICES

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

As the petroleum prices increase all around the world, decreasing fuel consumption is getting a more popular issue to be solved. Moreover, vehicle quantity is increasing in an uncontrolled manner so that the environmental concerns are also arising due to exhaust emissions. In order to decrease these problems, Hybrid Electric Vehicle (HEV) is a better solution than all electric vehicle in terms of initial cost and driving range. Hybrid Electric Vehicles (HEVs) make use of the energy through more efficient path i.e. electric and energy losses during braking are recovered. Hence HEVs are more efficient vehicles than the conventional ones.

1.1. Hybrid Electric Vehicle Architectures

Mostly used HEV architectures according to power flow are series, parallel and series-parallel which can be seen in Figure 1.1 [1], [2]. In this figure, parts that are connected mechanically are shown with double line links and electrically are shown with single bold line links. In this figure, E stands for Internal combustion engine (ICE), P is for power converter for dc bus and B is for battery.

Hybrid electric vehicles are also categorized according to the ratio of electric power output to the total output of the power sources available on the vehicle, which is called the hybridization ratio. According to this, vehicles are categorized as micro HEVs, mild HEVs and full HEVs. Micro HEVs have hybridization ratio lower than 5% where a small starter/generator is attached to engine. This starter is used to stop the engine when vehicle stops completely until brake pedal is released. When brake is released, engine is started again. This way, fuel efficiency is increased around 5-10% when compared to non-hybrid models. In Mild HEVs, there is an electric motor assist, up to 10% of engine power, during propulsion. 20-30% of fuel efficiency increase can be achieved in these types when compared to non-hybrid models. Lastly, in Full HEVs, there is a bigger electric motor and battery pack when compared to mild and micro HEVs and hence electric motor can be used as the single source of traction power so that engine can be downsized. Fuel efficiency increase is between 30-50% when compared to non-hybrid vehicles[3]. In this work, HEVs are investigated in terms of power flow paths, i.e. series hybrid, parallel hybrid and series-parallel hybrid vehicles.

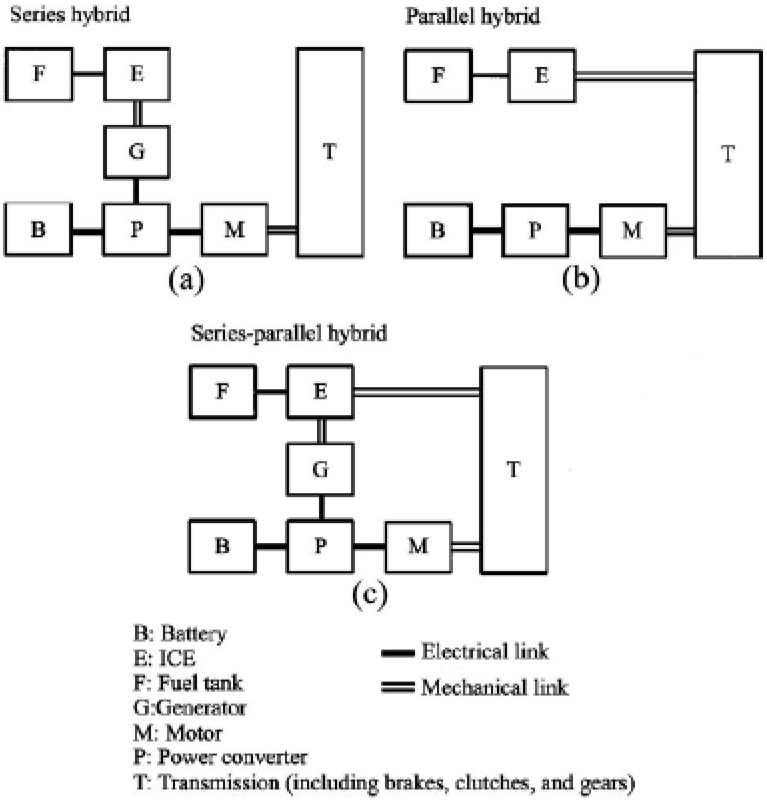


Figure 1.1. Power flow diagrams for different HEV architectures[1]

1.1.1. Series HEVs

In series hybrid electric vehicles, internal combustion engine drives a generator to charge the batteries or drive the electric motors. Electric motors are the only propulsion source for the vehicle and they use the battery plus generator power in order to drive the vehicle. This powerflow is seen in Figure 1.1-a. Regenerative braking also charges the batteries during deceleration.

Operating modes for series HEVs are as follows:

Battery alone mode: Electric motors are powered only by the battery. ICE/Gen set is shut off. This mode is used when battery is at SOC level higher than some pre-defined level.

Combined power mode: When power demand is high, battery and ICE/Gen set powers the electric motors together.

Engine alone mode: During highway driving conditions such as high and constant speed travelling, ICE/Gen set powers the electric motors and battery is nearly unused.

Power split mode: When battery SOC is low and power demand of electric motors are below the maximum power of the ICE, then some part of the ICE/Gen set power is used to recharge the batteries.

Stationary charging mode: Battery is charged via ICE/Gen set even if the vehicle is stationary.

Regenerative braking mode: During deceleration, electric motors are used as generators to store the kinetic energy in batteries.

Series HEVs are advantageous since ICE is decoupled from road so that it can be operated at its most optimum point. More, since electric motors are the only driving source, drivetrain is mostly simplified. Lastly, series HEVs are less complex in terms of both couplings and control algorithms. This leads to easier development and production of the vehicle.

Some disadvantages of series architecture are that the energy is converted twice which lowers the efficiency and electric motors should be able to supply peak torque and power.

1.1.2. Parallel HEVs

In parallel hybrid electric vehicles, internal combustion engine drives the vehicle together with the electric motors. Electric motors may be used as generators to recover the deceleration kinetic energy or absorbing some portion of ICE power to charge the batteries. Electric motors are normally driven by battery energy. This power flow is seen in Figure 1.1-b.

Operating modes for parallel HEVs are as follows:

Motor alone mode: When batteries have sufficient energy and power demand is low, electric motors are powered only by the battery. ICE is shut off.

Combined power mode: When power demand is high, electric motors and ICE drives the vehicle together.

Engine alone mode: During highway driving conditions such as high and constant speed travelling, ICE powers the wheels and battery and electric motors are nearly unused.

Power split mode: When battery SOC is low and power demand of vehicle is below some level, then some part of the ICE power is used to recharge the batteries via the electric motors used as generators.

Stationary charging mode: Battery is charged via ICE without the vehicle being driven.

Regenerative braking mode: During deceleration, electric motors are used as generators to recharge the batteries. In this mode, ICE may be turned on to recharhe the batteries quickly while the electric motors are already in generator mode.

In parallel architecture, having two sources of propulsion is a big advantage especially in military applications since a failure in one of the systems, ICE or electric motors, does not result in an immobile vehicle. Moreover, both ICE and electric motors can be dimensioned below peak torque and power since they can both drive the vehicle at the same time.

Main disadvantage of parallel architecture is that ICE cannot run at its most efficient operating point since it is not totally decoupled from the road. Secondly, both the control algorithm and mechanical coupling between ICE, electric motor and wheels are more complex when compared to series architecture since ICE and electric motors may drive the vehicle at the same time or not.

1.1.3. Series-Parallel HEVs

Series-Parallel HEV architecture can be seen from Figure 1.1-c. In addition to series HEV, engine is also connected to wheels mechanically and in addition to parallel HEV, there is a second electric motor that serves as generator.

This architecture can optimize fuel economy and efficiency since there is more flexible control over components. However, series-parallel HEV architecture is more complex and expensive when compared to other architectures.

There are some other hybrid electric vehicle architectures but they are not to be discussed here as they are not implemented much.

After the comparison between these architectures, series architecture is decided to be the best architecture for light commercial vehicle to be simulated.

1.2. Choice of Drive Type

In this thesis, an economical light commercial hybrid vehicle is intended to be designed. For initial costs to be lowered (especially for first 200 km), this vehicle is designed to be a plug-in vehicle so that it is charged from mains overnight due to the fact that charging the battery from mains is cheaper than using ICE/generator set of the vehicle. Since control algorithms and mechanical design are desired to be simple, series hybrid architecture is chosen.

Advantages of series hybrid electric vehicles are the simple transmission, easy control of engine, operation of the component with worst efficiency (i.e. engine) at its best efficiency point and having a smaller engine. Main disadvantages are higher fuel consumption in highway conditions, more powerful electric motor and battery requirement which increases the cost. As a results, considering simplicity and city drive conditions, series hybrid electric vehicle is found suitable for this work.

As indicated before, in SHEVs an ICE drives a generator to supply the DC bus so that electric motor and energy storage systems are fed through this DC bus. When ICE is off, energy storage system supplies the electric motor. Electric motor is the only source of tractive force. Since this is a plug-in vehicle, it can be charged overnight through the mains in order to reduce fuel consumption during daily use. Electric motor can also be used as generator during braking, called regenerative braking, to charge the batteries. Hence, electric motor driver should allow four quadrant operation for bidirectional power flow and two way rotation. For the vehicle in this thesis, energy storage system consists of battery pack and a supercapacitor bank. Adding supercapacitor gives better charging/discharging efficiency and increases battery lifetime. Moreover, supercapacitor allows more regenerative energy to be captured during braking. Drivers for both should also allow two-way power flow for both charge and discharge cycles. Lastly, between electric motor and wheels, there is a single stage reduction gear to reduce required drive torque and adjust the drive frequency to logical levels.

1.3. Literature Review on Design of Hybrid Vehicles

In literature there are many approaches for sizing of hybrid electric vehicle components. Gao and Ehsani [4] sized series hybrid electric vehicle with battery as the energy storage system. Electric motor of this vehicle is sized according to acceleration and gradeability power requirement and engine/generator unit power is chosen according to cruising power requirement of the vehicle. They have found battery maximum power rating by subtracting generator power from load peak power. Battery energy capacity is calculated by defining an energy/power ratio for the vehicle. Later in their book Ehsani, Gao and Emadi [5] sized battery in terms of capacity by using energy variation of the vehicle on FTP75 drive cycle and desired soc change of the battery.

Chanda [6] have made series and series-parallel plug-in vehicle sizing in his work. He used acceleration power requirement to find electric motor power rating and cruising power requirement to find out engine/generator set power rating. Peak power demand of the vehicle during 0-100 kph acceleration is given to battery power rating. Lastly, power demand of the vehicle while going by 45mph at 1% gradient and 10% drivetrain losses with a driver and passenger is calculated. Then energy required for 40 mile all electric range is found using this power demand. Battery energy capacity has been decided by scaling the required 40 mile all electric range with usable soc.

Mineeshma et al. [7] sized series hybrid electric vehicle with hybrid energy storage system composed of battery and supercapacitors. Firstly, vehicle is simulated on Modified Indian Drive Cycle(MIDC_III) and power and energy requirements of the vehicle on this drive cycle is found. Energy needed for desired range without using regenerative braking is calculated. Then, battery energy capacity needed in order to supply the vehicle short time and continuous power demand without exceeding short time and continuous discharge rates(C) respectively. Maximum of these two energy capacity requirements is taken as the battery energy capacity rating. Supercapacitor energy rating is chosen such that it can shave off the biggest peak in high frequency component of load power demand. Gear ratio is found by considering maximum torque required during acceleration. Electric motor is sized by dividing maximum power demand on the drive cycle by 1.5 which is the 60 seconds short power burst for electric motor. Internal combustion engine generator set power rating is taken as the average power requirement of the drive cycle.

Akli et al. [8] have sized a hybrid locomotive with diesel engine and battery supercapacitor hybrid energy storage system. Firstly, global power mission of typical BB63000 diesel generator in conventional locomotive is gathered and low-pass filter is applied. Engine/generator set is decided to run continuously at average power level of the mission profile which is 200 kW. Hence, diesel generator with 200 kW nominal power rating is replaced with original 600 kW diesel generator. High frequency part of power need is fed to supercapacitor as the power reference and supercapacitor energy capacity is calculated by dividing maximum energy change on this graph by prescribed discharge rate of supercapacitor which is chosen as 0.75 in this study.

Engine/generator set power output is subtracted from low frequency portion of global locomotive power need and fed to battery as the power reference. Lastly, in order to select battery energy capacity rating, energy versus power lines are drawn for charging and discharging regions of battery by imposing related power limits, i.e. 1C for charging and 0.2C for discharging. And using this graph and power&energy requirements in battery mission profile, battery energy capacity is determined. Daily battery cycle is also checked for battery life time.

Bayar et al. [9] have made electric motor sizing for a series-parallel hybrid vehicle. In order to achieve range extension and limited parallel operation the vehicle uses a 1.8L E85 engine which operates with 85% ethanol fuel and 15% gasoline by volume. Power requirement of the vehicle on US06 drive cycle is calculated and peak power rating of electric motor is taken as the maximum power level seen during drive cycle. Continuous power rating of electric motor is decided as 20% above the average power requirement of the vehicle on US06 drive cycle.

Bindu and Thale [10] presented sizing of electric motor and battery-supercapacitor energy storage system for an electric vehicle in their work. The vehicle is simulated on Indian Drive Cycle for 100km. By assuming that 60% of the regenerated energy is captured, energy requirement during 100km Indian drive cycle is calculated as 13.97 kWh. Moreover, peak and average power requirement on the same drive cycle are found to be 22.785 and 3.775 kW, respectively. Then, electric motor continuous power rating is chosen considering drive cycle peak power requirement and 10˚ gradeability maximum power. Battery energy capacity is chosen as the energy difference between required energy and regenerated energy during 100 km Indian drive cycle simulations. Supercapacitors power rating is chosen to supply the difference between peak power requirement of the drive cycle and battery maximum power level limited to 0.9C. Supercapacitors are sized in terms of energy capacity so that they can shave of all of the corresponding peaks above 0.9C battery power.

Porru et al. [11] have sized an electric vehicle hybrid energy storage system composed of battery and supercapacitors. Battery continuous power rating is chosen to be the same as electric motor continuous power rating. In energy capacity sizing, control method played an important role in this work. Speed range of the electric motor is divided into 3 regions. Speed values below 0.8 times the rated speed of electric motor is defined as low speed and values above 2.75 times the rated speed are as high speed. Speed range stays in between is called as mid speed. Then power supply from hybrid storage system is controlled in a different manner such that only supercapacitor supplies the propulsion system in low speed range. In middle speed range, battery increasingly supports supercapacitor. At high speeds, only battery supplies the system. Also, minimum motor voltage is included in calculations. According to all of these, required energy capacities for each component are calculated by simulating the vehicle on a start and stop case.

Table 1.1. Literature review comparisons

People	**Sizing Approach**
Gao and Ehsani (SHEV)	Acceleration and gradeability → Electric motor power Cruising power → Generator power Electric motor power-Generator power → Battery power Max soc change defined in FTP75 drive cycle → Battery energy capacity
Chanda (SHEV)	Acceleration → Electric motor power Cruising power → Engine/Generator set power Peak power demand during 0-100 kph acceleration → Battery power 40 miles all electric range while cruising at 45 mph with 1% slope → Battery energy capacity
Mineeshma et al. (HESS for SHEV)	Vehicle is simulated on Modified Indian Drive Cycle Battery energy capacity is found using continuous and peak C discharge rates SC energy rating is chosen that it can shave of the biggest power peak in high frequency component of load power demand Gear ratio is found using maximum torque during acceleration Peak power demand divided by 1.5 → Electric motor power rating Average power requirement of drive cycle → ICE/Gen set power rating

Table 1.1. Literature review comparisons (continued)

Akli et al. (HESS for hybrid locomotive)	Global power mission of typical BB63000 diesel generator in conventional locomotive is gathered and low-pass filter is applied Average power demand→ ICE/Gen set power Maximum energy change in high frequency power demand divided by 0.75 → Supercapacitor energy capacity Low frequency power demand – ICE/Gen set power→ Battery power rating Maximum 1C discharge at power demand→ Battery energy capacity
Bayar et al. (Electric motor for Series Parallel HEV)	Power requirement on US06 drive cycle → Electric motor peak power rating 20% above the average power demand on cycle → Electric motor continuous power rating
Bindu and Thale (Electric motor and HESS for EV)	Vehicle is simulated on Indian drive cycle for 100 km Assuming 60% of the regenerative braking is captured, energy requirement for 100 km, peak and average power requirements are calculated Drive cycle peak power and 10% gradeability power → Electric motor continuous power rating Peak power requirement – 0.9C battery max power → SC power rating Energy required to shave off all of the peaks above 0.9C battery max power→ SC energy capacity Net energy requirement of the cycle → Battery energy capacity
Porru et al. (HESS for EV)	Battery continuous power rating → Electric motor continuous power rating Vehicle is then simulated on a start-stop case and required energy capacities for battery and supercapacitor is found according to the rules below: - Supercapacitor supplies system at low speed (0.8 times the rated speed of electric motor) - Battery supplies the system at high speed (2.75 times the rated speed of electric motor) - In the middle range, battery increasingly supports supercapacitor.

In Table 1.1, a brief summary for each sizing method found in literature is given. The first method (Gao&Ehsani) is taken as the conventional method and third method (Mineeshma et al.) is the method closest to new sizing method proposed in this work.

1.4. Aim of Thesis

First aim of this thesis is to have a good simulation model of conventional and series hybrid electric vehicle. Second aim is to give an initial and fast sizing approach for the ratings of the main components of a series hybrid electric vehicle in order to buy and operate a light commercial vehicle in the most economical way. This is achieved by using energy usage and regeneration graphs of non-hybrid vehicle and electrical component sizes are decided accordingly.

1.5. Methodology

To have an overall cost optimized hybrid vehicle, first conventional vehicle is modelled and simulated in Matlab ADVISOR environment. Afterwards, this model is validated by comparing announced values and simulation results for NEDC fuel consumption and 0-100 kph acceleration. Then energy usage and regeneration graphs are studied so that electrical component ratings are determined. Moreover, sensitivity analysis is made for these components in order to see optimal points and sensitivity for each variable. Lastly, genetic algorithm based optimization method is applied to see how the new component sizing method results are close the optimum component sizes.

1.6. Thesis Layout

In Chapter 1, hybrid electric vehicles are explained and the drive type choice for this work is indicated. After literature review, aim and methodology of the thesis are explained. In Chapter 2, vehicle simulation methods are explained and vehicle modelling in ADVISOR environment is shown. Lastly in that chapter, reliability of the conventional vehicle model is tested. In Chapter 3, hybrid electric vehicle components are expressed. In Chapter 4, conventional approach and new approach in sizing methodology is explained and both are compared. Sizing of the Fiorino is made in both approaches. In Chapter 6, sensitivity analyses for different vehicle parameters are made and moved on to the optimization in Genetic Algorithm. In Chapter 7, conclusion part takes place with the findings of this work and future works can be done.

CHAPTER 2

PREDICTION OF VEHICLE PERFORMANCE VIA SIMULATION

Vehicles are under influence of very different parameters such as friction (engine, transmission, air, surface), braking and engine torques, requested power and torque, actual power and torque etc. during a drive cycle. In order to design a new vehicle, performance calculations using these parameters should be done and vehicle parameters should be optimized accordingly. These calculations are quite complex to be done by hand. Moreover, without simulations more prototypes must be produced which increases the cost. So, in order to decrease the design cost and man power needed during design process, a vehicle model is needed to make computer aided simulations to predict vehicle performance. With the help of simulation results, desired parameters such as fuel consumption, 0-100 km/h acceleration, top speed, gradeability etc can be optimized and the vehicle sizing to use minimum energy can be accomplished before building expensive prototypes. Sizing the vehicle means; determining the ratings of its components such as ICE, electric motor, generator and battery etc in order to obtain desired performance and fuel consumption levels at the minimum energy use level.

2.1. Simulation Approaches

There are 3 main types of vehicle simulation approaches.

2.1.1. Backward Facing Approach

In this type of approach, simulation takes desired speed trace of the vehicle as input and goes backward to find required torque and speed and then the parameters such as fuel consumption etc. First advantage is that automotive drivetrain is tested using this type of test benches. Secondly, simulating using backward facing approach is faster. However, disadvantage is that there is no input from the driver (such as throttle and brake commands), and engine efficiency maps are designed according to these driver inputs, this type of approach is not very accurate. Moreover, dynamic effects are not included in this type of approach. As last disadvantage, this approach assumes that the vehicle follows the desired speed curve but speed curve may be out of performance abilities of the vehicle such as acceleration, braking or top speed.

2.1.2. Forward Facing Approach

Here, there is a driver model that gives the simulation throttle and brake commands by considering present and desired speed. Then simulation calculates torque and then the new vehicle speed in the chosen time step. With the help of these variables, energy use rate and fuel consumption can be obtained. This type of simulation approach is useful in hardware and control system design since dynamic models can be tested easily. Main disadvantage is that this type of simulation is very slow due to the high order integrations while finding vehicle speed etc.

2.1.3. Hybrid Backward-Forward Facing Approach

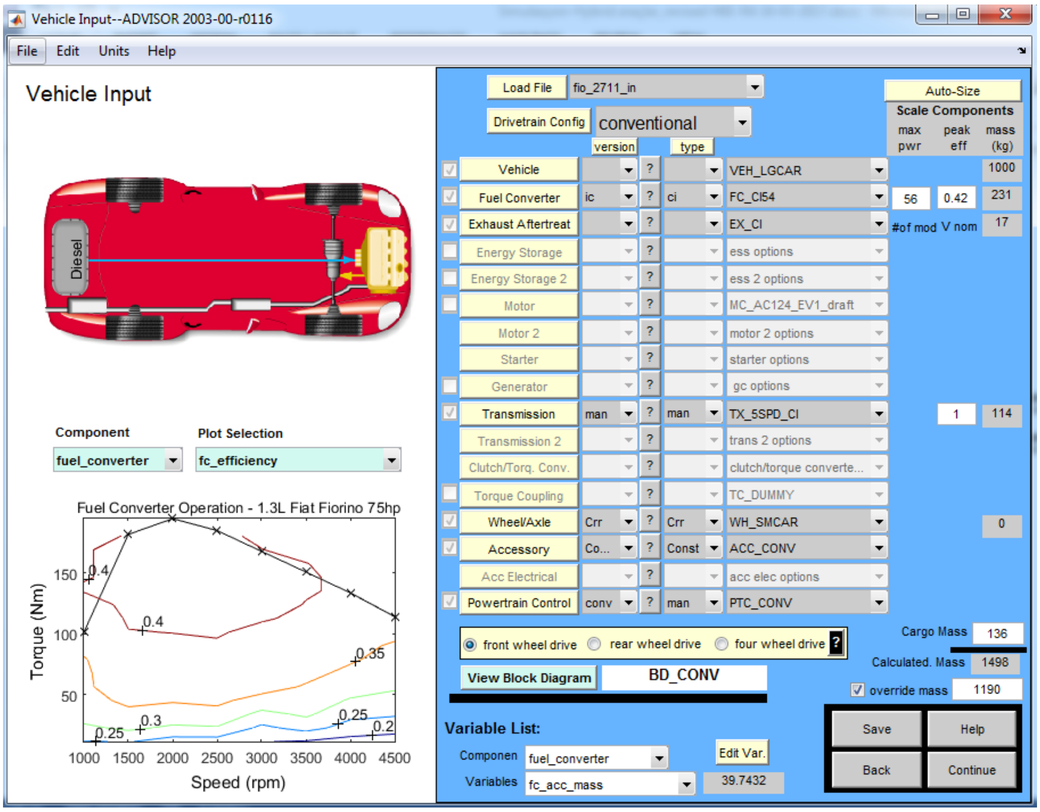
Simulations using this type of approach obtains required powertrain torque from actual and required speed (backward facing part) and available motor torque is transformed into available drivetrain torque using efficiencies and gear ratios of gearbox&final drive in order to gather vehicle’s new speed (forward facing part). Matlab ADVISOR has been chosen as the simulation environment for this thesis since it uses this hybrid approach so it makes a good mixture of simulation speed and accurate results.

Conventional Fiat Fiorino 1.3 Multijet 75 hp is first going to be simulated. If simulation results for fuel consumption and 0-100 km/h acceleration values match the real data, this simulation will be accepted as validated and hybrid Fiorino is going to be defined by taking the validated conventional Fiorino model as base. By the way, properties such as gear shifting will at first be taken to be ADVISOR’s default. Gear is changed according to engine load and vehicle speed which are explained in the powertrain part of the next section. Moreover, acceleration of the vehicle is calculated using the instantenous wheel torque, total instantenous friction on the vehicle and vehicle mass.

For each vehicle simulation, setup is divided into two parts. First part is the modelling of the vehicle and second part is modelling of simulation, both are explained in the succeeding sections.

2.2. Modelling the Vehicle in ADVISOR

In order to create a model for the nonhybrid vehicle, a vehicle with desired components such as engine, powertrain, electrical accessories etc is first created as seen in Figure 2.1 and its properties are defined in an *.m file, “fio_2711_in.m” namely. This file is a text file as seen in Figure 2.2 and it shows Matlab code to use which model for each component. Models for each component are defined in different text files and these text files define the variables for Simulink model which are run by ADVISOR (See Appendix A). While defining these vehicles, the closest models to Fiorino are found in ADVISOR and modified in order to obtain the desired vehicle properties.



Load File: fio_2711_in

Drivetrain Config: conventional

	version	type		mass (kg)
☑ Vehicle			VEH_LGCAR	1000
☑ Fuel Converter	ic	ci	FC_CI54 (56, 0.42)	231
☑ Exhaust Aftertreat			EX_CI	17
☑ Transmission	man	man	TX_5SPD_CI (1)	114
☑ Wheel/Axle	Crr	Crr	WH_SMCAR	0
☑ Accessory	Co...	Const	ACC_CONV	
☑ Powertrain Control	conv	man	PTC_CONV	

● front wheel drive ○ rear wheel drive ○ four wheel drive

BD_CONV

Cargo Mass: 136

Calculated. Mass: 1498

☑ override mass: 1190

Componen: fuel_converter

Variables: fc_acc_mass 39.7432

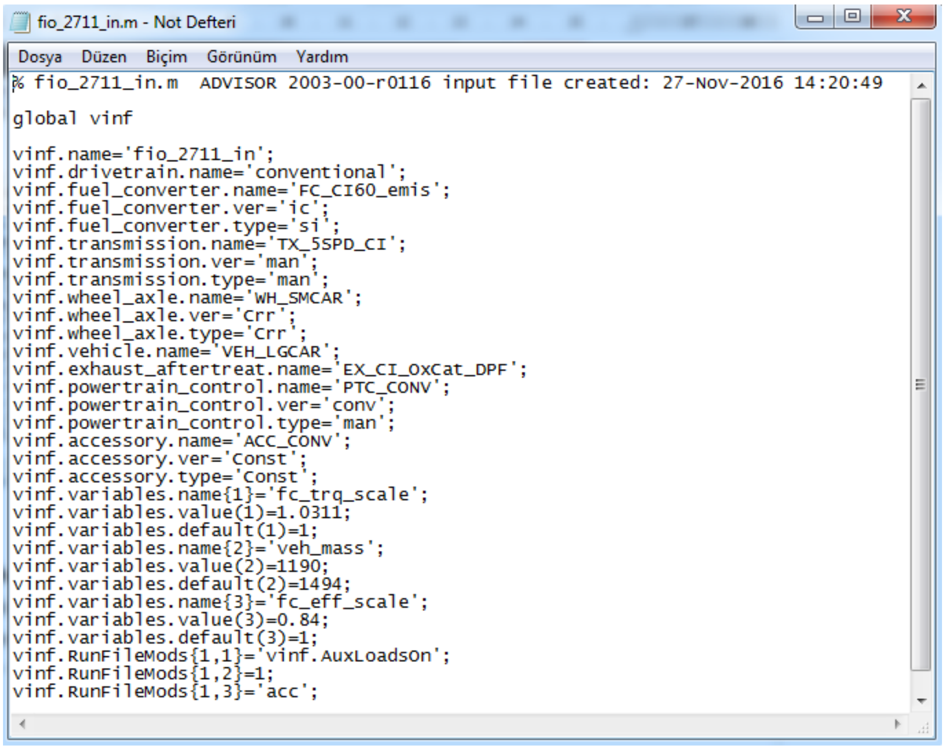
Component: fuel_converter

Plot Selection: fc_efficiency

Figure 2.1. Non-hybrid vehicle main model page

2.2.1. General Properties of the Vehicle

In this part, some physical properties of the Verification vehicle such as weight, frontal area and drag coefficient are adjusted in the chosen m-file VEH_LGCAR.m that can be seen in Vehicle tab in Figure 2.1. For fiat fiorino, mass is defined as 1190 kg, drag coefficient (Cd) as 0.31 and frontal area as 2.04 m^2 in the m-file [12], [13].



```
% fio_2711_in.m  ADVISOR 2003-00-r0116 input file created: 27-Nov-2016 14:20:49

global vinf

vinf.name='fio_2711_in';
vinf.drivetrain.name='conventional';
vinf.fuel_converter.name='FC_CI60_emis';
vinf.fuel_converter.ver='ic';
vinf.fuel_converter.type='si';
vinf.transmission.name='TX_5SPD_CI';
vinf.transmission.ver='man';
vinf.transmission.type='man';
vinf.wheel_axle.name='WH_SMCAR';
vinf.wheel_axle.ver='Crr';
vinf.wheel_axle.type='Crr';
vinf.vehicle.name='VEH_LGCAR';
vinf.exhaust_aftertreat.name='EX_CI_OxCat_DPF';
vinf.powertrain_control.name='PTC_CONV';
vinf.powertrain_control.ver='conv';
vinf.powertrain_control.type='man';
vinf.accessory.name='ACC_CONV';
vinf.accessory.ver='Const';
vinf.accessory.type='Const';
vinf.variables.name{1}='fc_trq_scale';
vinf.variables.value(1)=1.0311;
vinf.variables.default(1)=1;
vinf.variables.name{2}='veh_mass';
vinf.variables.value(2)=1190;
vinf.variables.default(2)=1494;
vinf.variables.name{3}='fc_eff_scale';
vinf.variables.value(3)=0.84;
vinf.variables.default(3)=1;
vinf.RunFileMods{1,1}='vinf.AuxLoadsOn';
vinf.RunFileMods{1,2}=1;
vinf.RunFileMods{1,3}='acc';
```

Figure 2.2. Vehicle main model text file

2.2.2. Engine

Internal structure of the internal combustion engine model is shown in Figure 2.3. In this model, it can easily be seen that requested torque and speed are inputs for ICE and output torque, speed and fuel consumption are outputs found by evaluating the torque and speed at a given instant. These models use some parameters that define them. For example, engine component requires some parameters such as fuel map, maximum power and torque curves, engine displacement, which are all defined in Appendix A.

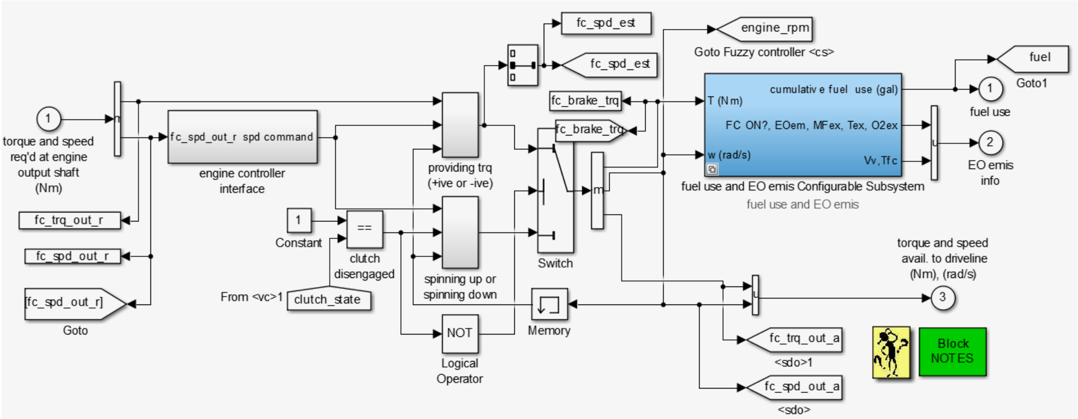


Figure 2.3. Internal combustion engine model in ADVISOR

To simulate Fiat Fiorino's 1.3 multijet engine, FC_CI54 model is chosen and modified in ADVISOR. FC_CI54 is the model for a 54 kW engine with 134 Nm torque rating. These values are very close to Fiorino engine's values which makes it the most suitable model for our purposes. So modifications below are applied to this model in order to obtain a simulation model for 75hp 1.3 Multijet engine. Engine efficiency is determined by the fuel map introduced to the simulation as fc_fuel_map. ICE power is scaled using the fc_pwr_scale variable in the optimization routines.

There are some matrices in the engine m-file used for the vehicle (FC_CI54_emis.m) to define the engine. Modified matrices are fc_fuel_map, fc_fuel_map_cold, fc_max_trq, fc_map_trq and fc_map_spd since the engine is to be examined in terms of acceleration performance and fuel consumption not exhaust emissions etc.

- fc_max_trq shows the maximum torque that the engine produces at a given engine speed value indicated in fc_map_spd matrix. With the help of plot digitizer software [14], these torque values are extracted from the Torque vs Engine Speed curve of Fiat Fiorino in Figure 2.4 [15] by sampling it at the rpm values fc_map_spd shows. By interpolating the digitized values to a curve, Matlab can obtain the maximum torque that can be produced at any rpm value.

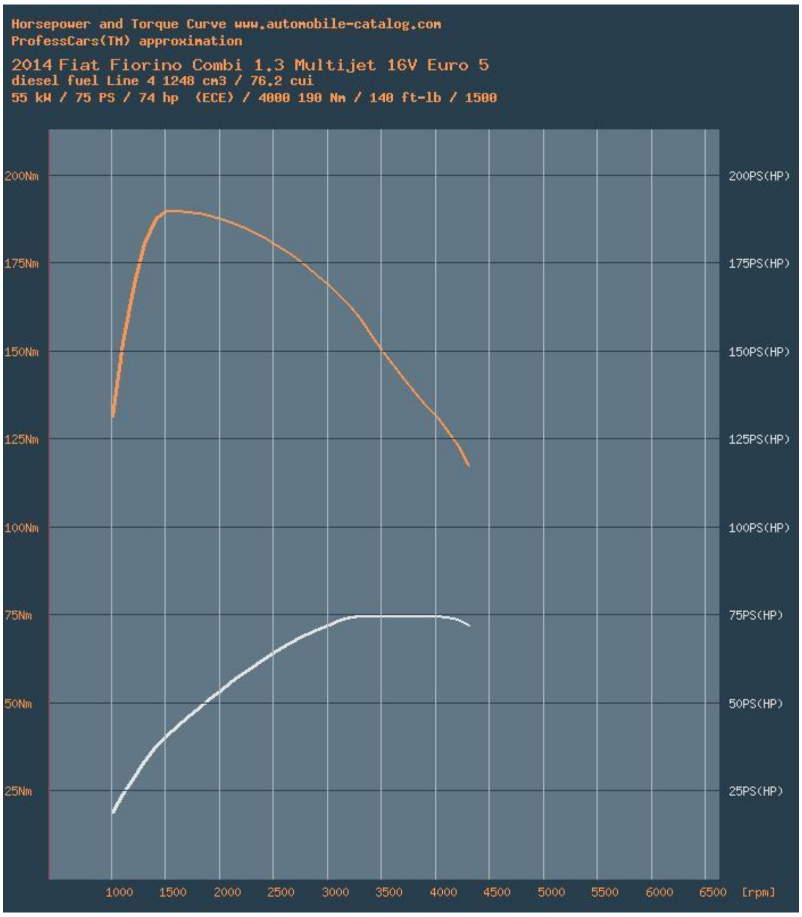
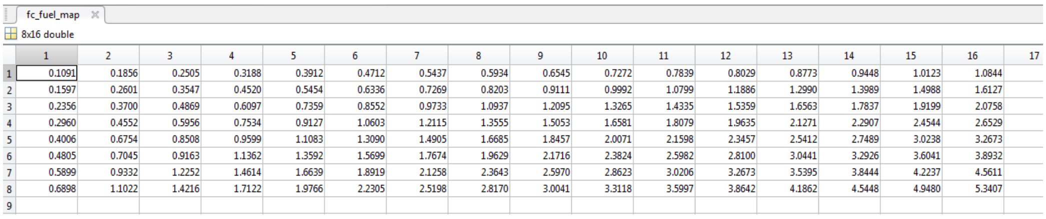


Figure 2.4. Maximum torque and power curves for Fiat 1.3 MJet 75 hp engine[15]

- Fuel maps are the matrices that shows the amount of fuel to be consumed per kWh in order to produce the desired torque at the given rpm. In ADVISOR, there are two fuel map matrices for an engine; one for hot engine conditions and one for cold engine conditions, fc_fuel_map and fc_fuel_map_cold, respectively. For this thesis both matrices are taken to be the same since the main idea here is not to identify hot and cold condition differences. In this manner, Figure 2.5 shows the fuel map matrix defined for Fiat Fiorino 1.3 Multijet 75 hp for both hot and cold engine conditions. This matrix is indexed by fc_map_trq horizontally and by fc_map_spd vertically. This matrice is obtained via digitizing the BSFC map taken from FIAT(See Appendix A).



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.1091	0.1856	0.2505	0.3188	0.3912	0.4712	0.5437	0.5934	0.6545	0.7272	0.7839	0.8029	0.8773	0.9448	1.0123	1.0844	
2	0.1597	0.2601	0.3547	0.4520	0.5454	0.6336	0.7269	0.8203	0.9111	0.9992	1.0799	1.1886	1.2990	1.3989	1.4988	1.6127	
3	0.2356	0.3700	0.4869	0.6097	0.7359	0.8552	0.9733	1.0937	1.2095	1.3265	1.4335	1.5359	1.6563	1.7837	1.9199	2.0758	
4	0.2960	0.4552	0.5956	0.7534	0.9127	1.0603	1.2115	1.3555	1.5053	1.6581	1.8079	1.9635	2.1271	2.2907	2.4544	2.6529	
5	0.4006	0.6754	0.8508	0.9599	1.1083	1.3090	1.4905	1.6685	1.8457	2.0071	2.1598	2.3457	2.5412	2.7489	3.0238	3.2673	
6	0.4805	0.7045	0.9163	1.1362	1.3592	1.5699	1.7674	1.9629	2.1716	2.3824	2.5982	2.8100	3.0441	3.2926	3.6041	3.8932	
7	0.5899	0.9332	1.2252	1.4614	1.6639	1.8919	2.1258	2.3643	2.5970	2.8623	3.0206	3.2673	3.5395	3.8444	4.2237	4.5611	
8	0.6898	1.1022	1.4216	1.7122	1.9766	2.2305	2.5198	2.8170	3.0041	3.3118	3.5997	3.8642	4.1862	4.5448	4.9480	5.3407	
9																	

Figure 2.5. Hot engine fuel map matrix for Fiat Fiorino 1.3 Multijet 75 hp

- Lastly in the engine description part, engine displacement (fc_disp) is changed to 1.25 and maximum power is scaled to 56 kW (75 hp) using the fc_trq_scale parameter since predefined engine model (FC_CI54_emis) has maximum power output of 50 kW.

2.2.3. Powertrain

TX_5SPD_CI is selected as the transmission model and modified for Fiat Fiorino. In this m-file, gearbox ratios including the final gear are defined as [13.93 7.96 5.2 3.67 2.74] which are the drivetrain ratios from engine to wheel for Fiat Fiorino [15].

Moreover, as a powertrain controller model PTC_CONV which is the simplest 5 speed conventional powertrain control is chosen and modified for gear change points. Gear is changed during simulation according to two parameters, engine load and vehicle speed. Gear change for gear 1 due to engine load is adjusted via gb_gear1_dnshift_load and gb_gear1_upshift_load matrices for downshift and upshift, respectively. For simplicity, each gear change is adjusted to be made at the same engine load percentage, 30% for 1 gear upshift, 60% for 1 gear downshift and 90% for 2 gears downshift. Engine torque is divided by the max torque that can be produced at that rpm and the result is compared to the value given by the matrices above. If the result is bigger than downshift matrix value, then gear is shifted down. If it is smaller than the upshift matrix value, then gear is shifted up. How many gears will be shifted up or down is defined by the index of the comparison matrix i.e.

gb_gear1_dnshift_load or gb_gear1_upshift_load. Secondly, gear change due to vehicle speed is defined by the two matrices, tx_spd_dep_upshift and tx_spd_dep_dnshift namely. Via these matrices, each gear number has vehicle speed interval defined in m/s. If engine load is at an appropriate interval, then gears are changed with respect to vehicle speed.

Lastly, modification in wheel/axle model for small cars, WH_SMCAR, is made to define the wheel radius that simulation uses for vehicle speed calculation. For Fiorino, 185/65R15 tyre size is used [16]. Let the tyre size be indicated as X/YRZ where X is base width of tyre in mm, Y is tyre profile in percent and Z is rim diameter in inches as shown in Figure 2.6 [17].

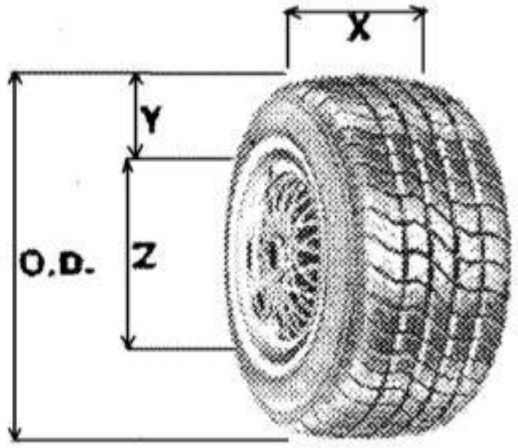


Figure 2.6. Tyre size indicators for X/YRZ tyre dimension[17]

For Fiorino case X=185, Y=65 and Z=15 so tyre radius is calculated as 0.311m according to the formula below and inserted in wh_radius variable.

$$radius = \frac{X * Y/100}{1000} + \frac{Z * 2.54}{200} \quad (meters) \tag{2.1}$$

2.2.4. Electrical accessories

In order to simulate NEDC test conditions, accessory loads are taken as zero. This is due to the fact that OEM tries to reach the lowest fuel consumption in NEDC test. Hence OEM “cheats” by removing all accessory loads from the engine, even the alternator [18]. Hence, electrical accessory load which is the parameter responsible for the losses due to electrical devices working on the vehicle was defined as 0 W in the chosen accessory file, ACC_CONV.m. However, since power dissipated for heating and cooling is not small, it should be taken into account in future simulations.

Simulation part of the non-hybrid Fiorino is explained in validation part. Modelling of hybrid vehicle components such as motor, ICE/Gen set, energy storage are explained in the simulation of hybrid electric vehicle chapter.

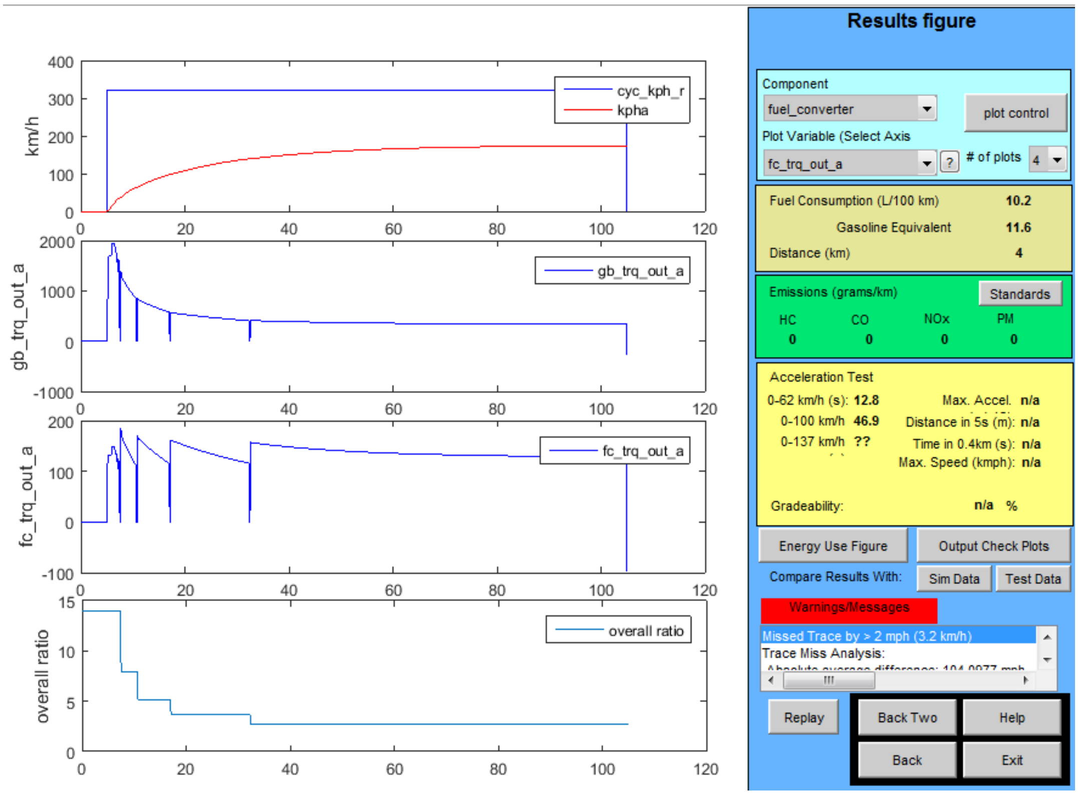
2.3. Reliability of the Conventional Vehicle Model

Simulation model and environment should be validated. In other words, the non-hybrid model to be hybridized should be a good model of the vehicle which gives the same or close results to the real-world values. Approach used here is that the 0-100 kph acceleration and average fuel consumption of the conventional Fiorino has been simulated and results are compared to the real-world values announced by FIAT. Since these two parameters generally change in different directions, simulation is accepted as valid if both are close to real world values.

Validation simulation has two parts, first is the acceleration test for 0-100 kph and second part is the fuel consumption test which is chosen to be NEDC according to Regulation (EC) No 715/2007 of the European Parliament and of the Council (See Appendix B).

2.4. Results of the Conventional Vehicle Simulation

In the first part, acceleration test, 300km/h is given as desired velocity input to the simulation model of the vehicle and simulation calculates the times for predefined speed intervals in mph. This is the default method that ADVISOR uses to calculate acceleration characteristics of the vehicle. Maximum speed defined in the simulator is given as the input to vehicle to see what it can do to reach that speed, i.e. max acceleration conditions. As it can be seen from Figure 2.7, 0-62.2 mph (0-100 km/h) acceleration for the test model is simulated to be 12.8 seconds which is 2.4% close to the value announced by ProfessCars (12.5 seconds) [19]. In the acceleration part of the figure, note that values are given in mph although kph is written as their units.



Component: fuel_converter
Plot Variable (Select Axis: fc_trq_out_a
# of plots: 4

Fuel Consumption (L/100 km) 10.2
Gasoline Equivalent 11.6
Distance (km) 4

Emissions (grams/km)

HC	CO	NOx	PM
0	0	0	0

Acceleration Test
0-62 km/h (s): 12.8
0-100 km/h 46.9
0-137 km/h ??
Max. Accel. n/a
Distance in 5s (m): n/a
Time in 0.4km (s): n/a
Max. Speed (kmph): n/a
Gradeability: n/a %

Compare Results With:

Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:

Figure 2.7. 0-100 km/h acceleration test result for Fiat Fiorino 75 hp

As the second part of the simulation for the validation of the nonhybrid Fiorino model, NEDC fuel consumption test is executed. NEDC test, The New European Driving Cycle test, is used for EU type approvals of emissions and fuel consumption for light duty vehicles. As it can be seen from Figure 2.8, there are 5 segments in NEDC testing procedure, 4 Urban Driving Cycles(UDC) and 1 Extra Urban Driving Cycle(EUDC) namely. UDC represents city driving conditions and EUDC represents aggressive high-speed driving conditions. See Appendix B for further details.

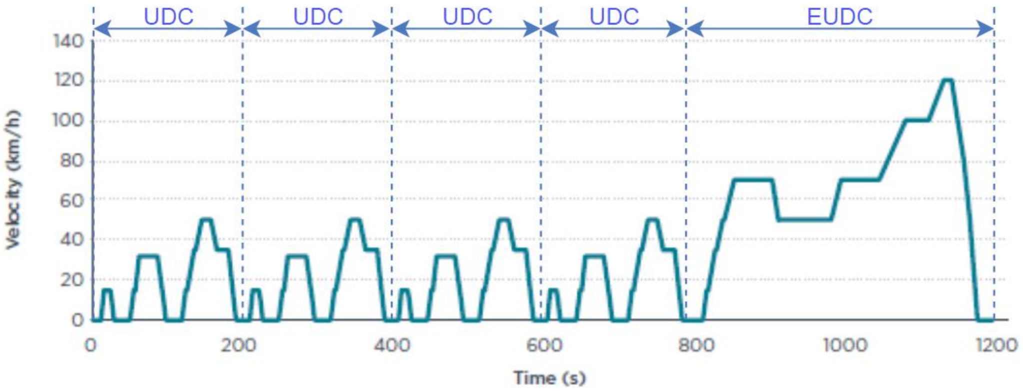
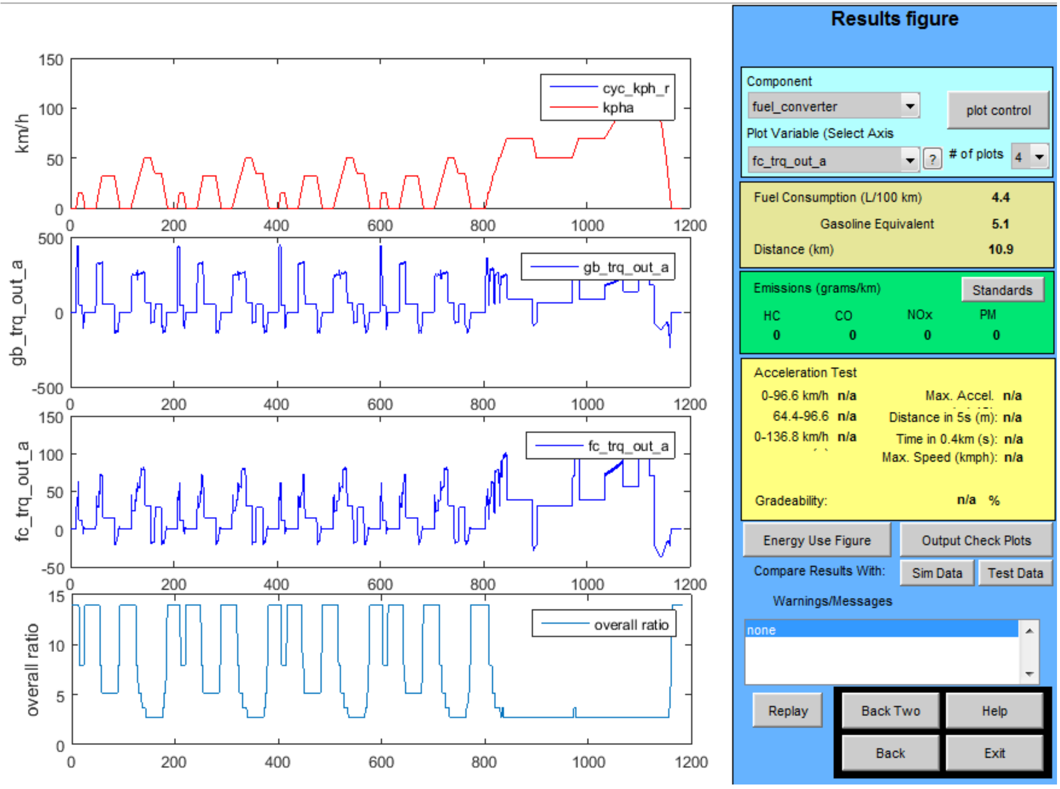


Figure 2.8. *Drive cycle for NEDC test*

Fuel consumption test is run on NEDC cycle, which is explained above, results can be seen in Figure 2.9. NEDC fuel consumption is found to be 4.4 l/100km in simulation, which is exactly same with the NEDC fuel consumption value announced by Fiat (4.4 l/100 km) [20].



Results figure

Component: fuel_converter

Plot Variable (Select Axis: fc_trq_out_a

\# of plots: 4

Fuel Consumption (L/100 km) 4.4

Gasoline Equivalent 5.1

Distance (km) 10.9

Emissions (grams/km)

HC	CO	NOx	PM
0	0	0	0

Acceleration Test

0-96.6 km/h n/a

64.4-96.6 n/a

0-136.8 km/h n/a

Max. Accel. n/a

Distance in 5s (m): n/a

Time in 0.4km (s): n/a

Max. Speed (kmph): n/a

Gradeability: n/a %

Compare Results With:

Warnings/Messages

none

Figure 2.9. NEDC Fuel consumption simulation of Fiat Fiorino 1.3 MJet 75 hp

Real values and simulation results for 0-100 km/h acceleration and fuel consumption of Fiat Fiorino 1.3 Mjet 75 hp diesel are tabulated in Table 2.1.

Table 2.1. Simulation results to real values comparison

	0-100 kph acceleration (seconds)	NEDC Fuel Consumption (L/100km)
Announced Value	12.5 [19]	4.4 [20]
Simulation result	12.8	4.4

2.5. Comments

As seen from Table 2.1 above, the difference between simulation results and the real data are acceptable. There is no difference between simulated and announced fuel consumption values. Difference between 0-100 kph acceleration values for real and simulated cases is 2.4%, which is quite acceptable. So, this small difference show that this simulation model for conventional vehicle can be accepted as valid and will be used to build hybrid vehicle model onwards.

The difference in acceleration time may arise from the fact that maximum torque curve in the simulation stay lower than the curves announced by FIAT for Fiorino (See Appendix A).

CHAPTER 3

HYBRID VEHICLE COMPONENTS

In this chapter, main hybrid electric vehicle components are studied. As it can be seen from Figure 3.1, there is a generator, converters, electric motor, energy storage system and charger as extra to the conventional vehicle. There is a smaller ICE when compared to conventional vehicle and a single reduction gear insted of a multi-speed transmission.

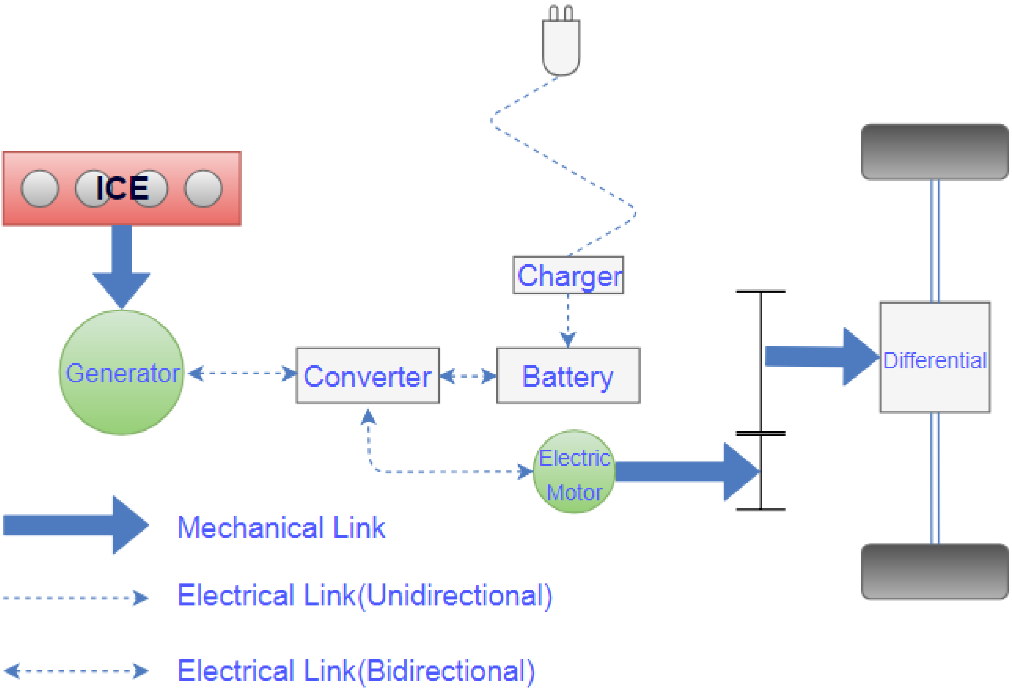


Figure 3.1. Series Plug-in Hybrid Vehicle power flow diagram

3.1. Energy Storage System (ESS)

Energy storage system in an HEV is battery only or hybrid systems. Second one generally refers to a storage system with batteries and supercapacitors. Throughout this chapter, batteries, supercapacitors and hybrid energy storage systems composed of batteries and supercapacitors will be studied.

3.1.1. Batteries

In this part, battery types, costs and aging are to be discussed. By combining the properties and costs, most optimized battery is going to be chosen for the Series HEV application.

There are some main terms defining the battery characteristics. These terms are specific energy, specific power, Depth of Discharge (DOD) and State of Charge (SOC).

- Capacity(C)

Capacity of a battery shows the amount of energy can be supplied before getting fully discharged. SI unit for capacity is coulomb, but generally Ampere-hour (1Ah = 3600C) is used. A 20Ah battery can supply 20A for 1 hour, 10A for 2 hours. Moreover, if this battery is said to be able to discharge at a discharge rate of 2C then it can be discharged at 40A and will be fully discharged in 30 minutes [1].

- Specific Energy

Specific energy is a measure of the amount of the energy that can be stored per unit mass of the battery. SI unit of specific energy is Wh/kg. For the same energy capacity, a battery with higher specific energy will be lighter than the one with lower specific energy.

- Specific Power

Specific power shows the power that can be drawn per unit mass of the battery.SI unit for specific power is W/kg.

- Depth of Discharge (DOD)

Depth of discharge is the discharged percentage of the battery. Discharging 80% of the battery is regarded as deep discharge and discharging beyond this point lowers the cyclelife of the battery drastically. Moreover, in order not to damage the battery, it should not be discharged to zero voltage. Voltage level called cut-off voltage is defined for each battery which shows the 100% DOD point and when this voltage level is reached, discharging should be stopped [1].

- State of Charge (SOC)

SOC is the remaining capacity of a battery after discharging. Typically, battery SOC is maintained between 20-95% depending on the application. In hybrid vehicles lower depth discharges are made to maintain good battery life whereas in all electric vehicles higher depth of discharge levels are used to have better vehicle range.

SOC is measured from the battery voltage. For example in 12V battery, at 100% SOC level battery voltage is 12.6V and at 0% SOC voltage drops near 10.5V [1].

3.1.1.1. Battery Types

There are 3 battery types that are used commonly in Hybrid Electric Vehicles, Lead-Acid, Lithium-Ion (Li-Ion) and Nickel Metal Hydride (NiMH), namely [5], [21]–[23]. Advantages and disadvantages of these types are to be discussed and chemical properties are excluded since this is out of the scope of this thesis.

- **Lead-Acid Batteries**

Their lower cost, higher power capacities and mature technology that allows less unexpected errors makes lead-acid batteries eligible. However, low energy density of this type and poor temperature characteristics (below 10°C specific energy and specific power reduces too much) are the disadvantageous sides for lead-acid batteries. Low energy density leads to heavier battery pack at the same energy capacity and poor efficiency at low temperatures makes the battery impractical for HEV use.

Cell voltage for Lead-Acid batteries is 2V and allows 50% DOD with around 1000 cycles of lifetime [24], [25]. Another problem in using Lead-Acid batteries is that this type of batteries diminish in energy when higher currents are drawn. For example the energy capacity of a Lead-Acid battery is given higher for 1C discharge rate and lower for 2C discharge rate.

- **Li-Ion Batteries**

High specific energy and power, low self-discharge and absence of memory effect are the main advantages of Li-Ion batteries but there are some disadvantages of this type of batteries such as overheating problem during recharging, high internal resistance and decreasing capacity with increasing temperature. Cell voltage of Li-Ion batteries is 3.6V.

Li-Ion batteries generally have 1000-10000 cycles of lifetime and higher DOD such as 80%. This type of batteries can also be discharged at higher rates than 1C without any decrease in the total battery capacity [25], [26]. With higher than 90% efficiency, Li-Ion batteries have the highes maximum efficiency among battery types [24]. Hence, Li-Ion batteries are the most common battery type used in electric vehicles.

- **NiMH Batteries**

High specific energy and power ratings and flatter discharge voltage profile (nearly constant voltage during discharge) make NiMH batteries eligible to be used in hybrid electric cars. This battery type is also environment friendly. In other words, there is no toxic material included in the battery. There are some important disadvantages of NiMH batteries such that high cost, overheating during charging, memory effect and higher self-discharge. Moreover, depth of discharge dramatically affects lifecycle of NiMH batteries. This problem can be overcome by controlling SOC and stabilizing it to a proper range in hybrid vehicles. Lastly, NiMH batteries can be reconditioned if any degradation in the battery performance occurs [27].

Cell voltage is 1.2V for NiMH batteries and lifetime of 500-3000 cycles is achievable. For this type of batteries, efficiency is lower than Li-Ion batteries, around 75% [24].

In Table 3.1 [1], [5], [22], [23], [28]–[33], general properties are compared for Lead-Acid, Li-Ion and NiMH batteries. As it can be seen from the table, Li-Ion battery would be the best choice for HEV without accounting for the initial cost.

Table 3.1. *General comparison of battery types*

Type	Wh/kg	W/kg	Cyclelife*
Lead-Acid	25-35	385	400-1000
Li-Ion	25-155	50-1600	300-4000
NiMH	45-75	465-770	1500

*Under the condition that DOD≥70

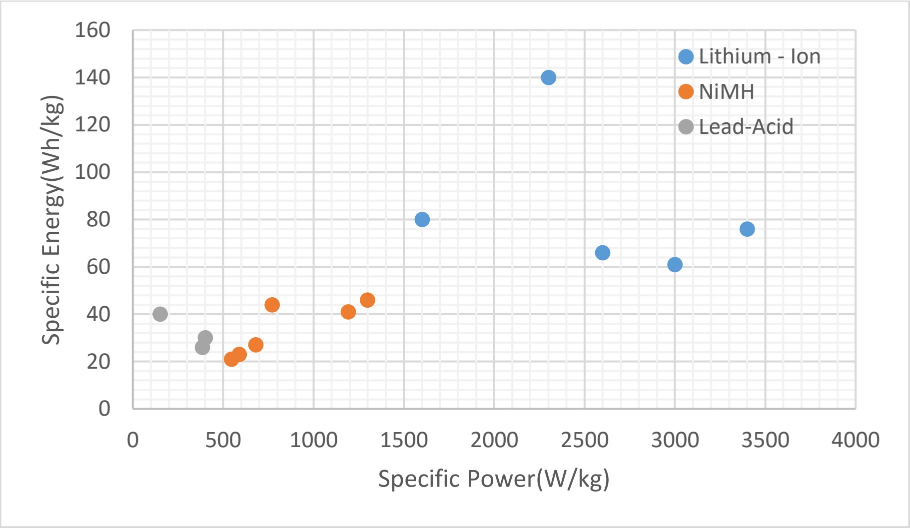


Figure 3.2. Specific Power and Energy Datas for some batteries from the literature and market

In Figure 3.2, the specific power and energy distribution for the 3 types of the batteries mentioned above are seen. These datas are collected from both literature and market. From this figure, it can be concluded that Li-Ion batteries have the best performance in terms of both specific energy and power, and Lead-Acid is the worst one.

In Table 3.2, battery brands, types and specific energies for some of the car manufacturers in HEV market are seen. Common attitude is in the direction of using Li-Ion batteries as it can be concluded from the table.

Table 3.2. *Batteries used by some HEV manufacturers*

Vehicle	**Battery Manufacturer**	**Battery Type**	**Specific energy(Wh/kg)**
Toyota Prius [34], [35]	Primearth EV Energy Co	NiMH	46
Tesla Model 3 [36], [37]	Panasonic	Li-Ion	156
Renault Fluence Z.E. & Nissan Leaf [38], [39]	AESC & NEC	Li-Ion	128
BMW i3 [40], [41]	Samsung	Li-Ion	190
Hyundai Sonata Hybrid [42]	LG Chem	Li-Ion Polymer	75

3.1.1.2. Battery Costs

Battery prices in the market are taken from some Chinese battery suppliers and tabulated in Table 3.3. Using this table, battery cost is to be calculated and optimized.

Table 3.3. *Battery prices from the market*

Type	**Voltage (V)**	**Capacity (Ah)**	**Max/Continuous Discharge Current(A)**	**Price($)**	**Specific Energy (Wh/kg)**	**Wh/$**
NiMH [43]	7.2	6.5	97.5/6.5	45	45	1
Li-polymer [44]	48	160	240/80	5180	25	1.5
LiFePO4 [45]	12	100	350/100	400	85	3
Li-Ion [46]	48	10	20/10	130	96	3.7
LiFePO4 [47]	3.3	20	400/100	25	132	2.6
LiFePO4 [48]	3.2	80	400/240	52	128	4.9
Li-Ion [49]	96	100	500/100	4460	109	2.2
NiMH [50]	7.2	10	-/100	48	57	1.5
Lead Acid [51]	6	200	1000/200	130	33	9

As it can be seen from Table 3.3, Lead-acid battery is the cheapest, Lithium based batteries are second cheapest and NiMH batteries are the expensive ones in terms of specific energy.

3.1.1.3. Battery Aging

Batteries complete their life spans in two ways. First one is the calendar aging which is the capacity loss as the time passes during storage or usage. This type of aging is related to the material of the battery and the temperature & SOC level that the battery is stored at. Calendar aging effect cannot be reduced by changing vehicle control strategy and parameters, only the battery temperature and max SOC level can be controlled to reduce calendar aging effect. Second one is the cycle aging in which the capacity loss caused by the charge-discharge cycles characteristics. This type of aging speeds up dramatically as DOD increases. To decrease the cycle life aging effect, battery DOD should be kept as low as possible. Precisely, HEV battery SOC should be kept between 30-80% to reduce the electrical stress and lengthen the battery life [52], [53].

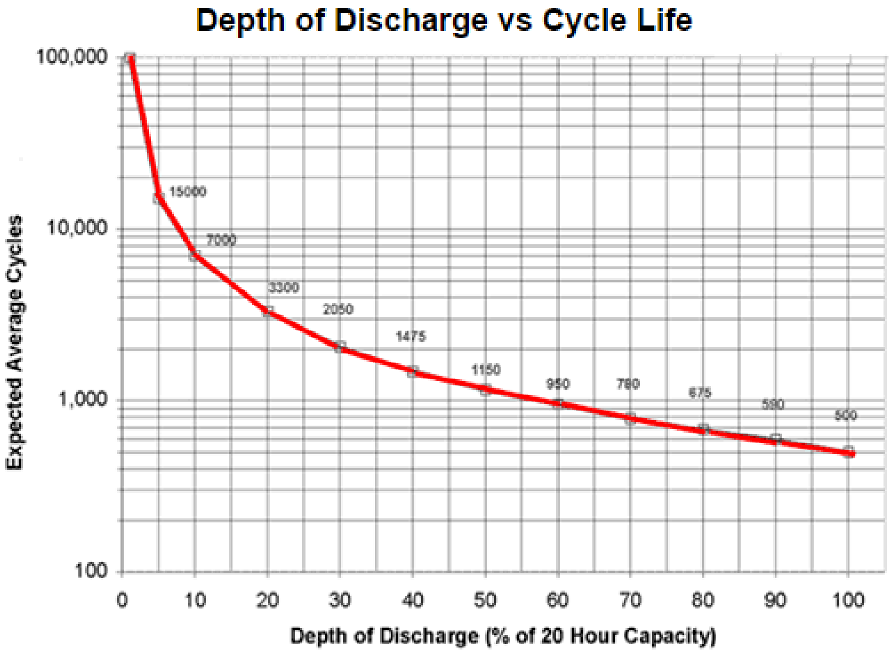


Figure 3.3. Expected Average Life Cycles and DOD for a Li-Ion battery [54]

As it can be seen from Figure 3.3, cycle life for the battery decreases as the DOD increases. For example, if battery is used at 20% DOD, then the expected cycle life is 3300 cycles which means that this battery can be charged and discharged between 40-60% SOC 3300 times. After this point, battery nominal capacity falls below 80% of its initial capacity. When the DOD level is increased to 70%, then the expected cycle life decreases to 780. However, decreasing DOD increases ICE operation time in order to charge the batteries in a series HEV. As a result, an optimization between fuel consumption and battery cycle life should be made here.

According to a test conducted by the US Department of Energy's FreedomCAR and Vehicle Technologies Program (FCVT) in 2006, battery aging in hybrid vehicles affects the fuel economy only slightly. This test included 2 Honda Civic, 2 Honda Insight and 2 Toyota Prius for 256000 km according to SAE J1634 standards (Electric Vehicle Energy Consumption and Range Test Procedure). All of these vehicles have NiMH batteries as the energy storage unit [55]–[57]. In Figure 3.4, battery capacities for new and used test vehicles are shown. As it can be obtained from the figure, battery capacities for Honda Civic, Honda Insight and Toyota Prius are faded to 68%, 85% and 39% of the original rated capacities, respectively. Despite the fade in battery capacities, fuel economy of Honda Insight is decreased by 1.2mpg (increased by 0.12 l/100km) and that of Toyota Prius is decreased by 3.2mpg (increased by 0.33 l/100km) [53].

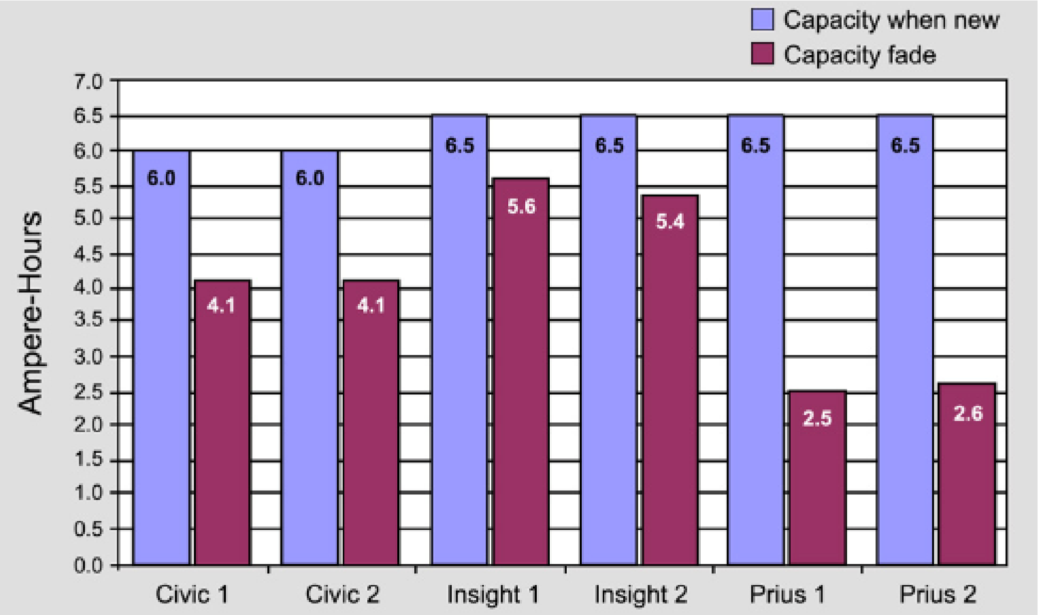


Figure 3.4. HEV battery capacities before and after the test[53]

3.1.2. Supercapacitors

Supercapacitors are the high capacity capacitors with lower voltage values. Structure of a supercapacitor is different from an electrolytic or ceramic capacitor. There is no dielectric material, instead there is an electrical double layer formed between the solid(electrode) and liquid(electrolyte) after being charged, as it can be seen from Figure 3.5. This electrical double layer is formed with physical placement of ions with the help of the activated carbon coatings on the collectors. Hence, there is no chemical reaction for discharge, which leads to greater lifetime compared to batteries. Fine pores on the activated carbon results in highly increased surface area of electrodes so that a lot more charge can be stored than the conventional electrolytic or ceramic capacitors, very high capacitance values may be reached. The separator in between prevents two oppositely charged electrodes to touch each other [58], [59].

This type of capacitors fall in the gap between electrolytic capacitors and batteries in terms of power and energy.

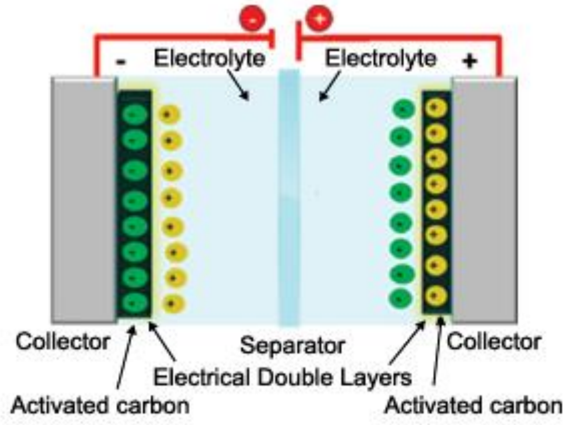


Figure 3.5. Structure of supercapacitors[58], [59]

Supercapacitors have some advantages over batteries such that:

- High lifecycle decreases the number of replacements so life time cost is decreased
- High cycle efficiency decreases the energy lost during charging and recharging
- High power density lets load draw high currents for short bursts
- Fast charging allows capturing more energy during regenrative braking
- Very low degradation in performance so that performance stay same during lifetime

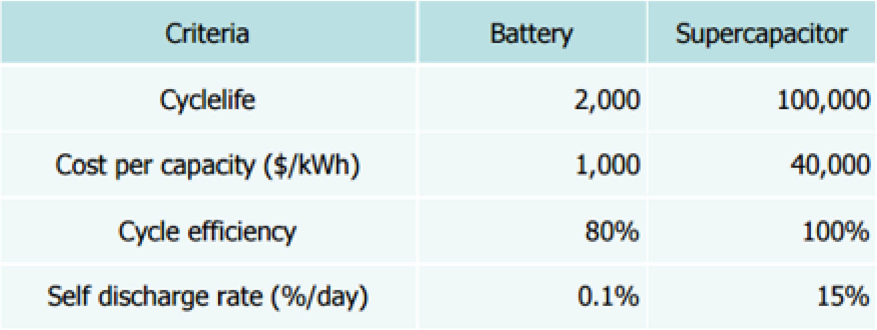
Main disadvantages of supercapacitors may be sorted as follows:

- High initial cost
- High self-discharge limits the use of supercapacitor during cycle
- Low energy density limits the duration of current supply to load
- High voltage variation makes the control harder, generally a converter is needed

3.1.2.1. Comparison with batteries

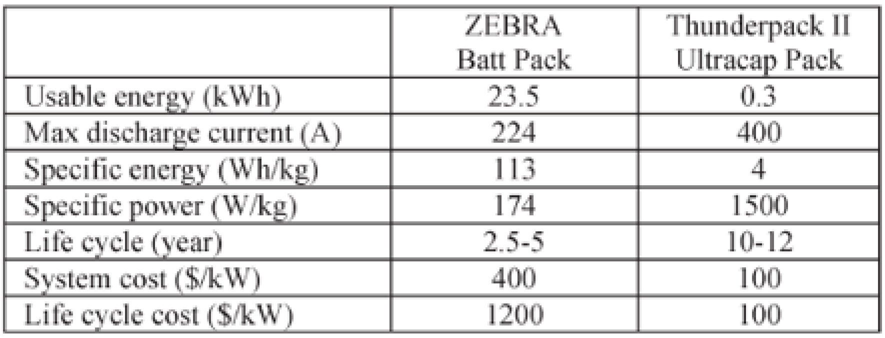
In Table 3.4, batteries and supercapacitors are compared in terms of cycle life, cost, efficiency and self discharge rate [60]. As it can be seen from the table, using supercapacitors alone as the energy storage unit in a hybrid vehicle is not very advantageous. However, when Table 3.5 is examined, it can be concluded that specific energy of batteries and specific power of supercapacitors is higher. If one manages supplying the load from battery for low currents of longer periods and from supercapacitor for high currents during short bursts, hybrid energy storage system would be a better choice. Here, $/kW rating of battery seems higher than supercapacitor. This is due to the higher power rating of the supercapacitors over batteries.

Table 3.4. *Battery and Supercapacitor comparison*[60]



Criteria	Battery	Supercapacitor
Cyclelife	2,000	100,000
Cost per capacity ($/kWh)	1,000	40,000
Cycle efficiency	80%	100%
Self discharge rate (%/day)	0.1%	15%

Table 3.5. *Battery and Supercapacitor comparison*



	ZEBRA Batt Pack	Thunderpack II Ultracap Pack
Usable energy (kWh)	23.5	0.3
Max discharge current (A)	224	400
Specific energy (Wh/kg)	113	4
Specific power (W/kg)	174	1500
Life cycle (year)	2.5-5	10-12
System cost ($/kW)	400	100
Life cycle cost ($/kW)	1200	100

3.1.3. Hybrid Energy Storage System (HESS)

Battery packs are the most utilized energy storage systems in electric and hybrid cars. However, as the improvements are made in the supercapacitor industry, they are getting more involved in hybrid cars especially together with the battery packs. Energy storage configuration having both the supercapacitors and battery packs is called hybrid energy storage system.

Main idea of putting batteries and supercapacitors together to form an ess for a hybrid car is making a system with higher efficiency and performance. Since battery only systems are not able to deliver high power in short times, battery capacity is also determined by the power requirement of the overall system. However, if the high power demands are supplied by the supercapacitors, only energy requirement will be a restriction for the battery size which makes the battery pack smaller. As a result, if average energy requirement of the drive cycle is low but there are some power peaks during the drive cycle of the vehicle, battery only system may increase the energy storage system size too much. Adding a small sized supercapacitor bank would shave these power peaks leading to a smaller size of battery pack which decreases battery cost and weight. Moreover, since the higher frequency components of load current is diverted to supercapacitor bank, life of the batteries would be extended [61].

3.1.3.1. Connection topologies

There are 3 main connection topologies for the hybrid ESS as seen from Figure 3.6 [62]. Passive hybrid, active hybrid with low voltage batteries and high voltage supercapacitors and active hybrid with low voltage ultracapacitors and high voltage batteries are shown in Figure 3.6-a, Figure 3.6-b and Figure 3.6-c respectively.

With the connection in Figure 3.6-a, load current division is made passively, i.e. with respect to internal resistances of supercapacitor and battery so this connection lacks the control on load current division. In this type, there is no voltage converter in the connection between battery and capacitor bank. Moreover, rapidly changing voltage of dc bus affects battery and inverter, causing some harmonics and hence electrical stress on them.

Connection in Figure 3.6-b requires high voltage supercapacitors making the system more expensive. There is a converter between battery and supercapacitor bank to boost lower battery pack voltage to higher supercapacitor bank. Another problem in this system is the frequently changing voltage of the supercapacitor bank is directly connected to electric motor inverter as in the previous case.

Hence, the best choice is the one in Figure 3.6-c since it regulates the changing voltage of supercapacitor and connects to DC bus, letting supercapacitor voltage to drop to lower values so that more energy can be extracted from the supercapacitor, using the converter in between. Moreover, load current division can be made actively using this converter. However, there will be the drawback of increased losses and current limitation imposed by the converter. Main advantage of this system is that slowly changing voltage source is directly connected to motor inverter and fast changing one which is the supercapacitor bank is connected with a converter.

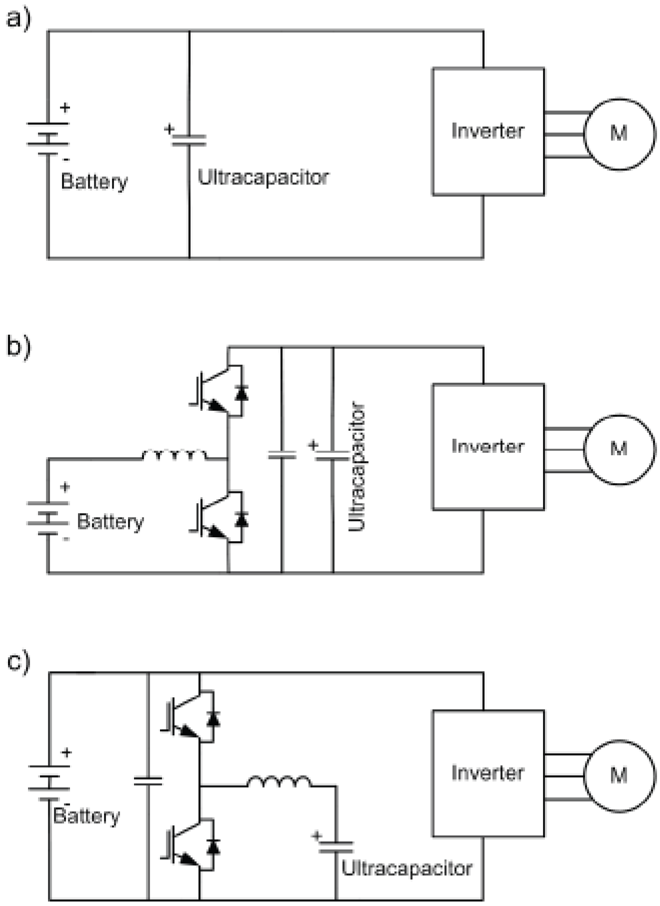
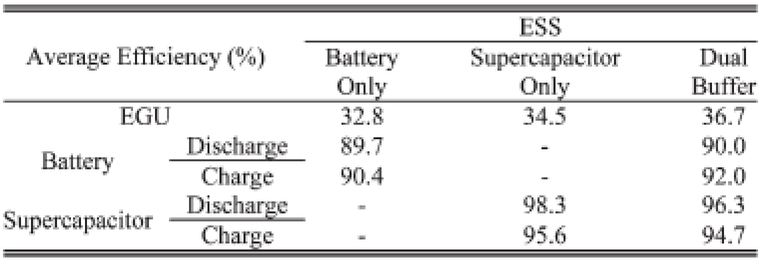


Figure 3.6. Different connection topologies for hybrid energy storage system[62]

3.1.3.2. Control

The main idea in controlling the hybrid ESS is to divert the high frequency components of load current to supercapacitor and low frequency components to battery. In other words, average power will be supplied by the battery and power peaks will be shaved by the supercapacitor. Since current variations hence electrical stress on the battery is reduced, its lifecycle will be improved. Moreover, overall efficiency of both energy storage unit and engine generator unit (EGU) increases since supercapacitors have better charging and discharging efficiencies as it can be seen from Table 3.6 [63], [64].

Table 3.6. *Average efficiencies for battery, supercapacitor and hybrid ESS*[63], [64]



Average Efficiency (%)		ESS		
		Battery Only	Supercapacitor Only	Dual Buffer
EGU		32.8	34.5	36.7
Battery	Discharge	89.7	-	90.0
	Charge	90.4	-	92.0
Supercapacitor	Discharge	-	98.3	96.3
	Charge	-	95.6	94.7

Supercapacitor is generally charged during regenerative braking or at the moments of low power demand.

3.1.3.3. Hybrid energy storage system components

Supercapacitor and battery properties are given in Table 3.7 and Table 3.8 [65], [66].

Table 3.7. *Maxwell K2 series BCAP3000 2.7V 3000F supercapacitor properties*[65][66]

Energy	3.04Wh
Maximum Continuous Current and temperature rise	130A_{RMS} at 15°C 210A_{RMS} at 40°C
Mass	0.51kg
Lifecycle	1000000 cycles
Cost	160$ for lot of 4
Specific Power	5.9kW/kg
Volumetric Energy	7.6 Wh/L

Table 3.8. *Li-Ion battery properties* [46]

Specific Energy	96W/kg
Maximum Specific Power	960W/5kg (30 seconds)
Continuous Specific Power	480W/5kg
Cost	26$/kg
Volumetric Energy	100 Wh/L

Main idea behind the hybrid energy storage systems is that battery supplies the average power during the drive cycle and supercapacitor shaves the peaks over this value and gets recharged with regenerative brakes or using battery energy during low power demands. Hence in this case, supercapacitor is sized to shave the biggest peak which occurs between 1071 – 1130 s during NEDC drive cycle. During this period, battery also works at maximum power for a short duration of time. At that peak, 295Wh of total energy storage system energy is required as calculated using the NEDC power requirement graph seen in Figure 3.7. More detailed analysis and comparison of HESS and battery only ESS will be made in sizing chapter.

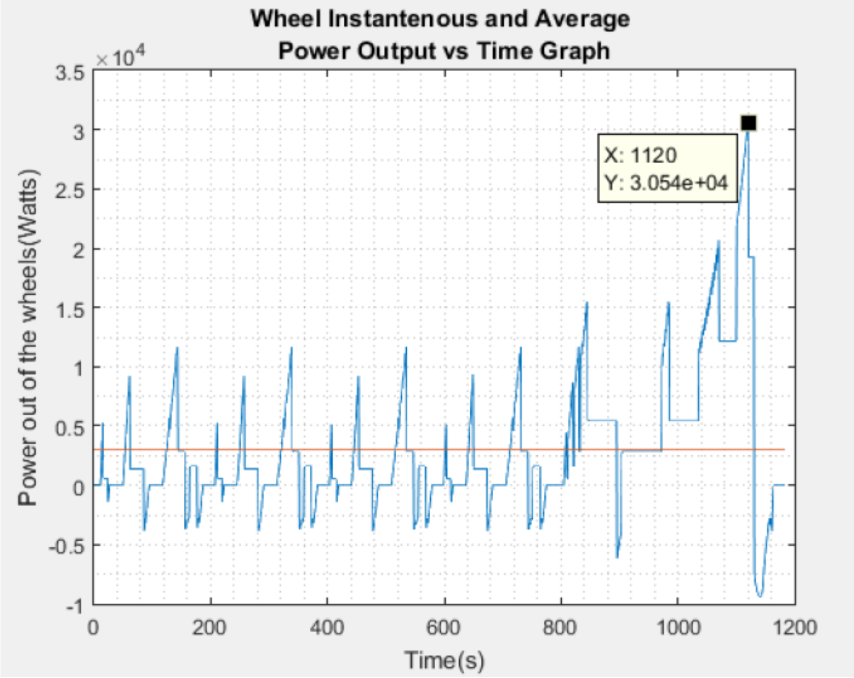


Figure 3.7. NEDC drive cycle power requirement for Fiorino

Hybridization of a battery pack might increase the cost and mass of the system slightly but there are some advantages such as increased overall storage system efficiency due to higher charging and discharging efficiency of supercapacitors. As an another advantage of HESS, battery life is increased since electrical stress on the batteries is reduced by supplying high frequency current through supercapacitors. However, control algorithm will be more complex in hybrid ESS case.

3.2. Electric Motor

There are mainly 3 types of electric motors used in the HEVs. These are Permanent Magnet (Synchronous or Brushless) Motors, Induction Motors and Switched Reluctance Motors. In this part, electric motors are examined in terms of torque and power density, speed range for constant torque and power operations, efficiency, reliability, robustness and cost.

3.2.1. Electric Motor Types for HEV

- **Permanent Magnet Machines**

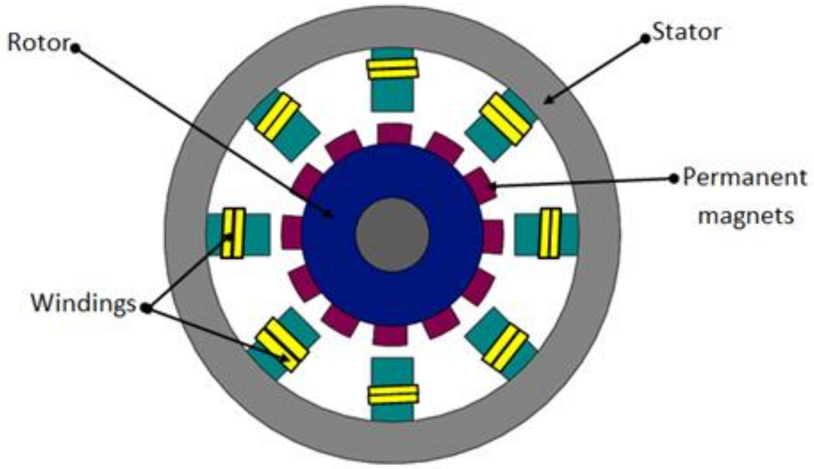


Figure 3.8. Synchronous AC motor[67]

Since there is a permanent magnet structure in Synchronous AC motors as seen in Figure 3.8, efficiency is high due to absence of rotor excitation current. Moreover, this type of motors present high torque and high power density and torque control is simpler. However, main disadvantage of this motor type is that constant power range is short due to limited field weakening capability. More, stator back emf at high speeds might be very high and inverter should be able to withstand this voltage level. This increases the inverter cost [67].

As an example, Toyota Prius and Honda Civic hybrid has PM motors in their hybrid drivetrains.

Table 3.9. *Advantages and Disadvantages of PM Machines*[67]

Advantages	**Disadvantages**
High Power and Torque Density	More Expensive
Simpler Control	Low Thermal Robustness
High Efficiency	Sensitive to Vibration
Fast Response	Low constant power speed range

- **Induction Machines**

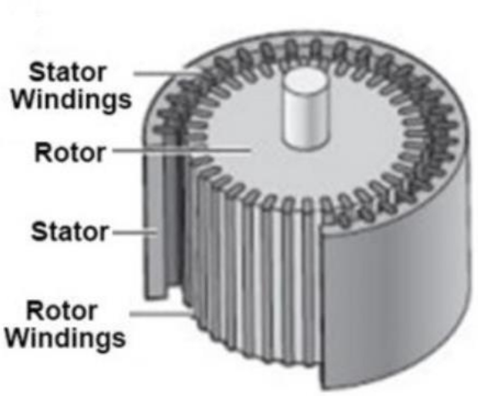


Figure 3.9. Induction Machine[68]

Induction Machines -also known as Asynchronous Machines- have very wide variety of use due to their simple and robust design (Figure 3.9). IM has high speed range and no back emf to deal with. Moreover, by field weakening, speed range can be extended. Field Oriented Control makes an IM behave like a DC machine. Efficiency of IM is lower than PM machine due to rotor excitation making the machine bigger than a PM machine at the same power and speed ratings. IMs are used in electric cars such as GM EV-1 and Tesla Roadster [67], [69].

Table 3.10. *Advantages and Disadvantages of IMs*[67], [69]

Advantages	**Disadvantages**
Speed range extension	Lower power density
Simpler design	
Low cost	
Safe and robust	Difficult control
Low maintenance need	

- **Switched Reluctance Motors**

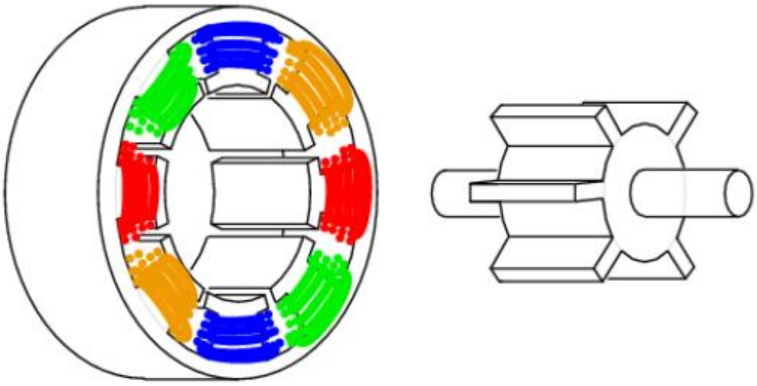


Figure 3.10. Switch Reluctance Motor[67], [69]

As seen from Figure 3.10, there are no windings or magnets on the rotor of Switched Reluctance Motor, making it very temperature stable and high speed motor. This type of electric motors uses the change of inductance between stator and rotor as the working principle. Inductance for a phase is maximum when a stator and rotor pole is aligned, minimum when not. The rotor is rotated by running a current through the winding of a stator pole as one of the rotor poles is aligning and increasing the inductance [67], [69].

Cost of these motors are normally very low but increasing rotor tolerance makes it more expensive. Peak torque capability is limited since stator is easily saturated by the flux. Although its properties such as simple control, rugged design, thermal stability, safe and extremely high speed operation makes SRM a good choice for HEVs, it has not been a preferred choice for a mass production vehicle up to now.

Table 3.11. *Advantages and Disadvantages of SRMs*

Advantages	**Disadvantages**
Low Cost	Risk of erratic torque output
Simple design	Noise
Robust and stable	Low peak torque density

General properties of electric motors used in HEVs are summarized in Table 3.12 [67], [69]. According to this table, Induction machine is a good choice for this work, considering cost.

Table 3.12. *Comparison of electric motor types used in HEVs*

	PMSM	**IM**	**SRM**
Weight and Volume	Good	Bad	Medium
Efficiency	Good	Medium	Medium
Robustness	Medium	Good	Good
Cost	Bad	Good	Medium
Torque Density	Good	Medium	Bad

CHAPTER 4

SIZING OF THE HYBRID VEHICLE COMPONENTS

4.1. Conventional Approach

In this part, ratings for hybrid Fiorino main components such as hybrid energy storage system, electric motor, ICE/gen set etc have been determined using the conventional sizing methods found in literature up to now [5], [6], [9].

In order to execute sizing formulas, some vehicle parameters for Fiat Fiorino 1.3 Multijet 75 hp are needed. In Table 4.1, main parameters are shown (See Appendix A).

Table 4.1. *Fiat Fiorino main vehicle parameters*[70]

Drag Coefficient(C_d)	0.31
Rolling Resistance(f_r)	0.01
Frontal Area(f_A)	2.04m^2
Wheel Radius	0.31 m
Air Density(ρ_a)	1.202kg/m^3

Moreover some vehicle performance parameters and component properties should be defined for an initial design of the hybrid vehicle, shown in Table 4.2. Note that efficiency values are taken from ADVISOR models.

Table 4.2. *Design parameters*

Mass(with hybrid components)	1450kg
Maximum SOC level for battery	0.7
Minimum SOC level for battery	0.3
0-100 Acceleration	17s
Top Speed	150kph
Transmission Efficiency(η_t)	97%
Motor Drive Efficiency(η_m)	90%
Battery Efficiency(η_{bat})	92%
Generator Efficiency(η_{gen})	96%

Mass is chosen as 1450 kg considering the mass increase due to hybrid components and mass decrease due to reduced ICE and transmission. This mass is used during initial sizing and subject to change with respect to hybrid component ratings during optimization. 0-100 acceleration and top speed values are determined according to average daily car use. Transmission efficiency is a general 1-speed transmission efficiency.

Electric motor rating is found from power requirement at the desired acceleration rate, generator rating from power requirement at top speed and battery energy capacity from energy use at the desired range. Battery power is directly found by subtracting generator power from motor power consumption [5], [9].

4.1.1. Calculation of Electric Motor Rating

$$P_{motor} = \frac{\delta M}{2t_a}\left(V_f^2 + V_b^2\right) + \frac{2}{3}Mgf_rV_f + \frac{1}{5}\rho_a C_d f_A V_f^3 \qquad (4.1)$$

Here, in electric motor power formula (P_{motor}), δ stands for vehicle mass factor (1.01 generally), M is for mass in kg, V_f and V_b are for final and initial speeds for acceleration calculation in m/s, f_r is rolling resistance, ρ_a is air density in kg/m^3, C_d is drag coefficient, f_A is frontal area of the vehicle in m^2 and t_a is desired acceleration time in seconds.

Using this formula, desired parameters and general vehicle properties, traction motor size is calculated to be 39 kW. This is the peak power requirement since it is used during acceleration period which is under 20 seconds. Thus, taking overtorque capability of the motor as 1.4 continuous power rating can be chosen as $\frac{39}{1.4} = 27.9\ kW$.

4.1.2. Calculation of Generator Rating

$$P_{e/g} = \frac{V_{max}}{1000\eta_t\eta_m}\left(Mgf_r + \frac{1}{2}\rho_a C_d f_A V_{max}^2\right) \tag{4.2}$$

In this equation, V_{max} stands for top speed in m/s, remaining are the same with previous formula and Table 4.1 and Table 4.2. Using all of these parameters, generator size is calculated as 38.3 kW.

4.1.3. Calculation of ESS Ratings

$$P_{ESS} = \frac{P_{motor}}{\eta_m} - P_{e/g} \tag{4.3}$$

In Equation 4.3, P_{ESS} stands for energy storage system power rating, P_{motor} for electric motor power rating and $P_{e/g}$ for engine generator set power output rating.

Calculating this, HESS total power is found to be 5 kW.

And,

$$C_{Ah} = \frac{1000K_{ev}S_{bat}}{K_{SOC}V_{bus}} \tag{4.4}$$

Where K_{ev} is average energy consumption per km (0.155kWh/km for a similar car on NEDC) [71], K_{SOC} is discharge coefficient (0.4), V_{bus} is DC bus voltage (300V), S_{bat} is the electric only range for the vehicle. If only electric range is taken to be 70km, C_{Ah} = 90.4 Ah. This makes 27.1 kWh at 300V DC bus voltage.

4.1.4. Calculation of Gear ratio

$$i_g = \frac{\pi n_{m,max} r}{30 V_{max}} \tag{4.5}$$

i_g is the gear ratio for 1-speed transmission, $n_{m,max}$ is maximum motor rpm, r is wheel radius in m and V_{max} is the top speed of the vehicle in m/s.

For Fiorino, gear ratio of 4.675 is calculated considering maximum electric motor speed as 6000 rpm, top speed as 150m/s and original tyre size.

To summarize, hybrid Fiorino with the properties in Table 4.3 is the result of the conventional sizing method.

Table 4.3. *Determined ratings for Hybrid Fiorino simulation via conventional approach*

Motor Power	27.9 kW
ICE/Gen Power	38.3 kW
Battery Power	5 kW
Battery Capacity	27.1 kWh
Gear Ratio	4.675

4.2. Proposed Approach

In the new approach, it is intended to size the main electrical components in a more accurate manner using the energy graphs through the drive cycles. In other words, after making the energy calculations of the non-hybrid vehicle that is running through the pre-defined drive cycle (NEDC cycle), obtaining closer values to the optimization results for electrical component sizes when compared to the conventional method is aimed. This results from the nature of the electrical components such as electric motor which can reach maximum power of up to 2-3 times of its continuous power for short bursts. More, energy algebra is done according to the gained energy from braking, required energy to drive the electric motors and energy supplied by the ICE/Gen set. Efficiency of the energy flow path for each component is also taken into account. After all these steps, obtained component ratings are to be optimized, new approach is only intended to give closer values to the optimized ones.

To make first decisions on motor, ICE/generator and battery power ratings, power analysis of non-hybrid Fiorino on NEDC cycle should be made. Only mass of this vehicle is changed to expected hybrid vehicle mass(1450 kg) for power and energy compatibility. For this purpose, Figure 3.7 is used.

4.2.1. Calculation of Electric Motor Rating

The traction motor should be able to provide both the DC power (average tractive power) requirement and also the maximum power requirement during the driving cycle. Maximum power requirement for the test vehicle is 30kW as seen from Figure 3.7 while accelerating to 120 kph top speed of NEDC cycle at around 1100th second of the test.

It is well known that commercial traction motors may have maximum/continuous power ratio of around 1.5 for 30 seconds. This ratio is taken as 1.4 for this work, to be on the safe side. So, motor continuous power can be chosen as $\frac{30kW}{1.4} = 21.4\ kW$.

4.2.2. Calculation of Generator Rating

ICE/Gen set maximum power is chosen to be the continuous (average) power of the electric motor since generator is intended to drive the electric motor through long highway cruising. In other words, ICE is the main component that makes the battery stay at the same SOC at the end of the drive cycle. Then ICE/generator pair should be able to supply average power used by the motor during the work cycle to energy storage system, which is 21.4 kW found in previous part 4.2.1. However, using efficiency value of generator in Table 4.2;

$$ICE\ power\ output = \frac{21.4}{\eta_{gen}} = 22.3kW \tag{4.6}$$

Original Fiat Fiorino engine shown in Figure 0.1 is scaled to 5 different maximum power ratings as 18, 25, 30, 35 and 45 kW. Efficiency maps for each are shown in Figure 4.1 - Figure 4.5. Here it is seen that the maximum power point and most efficient operating points are different. It can be inferred from the figures that most efficient operating point is at a narrow band around 2000 rpms for each. Maximum torque that can be reached at the most efficient operating point and resulting ICE power outputs are tabulated in Table 4.4. Since the ICE/gen set is desired to run as efficient as possible, then ICE sizing should be made according to most efficient operating point rather than its rated power.

Table 4.4. *Fiorino ICEs scaled to different rated power levels and corresponding operating points*

ICE rated power	**Maximum torque in most efficient region**	**Maximum power in most efficient region**
56 kW	168 Nm	35.2 kW
45 kW	136 Nm	28.5 kW
35 kW	106 Nm	22.2 kW
30 kW	90 Nm	18.8 kW
25 kW	75 Nm	15.7 kW
18 kW	54 Nm	11.3 kW

Generator output is desired to meet average power of electric motor, 21.4kW. ICE rating is selected as 35 kW in order to have most efficient operating point around 22.3kW, as it is interpolated from the datas shown in Table 4.4.

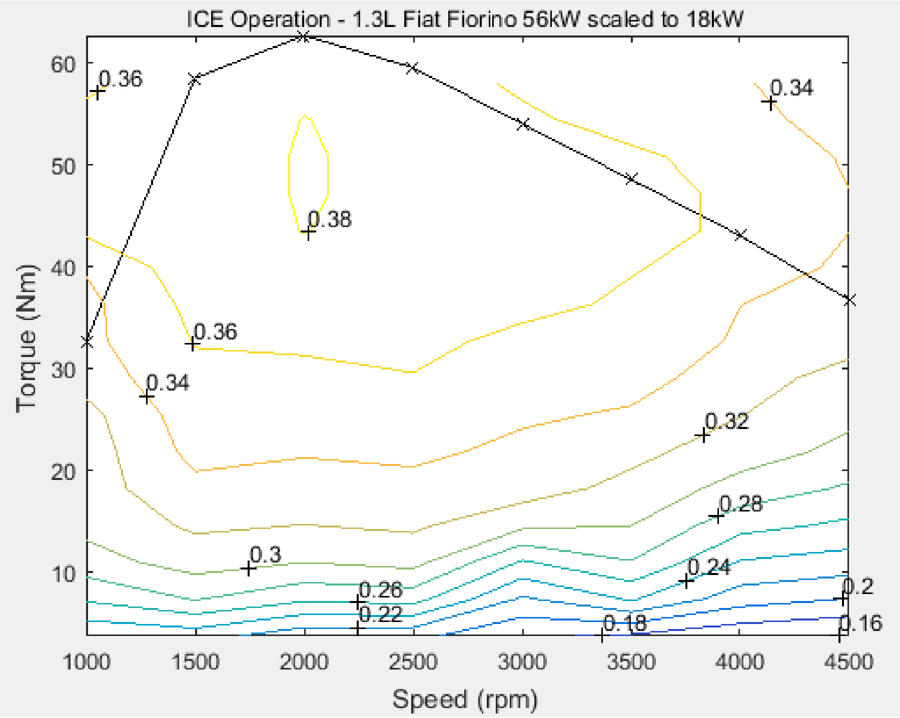


Figure 4.1. Efficiency map for 1.3L 56kW(75hp) ICE scaled to 18kW

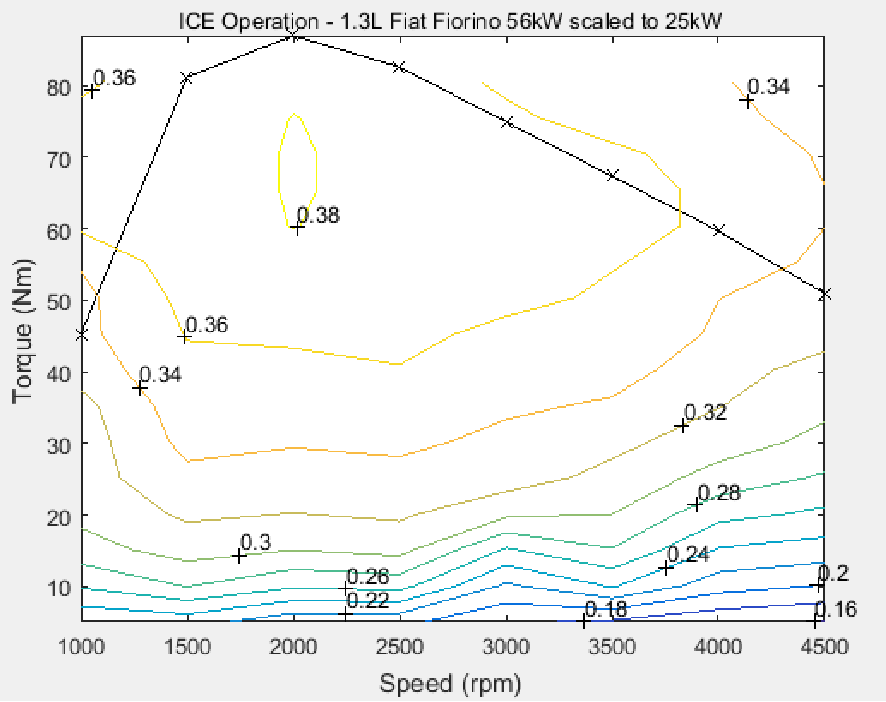


Figure 4.2. Efficiency map for 1.3L 56kW(75hp) ICE scaled to 25kW

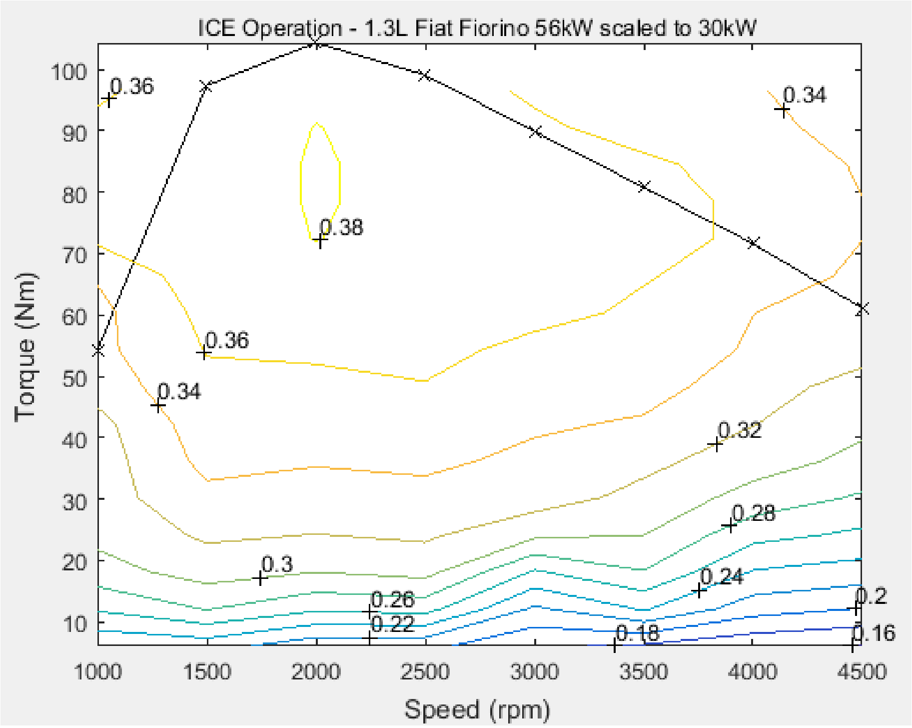


Figure 4.3. Efficiency map for 1.3L 56kW(75hp) ICE scaled to 30kW

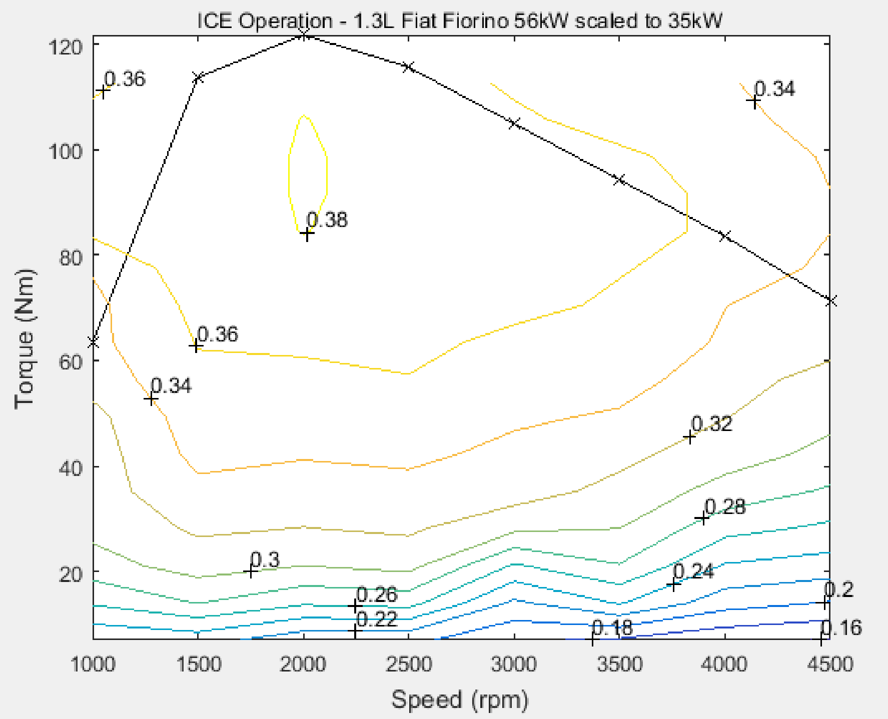


Figure 4.4. Efficiency map for 1.3L 56kW(75hp) ICE scaled to 35kW

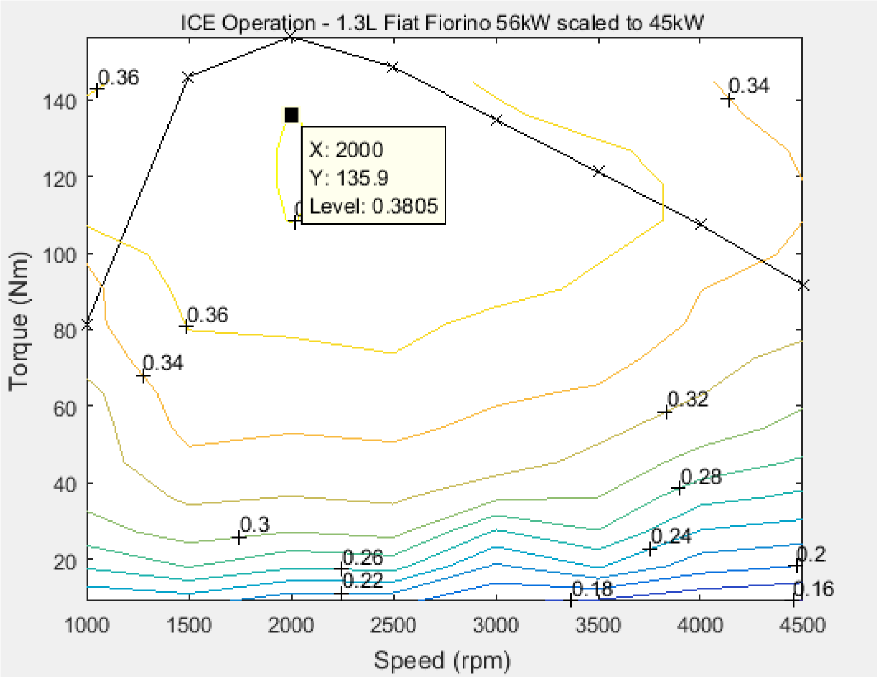


Figure 4.5. Efficiency map for 1.3L 56kW(75hp) ICE scaled to 45kW

4.2.3. Calculation of ESS Ratings

It is assumed that the hybrid vehicle will be charged from the mains overnight, as the cost of energy is lower at night. Moreover, energy which is obtained from renewable sources and stored during the day might be used for charging. It is wise to supply some of the energy requirement during vehicle operation from ICE/gen set to keep the initial cost of the vehicle low by minimizing battery capacity, which is one of the optimization requirements.

The ESS here is configured to have a battery pack and a super capacitor pack. The super capacitor storage is responsible for supplying high frequency power fluctuations. In this manner the battery pack life can be extended. This is a very important point as the battery pack cost is high and its early replacement would cause running costs to be very high resulting in an economically uncompetitive hybrid vehicle.

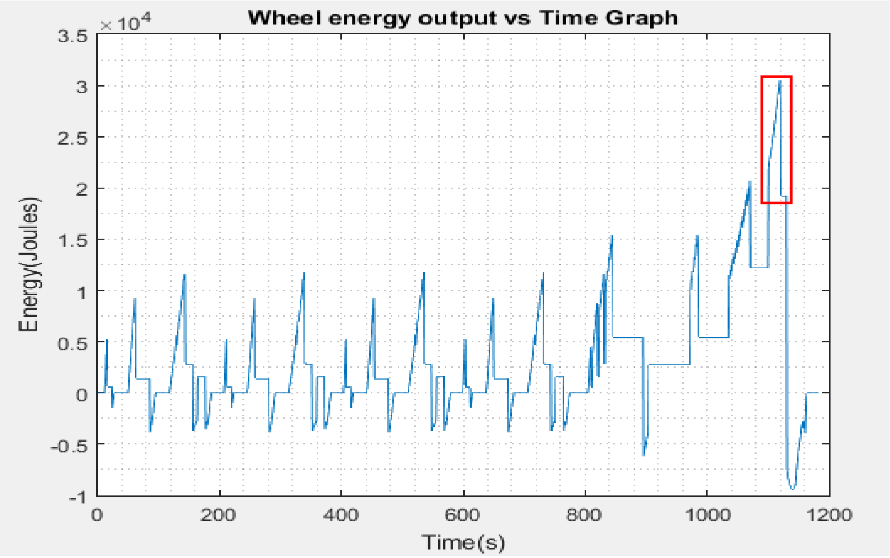


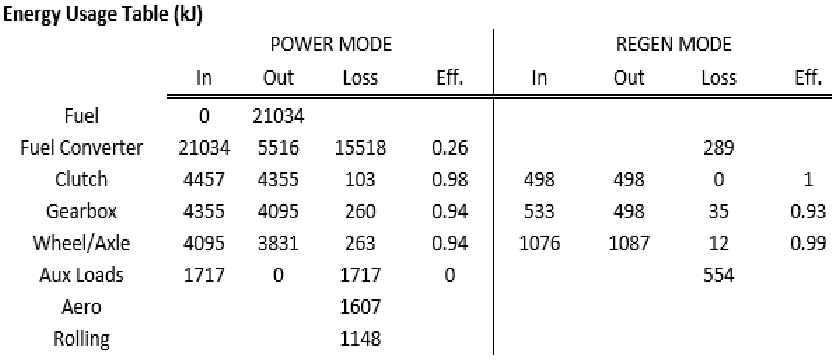
Figure 4.6. Energy output at the wheels

Energy required at the wheels of conventional Fiorino on a single cycle of NEDC is simulated as given in Figure 4.6. Positive values show energy consumed, while negative values show the energy recovered during braking. When calculated from the simulation results energy consumed in each NEDC cycle is found as 4094.7 kJ and energy recovered is found to be 533kJ. Energy use table provided by the simulation tool is shown in Figure 4.7.

Therefore,

- Each NEDC cycle energy consumption is 4095 – 533 = 3562 kJ ≈ 1 kWh.
- Taking fuel consumption as 2 L/100km and length of one cycle of NEDC as 10.93 km, 0.2186 L of fuel is allowed to be used for each cycle.
- It is assumed that the ICE/Generator set is run at minimum fuel consumption point of ICE, i.e. at 2000 rpm (240 g/kWh is read from BSFC map, see Figure 0.1 in Appendix A). Taking diesel fuel density as 832g/L, 0.2186 L of fuel is equal to 181.9 g, and $\frac{181.9g}{240g/kWh} * 0.96 = 0.73\ kWh$ energy can be extracted from it at that operating point at each cycle. Note that, 0.96 is the generator efficiency.

- This means that 0.73 kWh of energy to be supplied by the generator in each NEDC cycle. The remaining energy must be supplied by the ESS, which is $1.000 - 0.73 = 0.27\ kWh$. Over the desired 200 km range this corresponds to 4.94 kWh.



Energy Usage Table (kJ)

	POWER MODE				REGEN MODE			
	In	Out	Loss	Eff.	In	Out	Loss	Eff.
Fuel	0	21034						
Fuel Converter	21034	5516	15518	0.26			289	
Clutch	4457	4355	103	0.98	498	498	0	1
Gearbox	4355	4095	260	0.94	533	498	35	0.93
Wheel/Axle	4095	3831	263	0.94	1076	1087	12	0.99
Aux Loads	1717	0	1717	0			554	
Aero			1607					
Rolling			1148					

Figure 4.7. Energy use table for non-hybrid Fiorino on NEDC cycle

To have the optimum point between the lifetime of the battery and battery initial costs, usable SOC (State of Charge) should be chosen accordingly. As it can be seen from Figure 4.8, ESS capacity increases as DOD is decreased and annual and initial costs increase. Conversely, if DOD is increased battery lifetime is decreased without affecting costs considerably. To have 5 years of battery life as Toyota and most of the car makers offer [72], 1500 cycles of battery life is required when 300 workdays is assumed per year. Hence, 40% DOD is chosen for battery pack as is can be seen from Figure 4.8.

As a result, ESS energy rating can be calculated as $\frac{4.94\ kWh}{0.4} = 12.35\ kWh.$

Moreover, all electric range can be calculated as;

$$(1.0 - 0.3) * 12.35\ kWh * \frac{10.93\ km/cycle}{1\ kWh/cycle} = 95\ km.$$

Since the battery supplies the electric motor directly, efficiency of the energy flow path is;

$$\eta_{Battery\_path} = \eta_{Motor} * \eta_{Battery} = 0.9 * 0.92 = 0.828 \qquad (4.7)$$

So, 12.35 kWh of energy capacity requirement should be revised as $\frac{12.35\ kWh}{0.828} = 14.9\ kWh$.

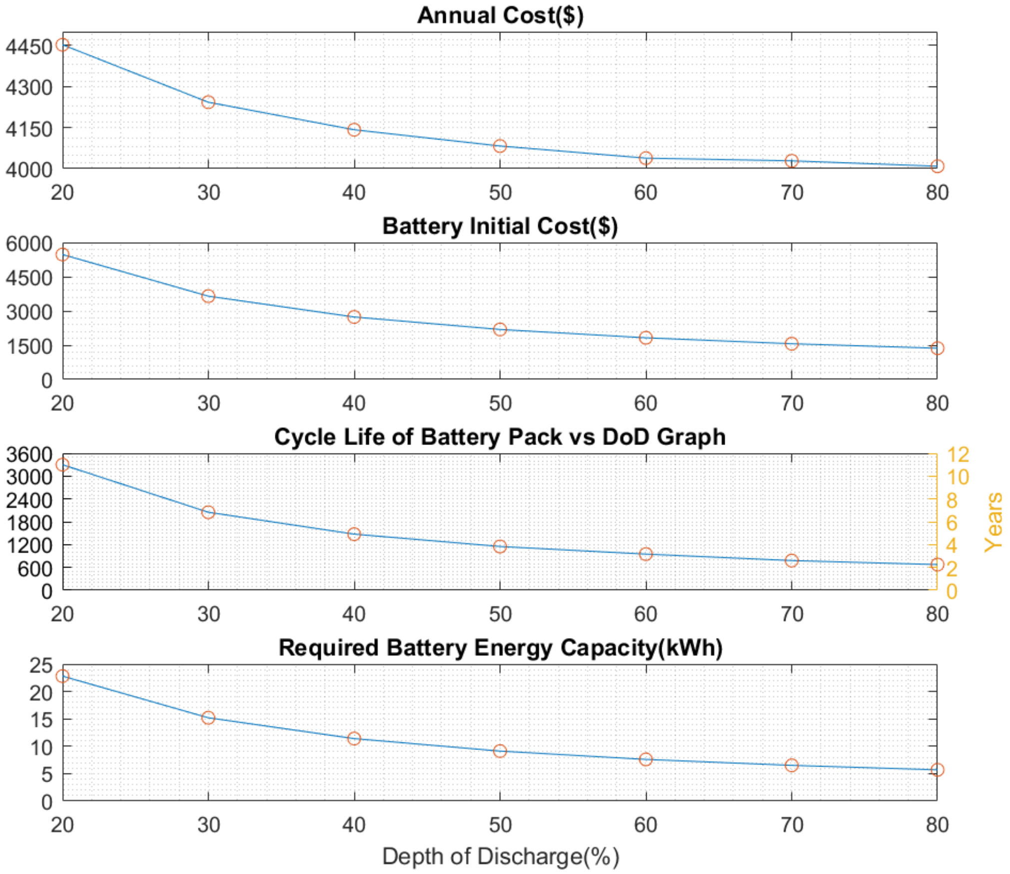


Figure 4.8. ESS costs, cycle life and capacity change with respect to DOD

Variation of needed energy at the motor drive input with permitted fuel consumption is given in Figure 4.8. This figure clearly illustrates how sharply the storage capacity decreases with permitted fuel consumption. The role of this parameter in the optimization of the storage capacity for minimizing initial cost is very significant. Meanwhile however, running cost of the vehicle rises.

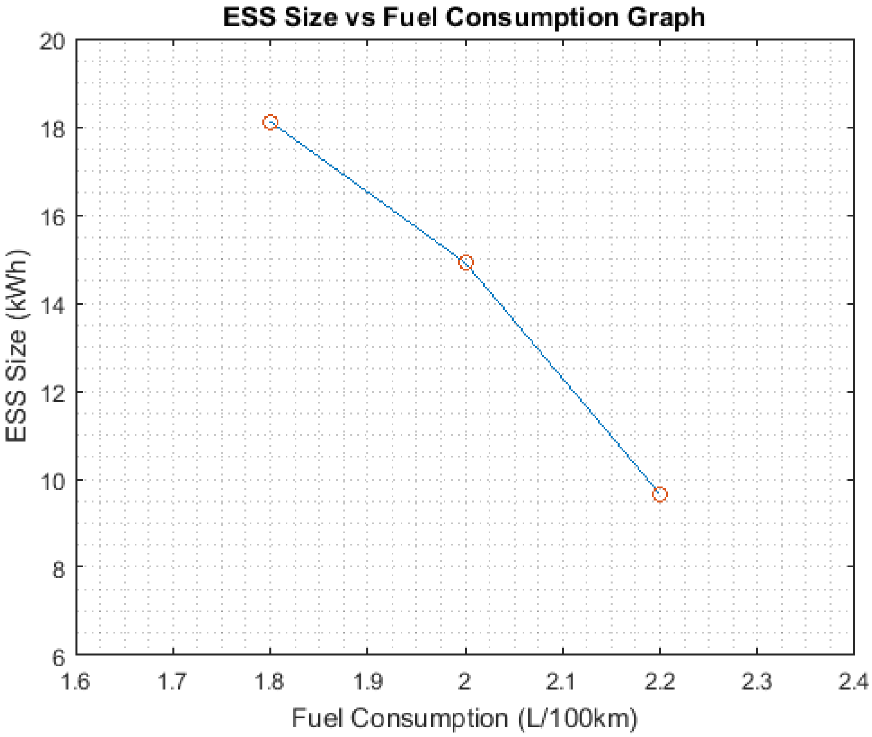


Figure 4.9. ESS Size change with respect to fuel consumption

In summary, the calculations from the approach used for sizing here indicate the need for 14.9 kWh energy storage capacity. As an initial assumption, battery and supercapacitor are assumed to share the maximum power requirement equally after subtracting the generator power. Note that power sharing is one of the parameters of optimization. In other words, according to the power supplied by battery and supercapacitor, their energy and power capacities change and thus power sharing algorithm affects the sizing. In this work, power load is thought to be shared equally by battery and supercapacitor at maximum power, for simplicity.

Using Table 3.8 14.9 kWh battery pack is estimated to cost;

$$14.9(kWh) * 1000\left(\frac{Wh}{kWh}\right) * \frac{26\left(\frac{\$}{kg}\right)}{96\left(\frac{Wh}{kg}\right)} = 4025\ \$$$

Considering the simulation results, it is observed that the peak power requirement occurs for about 59 s, in each NEDC cycle and is 30 kW. Assuming that 21 kW of this power comes from the generator, supercapacitor power supply is found to be 4.5 kW as battery supplies the remaining 4.5 kW. Therefore, 74 Wh of energy is to be supplied by the supercapacitor in this interval as calculated from Figure 4.6.

Efficiency of the energy flow path from supercapacitor to electric motors is;

$$\eta_{SC\_path} = \eta_{Motor} * \eta_{SC} = 0.92 * 0.95 = 0.874 \qquad (4.8)$$

Hence, 74 Wh is increased to $\frac{74Wh}{0.874} = 85\ Wh$ and 4.5 kW to $\frac{4.5kW}{0.874} = 5.15\ kW$.

75% of the supercapacitor energy is usable due to output voltage restrictions for the supercapacitor bank, energy rating should be $\frac{85}{0.75} = 112\ Wh$ for supercapacitor.

Moreover, maximum power battery should supply is calculated as $\frac{4.5\ kW}{0.828} = 5.43\ kW$ when the efficiency is included. Since this value is lower than 1C discharge rate of the battery which is 14.9 kW, battery can supply this current.

Properties of the battery and supercapacitor to be used are given in Table 3.7 and Table 3.8.

With the chosen specifications, it is easy to show that $\frac{112\ Wh}{3.04Wh/cap} = 37$ supercapacitors are required in this vehicle. Using Table 3.7, 28 supercapacitors costs;

$$37(SC) * \frac{160\left(\frac{\$}{4\ SC}\right)}{4} = 1480\$$$

In summary, the sizing approach presented here points out to the hybrid vehicle component ratings listed in Table 4.5. In this table, generator cost is taken to be same with the electric motor. Moreover, ICE cost is taken from literature and cost of other components are taken from market.

Table 4.5. *Determined ratings for Hybrid Fiorino simulation via new approach*

Traction Motor Rated Power	21.4 kW	2870 $ [73]
ICE Rated Power	35 kW	1460 $ [74]
Generator Rated Power	21.4 kW	2870 $ [73]
HESS Power	9 kW	1480$ for SC [65], [66]
HESS Capacity	15 kWh	4025$ for battery [46]

4.2.4. Calculation of Gear Ratio

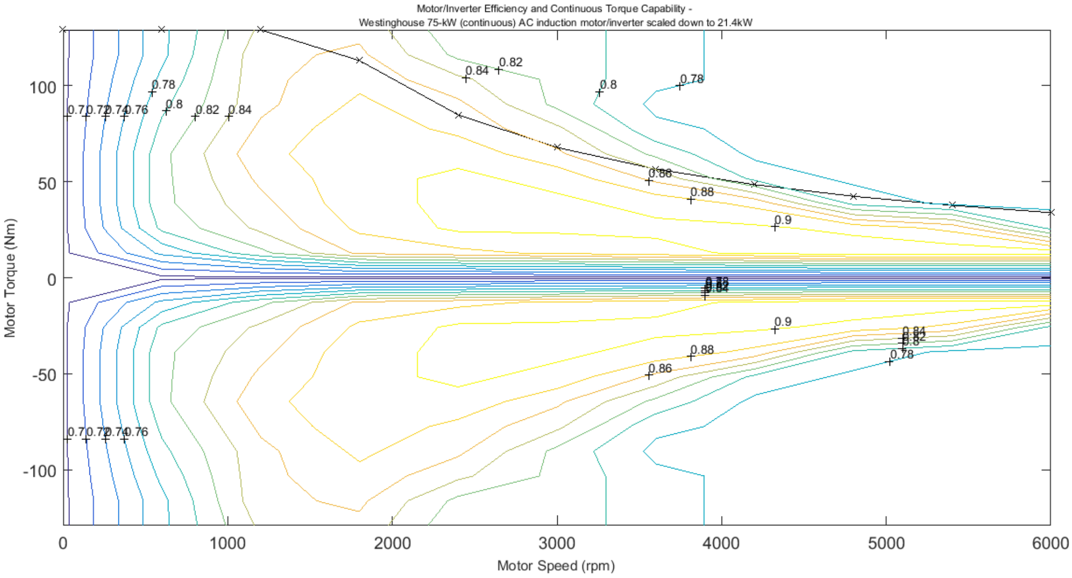


Figure 4.10. 21.4 kW Induction motor/inverter efficiency map

In Figure 4.10, efficiency map for the 75kW induction motor and inverter set scaled to 21.4 kW maximum power and set to 6000 rpm maximum speed. This scaling is done using mc_trq_scale and mc_spd_scale variables, and 75 kW induction motor defined by ADVISOR. Here it is seen that maximum efficiency region (>0.90) of motor/inverter set lies between 2000-6000 rpm. Hence, a gearbox ratio should be selected so that electric motor is utilized mostly at its maximum efficient speed and vehicle speed satisfies 150 kph maximum speed. As stated earlier, wheel radius of Fiat

Fiorino is 0.31m. And as it can be seen from Figure 4.11, vehicle is driven at 50 kph for 119s, 32 kph for 102s and 70 kph for 101s.

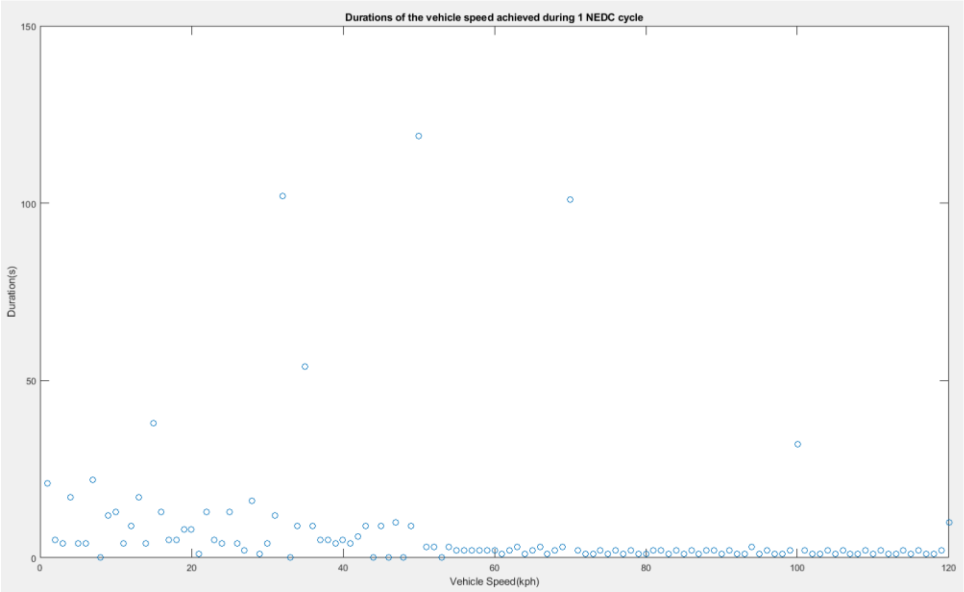


Figure 4.11. Vehicle speeds used during NEDC cycle in seconds

50 kph is selected to be reached at 1900 rpm so that all vehicle speeds above can have operating point in the maximum efficiency region for electric motor operation and maximum vehicle speed>150 kph can be satisfied. So gearbox ratio is calculated to be 4.44 resulting in 157 kph of maximum vehicle speed with electric motor drive frequency of 100 Hz, which is acceptable.

4.3. Comments and Comparison

Comparisons of electrical component sizes are tabulated in Table 4.6. As it can be seen from Table 4.6, components are downsized to smaller values. Simulations in upcoming sections show the results for fuel consumption and performance. Even these smaller ratings found via the new approach can meet the performance and drive cycle requirements at the same or better fuel consumption level, they still may require some optimization.

Table 4.6. *Ratings comparison for two Hybrid Fiorinos*

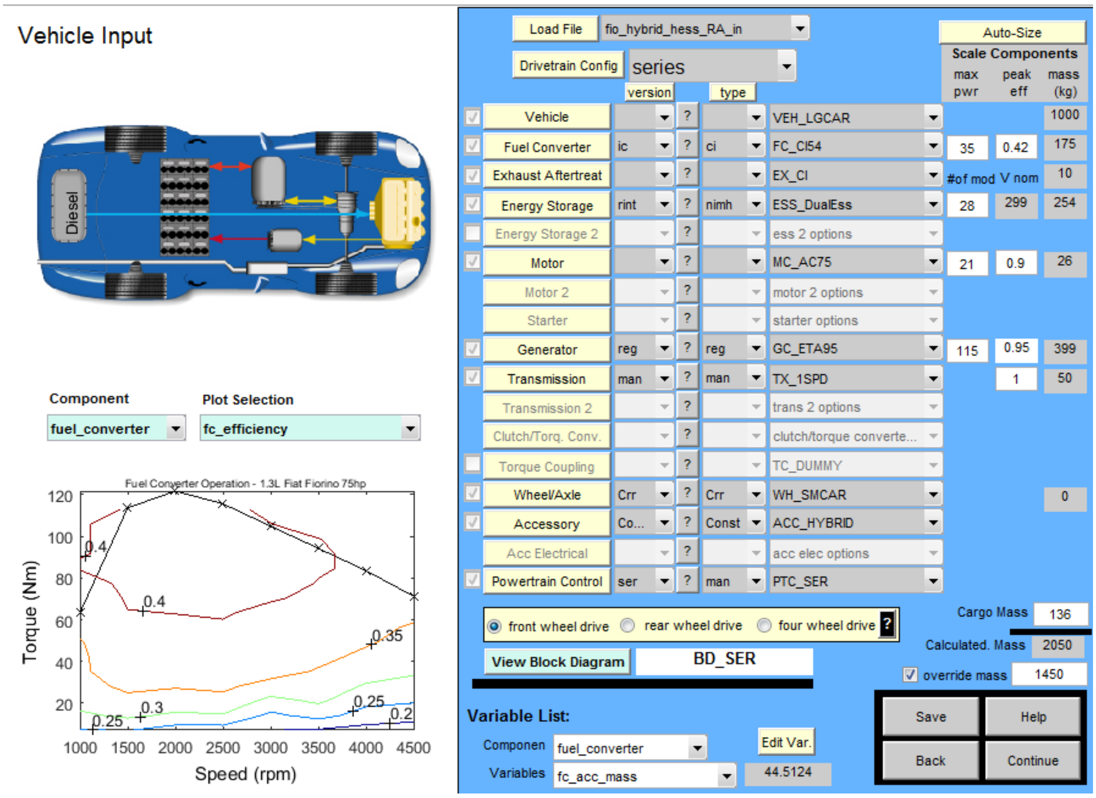
	New Approach	Conventional Approach
Motor Power	21.4 kW	27.9 kW
ICE/Gen Power	35/21.4 kW	38.3 kW
HESS Power	9 kW	5 kW
HESS Capacity	15 kWh (50 Ah)	27.1 kWh (90.3 Ah)
Gear Ratio	4.44	4.675

CHAPTER 5

SIMULATION OF THE HYBRID VEHICLE

5.1. Modelling of Hybrid Fiorino

In this chapter, modelling of hybrid Fiorino in ADVISOR with the initial component ratings is discussed. Mainly, electric motor, generator and hybrid energy storage system are added to the conventional Fiorino which is modeled and validated in previous chapters. Transmission is changed with 1-speed gearbox model. Powertrain control is selected as “Series Thermostat” control. Mathematical model for each component will be given by referring to the previous chapters. These models are suitable for the optimization algorithm. End of this chapter will discuss the design issue.



Component: fuel_converter

Plot Selection: fc_efficiency

Load File: fio_hybrid_hess_RA_in

Drivetrain Config: series

		version	type		max pwr	peak eff	mass (kg)
☑	Vehicle			VEH_LGCAR			1000
☑	Fuel Converter	ic	ci	FC_CI54	35	0.42	175
☑	Exhaust Aftertreat			EX_CI	#of mod	V nom	10
☑	Energy Storage	rint	nimh	ESS_DualEss	28	299	254
☐	Energy Storage 2			ess 2 options			
☑	Motor			MC_AC75	21	0.9	26
	Motor 2			motor 2 options			
	Starter			starter options			
☑	Generator	reg	reg	GC_ETA95	115	0.95	399
☑	Transmission	man	man	TX_1SPD		1	50
	Transmission 2			trans 2 options			
	Clutch/Torq. Conv.			clutch/torque converte...			
☐	Torque Coupling			TC_DUMMY			
☑	Wheel/Axle	Crr	Crr	WH_SMCAR			0
☑	Accessory	Co...	Const	ACC_HYBRID			
	Acc Electrical			acc elec options			
☑	Powertrain Control	ser	man	PTC_SER			

● front wheel drive ○ rear wheel drive ○ four wheel drive

View Block Diagram: BD_SER

Cargo Mass: 136

Calculated. Mass: 2050

☑ override mass: 1450

Variable List:

Componen: fuel_converter

Variables: fc_acc_mass 44.5124

Figure 5.1. Main vehicle properties adjustment in ADVISOR

Initial ratings for hybrid Fiorino can be adjusted using the main screen in ADVISOR which can be seen in Figure 5.1. However, for the optimization algorithm, no gui mode of advisor will be used. In this mode, everything is executed by hard coding instead of GUI.

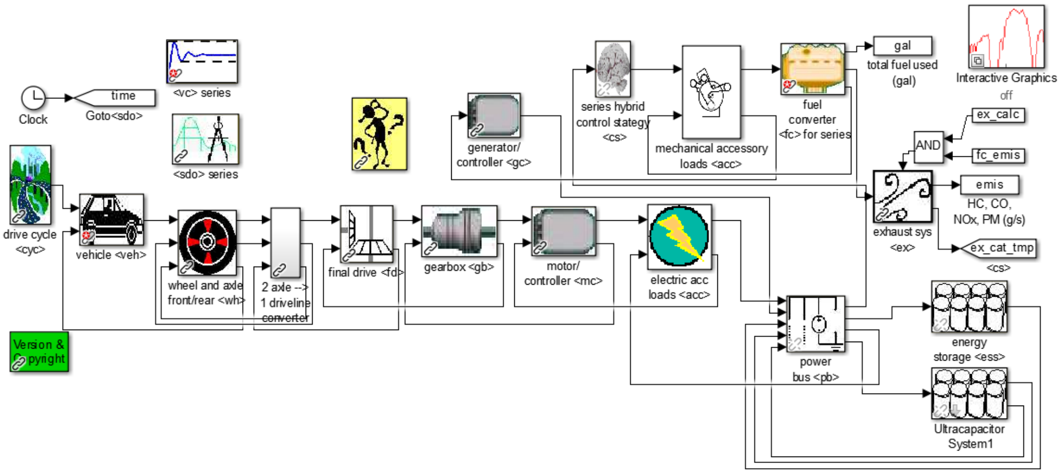


Figure 5.2. Series hybrid electric vehicle main model in ADVISOR

Simulation model for series hybrid electric vehicle in ADVISOR is shown in Figure 5.2. This model composes of the vehicle components as described earlier. Each component behaves as modeled so that outputs of each simulink box is an input for another. Control algorithms between these components are applied by some other boxes such as power bus box, series hybrid control strategy box etc.

5.1.1. Electric Motor Model

Electric motor model used for the hybrid Fiorino is MC_AC75, obtained from ADVISOR database. This is a 75 kW Westinghouse AC Induction motor including the inverter and scaled to 21.4 kW for initial simulation. Maximum efficiency of this motor is taken as 0.92 and the efficiency map for the scaled motor (21.4 kW) is shown in Figure 5.3. During optimization, maximum motor power is scaled using mc_trq_scale variable.

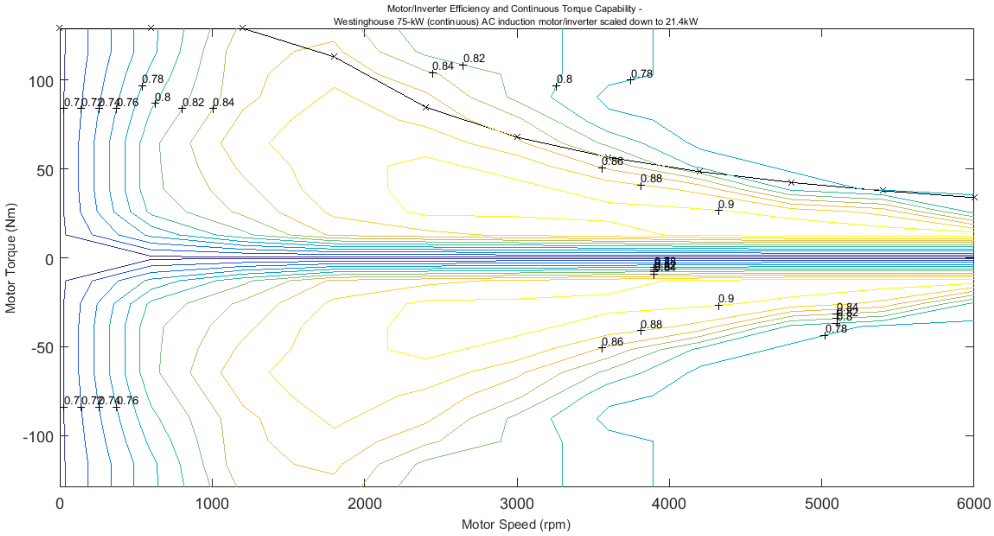


Figure 5.3. Electric motor efficiency map

Mass of this motor is to be calculated using 300W/kg relation. And, cost calculations will be made using 7.45W/$ [73].

5.1.2. Generator Model

GC_ETA95 is used as the generator model, from ADVISOR database which is seen in Figure 5.4. This is a 147 kW generator model with constant efficiency of 0.96. By changing gc_spd_scale parameter, maximum power output of the generator can be scaled. gc_spd_scale is initially adjusted to 56/147=0.381 in order to achieve 56kW=75hp of maximum power output. Note that this power level is the maximum power output of the ICE.

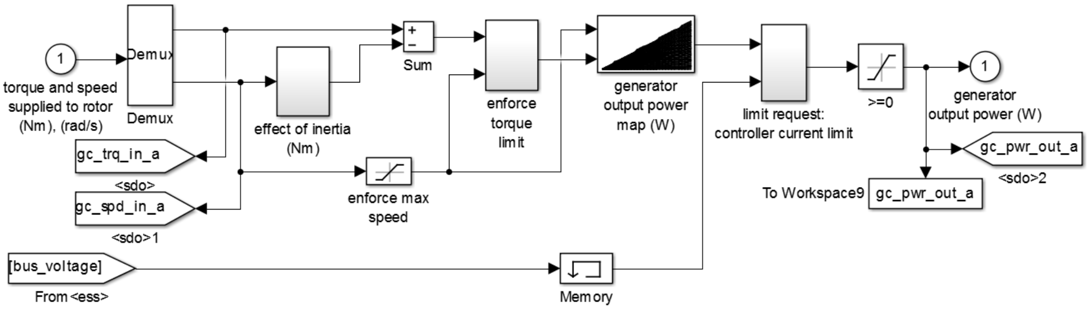


Figure 5.4. ADVISOR generator model used

Generator is controlled through the Series Thermostat Control model in ADVISOR. In this control algorithm, ICE/gen set is started when battery storage system soc goes below cs_lo_soc and ICE/gen set is shut off when soc gets over cs_hi_soc. ICE/gen set is operated at the most efficient operating point of the engine and generator assembly.

5.1.3. HESS Model

HESS model is composed of battery and supercapacitor banks in this work. However, in ADVISOR there is no simulation model using both storage systems at the same time. So, ultracapacitor is added to model and its parameters starting with ”ess_” are changed to “ess2_” in order to prevent confliction of variables. Moreover, both battery and supercapacitor parameters are defined in the same m-file which is used as main ESS file. This file is “ESS_DualEss.m” as it can be seen from Figure 5.1. Supercapacitor converter efficiency is included by the model but in order to account for the battery converter efficiency, battery efficiency map is multiplied by 0.95.

Since an extra energy storage system is added to the model, ultracapacitor namely, some changes are made in powerbus to share the load current between supercapacitor and battery. As it can be seen from Figure 5.5, a MATLAB function is created for this purpose. This function takes total power request from hybrid energy storage system, last 3 samples of the supplied power by the battery, ultracapacitor bank soc and actual power output of generator as inputs. Output of the power share function is the power request from the battery. Ultracapacitor power request is found by simply subtracting the battery power request from hess power request.

Power requested from battery is calculated according to the following rules:

- ➢ During motoring session,
- If power requested from HESS is smaller than maximum power that battery can supply then battery power req is moving average of power requested from HESS and the last 3 power levels supplied by battery.

- If power requested from HESS is higher than maximum power that battery can supply and ultracapacitor soc level is higher than lowest ultracapacitor soc level allowed then power requested from battery is maximum power that battery can supply.
- If power requested from HESS is lower than maximum power that battery can supply and ultracapacitor soc level is lower than lowest ultracapacitor soc level allowed then ultracapacitor charging power is added to power requested from battery in order to charge the empty supercapacitor.

➢ During regeneration session,

- If ICE/gen set is not active and ultracapacitor soc is lower than highest ultracapacitor soc level allowed then ultracapacitor is charged.
- If ICE/gen set is not active and ultracapacitor soc is higher than highest ultracapacitor soc level allowed then battery is charged.
- If ICE/gen set is active and ultracapacitor soc is lower than highest ultracapacitor soc level allowed then both ess are charged.
- If ICE/gen set is active and ultracapacitor soc is higher than highest ultracapacitor soc level allowed then battery is charged only.

➢ Battery power is limited during both charging and discharging periods.

➢ Regeneration efficiency is taken to be 0.8 times the efficiency map of used ess.

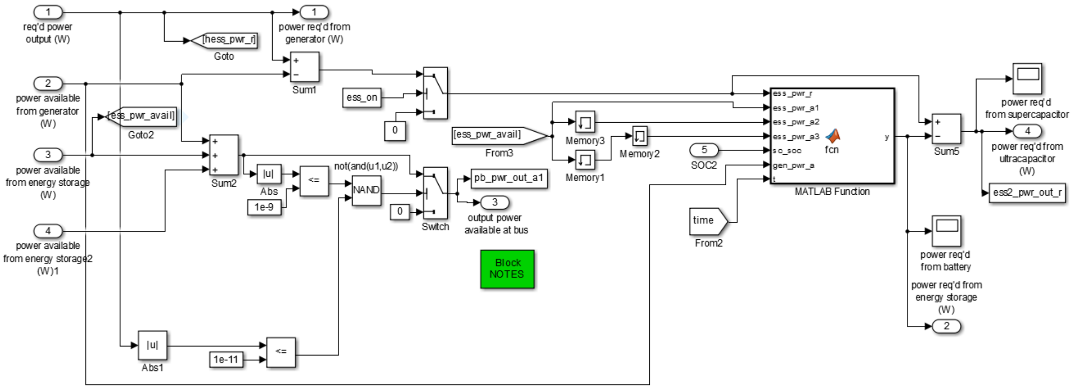


Figure 5.5. New power bus configuration in ADVISOR

Battery model is the default Lithium Ion battery model in ADVISOR which can be seen in Figure 5.6. This is a 6 Ah battery module. There are 2 main parameters for battery, “ess_module_num” and “ess_cap_scale”, namely. ess_module_num is the number of modules to be connected in series that determines the battery voltage and hence the DC bus voltage. On the other hand, ess_cap_scale is used to scale the energy rating of a single module.

As the cost and the mass coefficients for the battery pack, 96Wh/kg and 3.7Wh/$ are to be used as indicated in Table 3.8.

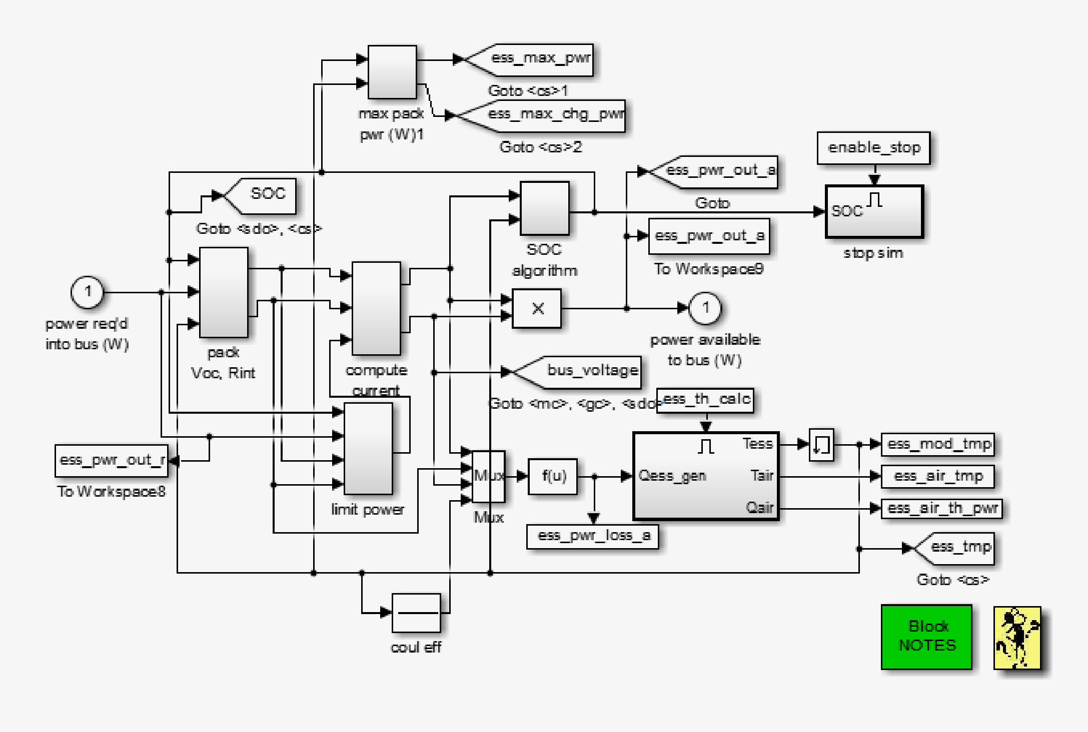


Figure 5.6. Battery model used in ADVISOR

In the supercapacitor part of the HESS model, Maxwell PC2500 test data supplied by NREL is used. This data is taken from the ADVISOR supercapacitor m-file, related to the Simulink model shown in Figure 5.7. There are 3 related to supercapacitor rating determination, “ess2_module_num”, “ess2_parallel_mod_num” and “ess2_cap_scale”, namely. “ess2_module_num” and “ess2_cap_scale” are used in the same way as their counterparts in battery. “ess2_parallel_mod_num” is the number of supercapacitors connected in parallel to share the current between them ideally by ADVISOR.

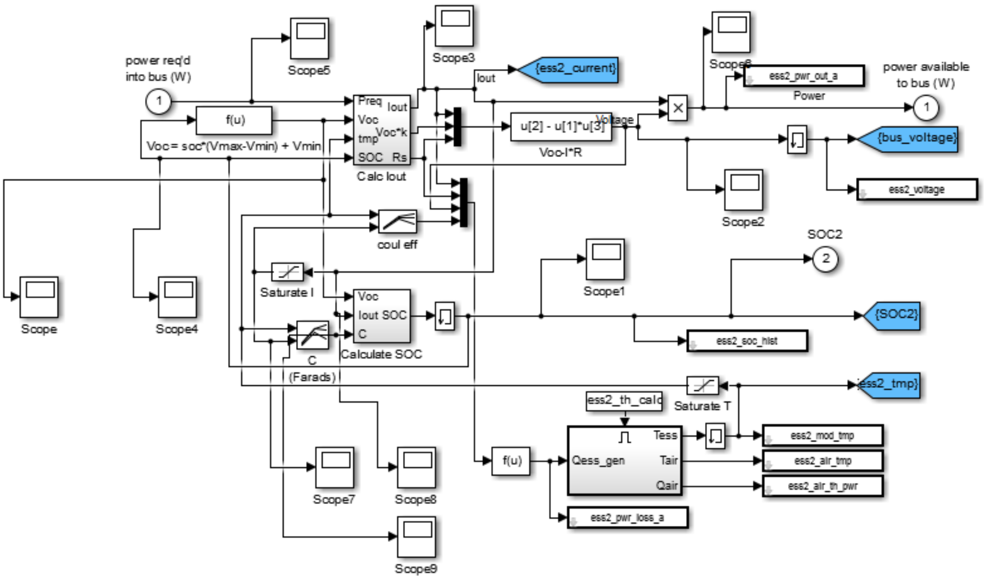


Figure 5.7. Supercapacitor Model in ADVISOR

As the supercapacitor mass and cost calculation coefficients, 75W/$, 5900W/kg and 5.96Wh/kg are to be used as indicated in Table 3.7.

5.2. Mass calculation of the hybrid vehicle

In order to calculate the mass and the cost of the components and hence the total mass and the cost of the hybrid vehicle, mass and cost formulas are constructed based upon the datas given in previous parts and datas taken from ADVISOR.

To find the hybrid vehicle mass (HVM) mass, electric motor, generator, supercapacitor, battery and reductor mass are added to the conventional vehicle mass(1190 kg), and transmission mass is subtracted. Masses and costs of electric motor, supercapacitor and battery are taken according to their sizes.

$$\begin{aligned} HVM &= m_{Fiorino} + m_{motor} + m_{generator} + m_{supercap} + m_{battery} + m_{reductor} \\ &\quad - m_{transmission} \\ &= 1190 + (P_{motor}/0.30) + 30 + \max(P_{supercap}/5.9,\ E_{supercap}/5.96) \\ &\quad + E_{battery}/96 + 20 - 114 \quad (kg) \end{aligned} \qquad (5.1)$$

Pmotor and Psupercap are continuous motor power and maximum supercapacitor power in kW, respectively. Esupercap and Ebattery are supercapacitor and battery energy capacities in Wh, respectively. Note that, generator mass is taken as 30 kg and reductor mass as 20 kg since both do not change too much according to sizing. Transmission mass is directly taken from data of a 5-speed manual transmission supplied by ADVISOR.

CHAPTER 6

OPTIMIZATION

6.1. Sensitivity Analysis

In this part, sensitivity analysis for the key parameters of the simulated vehicle is made. Sensitivity analysis is the illustration of the relation between design and performance parameters. For example, change in fuel economy with respect to change in vehicle mass is observed. In this analysis, only one variable is changed per case and others are kept constant at their nominal values i.e. at initial sizing values. However, dependent variables are also changed. For example, while changing battery capacity, vehicle mass is also changed accordingly. At the end of the sensitivity analysis, which parameter is affected by which component and at what severity is observed.

In this work, same components used for hybrid vehicle are used. Li-Ion batterty and Maxwell K2 series BCAP3000 2.7V 3000F supercapacitors are used. As electric motor, Induction machine is used due to its higher overall efficiency than other types of electric motors. Fiorino 1.3 75hp Multijet diesel engine is used as ICE. When ICE with lower power rating is required, this diesel engine is scaled by ADVISOR as given through Figure 4.1 - Figure 4.5.

Optimization variables are the variables of which ratings are to be determined during sizing process satisfying the desired performance and cost criterias. Optimization variables in simulation model and the corresponding vehicle component characteristic affected are given in Table 6.1.

Table 6.1. Optimization variables in simulation model and the vehicle component characteristic affected

Simulation Variable	Component Characteristic
fc_trq_scale	ICE maximum power rating
mc_trq_scale	Electric motor continuous power rating
ess_cap_scale	Battery energy capacity rating
ess2_cap_scale	Supercapacitor energy capacity rating

Sensitivity analysis is to be made between optimization variables and performance criterias according to Table 6.2. Variable calculations, limits and simulation details for each case are explained below that table. At the end of the sensitivity analysis, how changes in optimization variables within predefined intervals affect corresponding performance criteria is to be determined.

Table 6.2. Sensitivity analysis cases

Optimization Variable	Performance
Battery energy capacity	Fuel consumption
Battery energy capacity	All electric range, Initial Cost
ICE maximum power	Fuel consumption
Vehicle mass	Fuel consumption
Electric motor continuous power	Fuel consumption
Electric motor maximum efficiency	Fuel consumption

6.1.1. Internal Combustion Engine

Fiorino ICE is modeled as explained in previous chapters. However, during optimization it is needed to scale the engine power in order to find the optimum value. This scaling is done by ADVISOR using the fc_trq_scale variable. This variable moves the maximum torque curve of the ICE along the y-axis without changing the speed range as shown in the figures through Figure 4.1 - Figure 4.5. Hence power output of ICE is scaled as desired [75]. Efficiency point islands are also scaled accordingly. In other words, y-axis is scaled by the ratio imposed by fc_trq_scale.

ICE/Generator output is desired to meet average power of electric motor, 21.4kW. Hence ICE rating should be selected accordingly in order to have most efficient operating point around 21.4kW. Moreover, for generator not to restrict operating point of ICE, generator maximum power rating is selected to be far above the ICE power rating. At the end of optimization, generator power and torque ratings are to be automatically determined via the operating point of ICE. There is no problem in doing so, since generator is modeled as constant efficiency electrical machine in this work.

Concerning the ICE types, motorcycle engines are cheaper and lighter than marine or automobile engines at the same power level. Moreover, motorcycle engines can rev up to higher rotational speeds and hence generator connected to these engines can be designed to be smaller and lighter since higher speed means less magnetic material to be used in generator. For example, Suzuki F10A/465Q motorcycle engine which is sold at a price around 1000$ in Chinese market, outputs 29kW at 5300 rpm and weighs 96kg [76]. On the other hand, CAINIAO Power K4100D1 diesel engine which is sold at 1200$ in chinese market, outputs 30kW at 1500 rpm and weighs 320kg [77].

6.1.2. Generator Size and Volume

Generator rating is taken to be 21.4 kW as stated previously. According to electrical machine design rules [78], initial mechanical dimensions for such an asynchronous generator are given in Table 6.2.

Table 6.3. 21.4 kW asynchronous generator dimensions according to pole number[78]

Pole Number	Length(mm)	Diameter(mm)	Volume(L)
2	151.6	255.3	7.8
4	151.2	404.2	19.4
6	153.6	538.0	34.9
8	148.7	631.2	46.5

6.1.3. Dimensions of Fiorino

General dimensions of Fiorino are as seen in Figure 6.1. These dimensions restrict the battery and ICE/Gen set volume. Since hybrid energy storage system is to be placed to the floor of the Fiorino, Battery+Supercapacitor volume is restricted by wheelbase (2513 mm) and width (1716 mm). As the third dimension, thickness namely, 200 mm is to be taken. For the dimensions under the hood, 760x1469x573 mm are taken. 573 mm which is height, is taken as one-third of the height of the vehicle, 1721 mm. To be on the safe side, 0.7 of the volumes calculated is taken into account for both HESS and ICE/Gen set volumes.

Volume under the hood = 0.76 x 1.469 x 0.573 = 0.64m^3 = 640L

Usable volume under the hood = 640 x 0.7 = 448L

Volume on the floor = 2.513 x 1.716 x 0.2 = 0.86m^3 = 860L

Usable volume on the floor = 860 x 0.7 = 602L

As a result, ICE/Gen set should fit into 448L and HESS should fit into 602L.

As sized in sizing chapter, initial energy ratings for supercapacitor and battery are 112 Wh and 14.9kWh, respectively. By using the volumetric energy ratings for supercapacitor and battery, i.e. 7.6Wh/L and 100Wh/L, required volume for supercapacitor bank is calculated as $\frac{112}{7.6} = 14.7L$ and for battery pack as $\frac{14900}{100} = 149L$. Hence, both of the supercapacitor and battery capacities can go up to 3.67 times of their initial values during optimization. However, energy capacity scales for these, ess_cap_scale and ess2_cap_scale namely, are limited to 2 initially for optimization purposes.

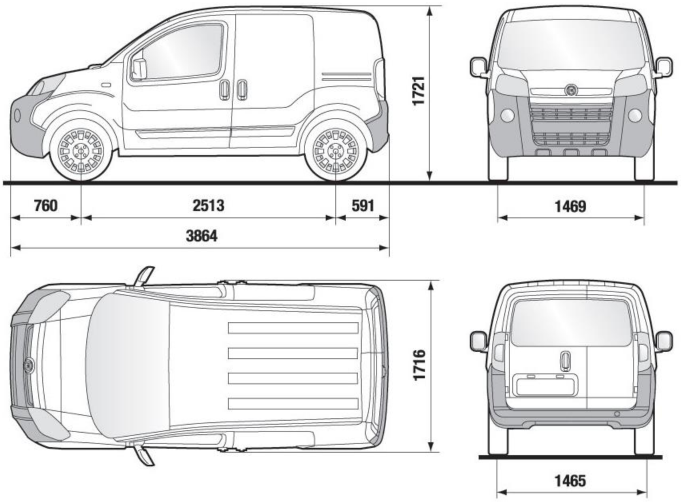


Figure 6.1. Fiat Fiorino general dimensions in mm [79]

Among Yanmar diesel engines found, Volumetric power of ICE is around 0.116kW/L [80]. Since ICE is initially sized to 35 kW, ICE volume is $\frac{35}{0,116} = 301.7L$ initially. For 21.4kW, generator volume is around 50L as it can be seen from Table 6.3. So that initial volume for ICE/Gen set is 351.7 L and can be scaled up to $\frac{448}{351.7} = 1.27$ of the initial value.

6.1.4. Mass of the vehicle

In order to calculate the total mass of the hybrid vehicle during sensitivity analysis, mass formula is constructed based upon the datas given in previous parts and datas taken from ADVISOR.

To find the hybrid vehicle mass (HVM), electric motor, generator, supercapacitor, battery, gearbox and new ICE masses are added to the conventional vehicle mass of 1190 kg, and original ICE and transmission masses are subtracted from this value. Masses and costs of ICE, electric motor, supercapacitor and battery are taken according to their sizes. Although ICE fuel consumption and performance are calculated using original and scaled Fiat Fiorino 1.3 75hp Multijet diesel engine, for ICE mass calculation Yanmar diesel engines are used. These Yanmar engines have power to weight ratio of 0.12-0.2 kW/kg in 10-35kW power range [81]. To calculate generator and controller mass, power density of 0.8663kW/kg is used. This is the general power density for generators in ADVISOR.

$$\mathrm{HVM} = m_{\mathrm{Fiorino}} + m_{\mathrm{motor}} + m_{\mathrm{generator}} + m_{\mathrm{new\_ICE}} + m_{\mathrm{supercap}} + m_{\mathrm{battery}} + m_{\mathrm{gearbox}} - m_{\mathrm{original\_ICE}} - m_{\mathrm{transmission}}$$

$$= 1190 + \left(\frac{Pmotor}{0.30}\right) + \left(\frac{Pgen}{0.8663}\right) + \frac{Pnew_{ICE}}{0.16} + max\left(\frac{Psupercap}{5.9}, \frac{Esupercap}{5.96}\right) + \frac{Ebattery}{96} + 20 - 143 - 50\ (kg)$$

P_{motor} and P_{supercap} are continuous motor power and maximum supercapacitor power in kW, respectively. E_{supercap} and E_{battery} are supercapacitor and battery energy capacities in Wh, respectively. Note that, gearbox mass is taken as 20 kg since it does not change too much according to sizing. Original Fiorino engine mass is 140 kg [82] and since it uses 3.2L 5W30 engine oil [83] and this oil has 859kg/m^3 density [84], 3kg oil mass is added. Hence, total original ICE mass is taken as 143 kg. Transmission mass is directly taken from FIAT auto service.

Initial sizing values of related component parameters for vehicle mass calculation are given in Table 6.4, taken from Chapter 4.2. During optimization and sensitivity analysis work, vehicle mass and costs are updated according to component ratings.

Table 6.4. Initial sizing ratings of hybrid vehicle to be optimized

Component	Rating	Comments
Traction motor	21.4 kW	40% overtorque
Internal combustion engine	35 kW	Most efficiency point at 22 kW
Battery	14.9 kWh	300V bus voltage
Supercapacitor	112 Wh	
Generator	21.4 kW	Operated at best point of ICE

According to Table 6.4 and HVM formula given above, inital vehicle mass is calculated to be 1452 kg.

6.1.5. Cases

- Fuel consumption versus Battery energy capacity

In this case, how fuel consumption is affected with respect to battery energy capacity is simulated. Battery energy capacity is changed between 6 and 28 kWh and vehicle mass is changed accordingly. All other variables are kept constant at their nominal values, which can be seen from Table 6.4, and vehicle is simulated for 25 NEDC cycles starting from 1.0 SOC i.e. full charged battery and supercapacitor. Note that conventional Fiorino is 1190 kg and consumes 4.4L fuel per 100 km on NEDC cycle. In order to calculate the real fuel consumption performance of the hybrid vehicle, fuel equivalent of the remaining battery energy is subtracted from the calculated consumption. For example, 25 NEDC cycles end up with 0.4 battery SOC, then fuel equivalent of 0.4-0.3=0.1 times battery energy capacity is subtracted from the consumption. This is done not to include the remaining battery energy at the end of the simulation. It can be seen from the figure below that fuel consumption decreases as the battery capacity increases. This is due to the fact that more energy is supplied by mains to charge the battery instead of generator.

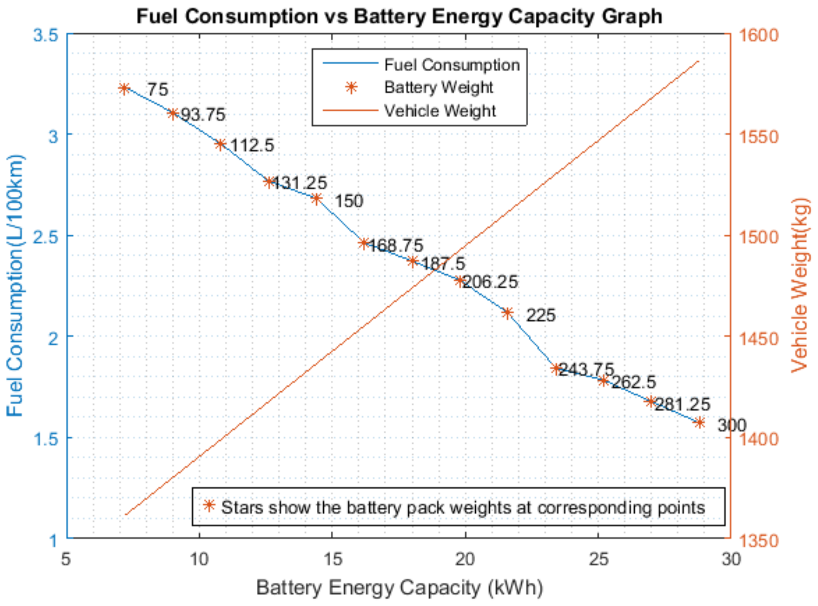


Figure 6.2. Sensitivity of fuel consumption to battery capacity, in 25 NEDC cycles

- Initial Cost versus All electric range

In this case, battery energy capacity is changed between 0.5 and 2.0 times its nominal value and vehicle mass is changed accordingly. Note that ICE is powerful enough to operate the vehicle under city driving conditions alone, even if all electric range is exceeded. Initial cost of each configuration is calculated where initial cost of the cnventional vehicle is 14510 $. All other variables are kept constant at their nominal values, which can be seen from Table 6.4, and NEDC cycle simulation tests are done consecutively starting from 1.0 battery SOC until 0.3 SOC is reached. Distance covered up to this point is taken as the all electric range of the vehicle. In Figure 6.3, results are as expected that initial cost and all electric range increase as the battery capacity is increased.

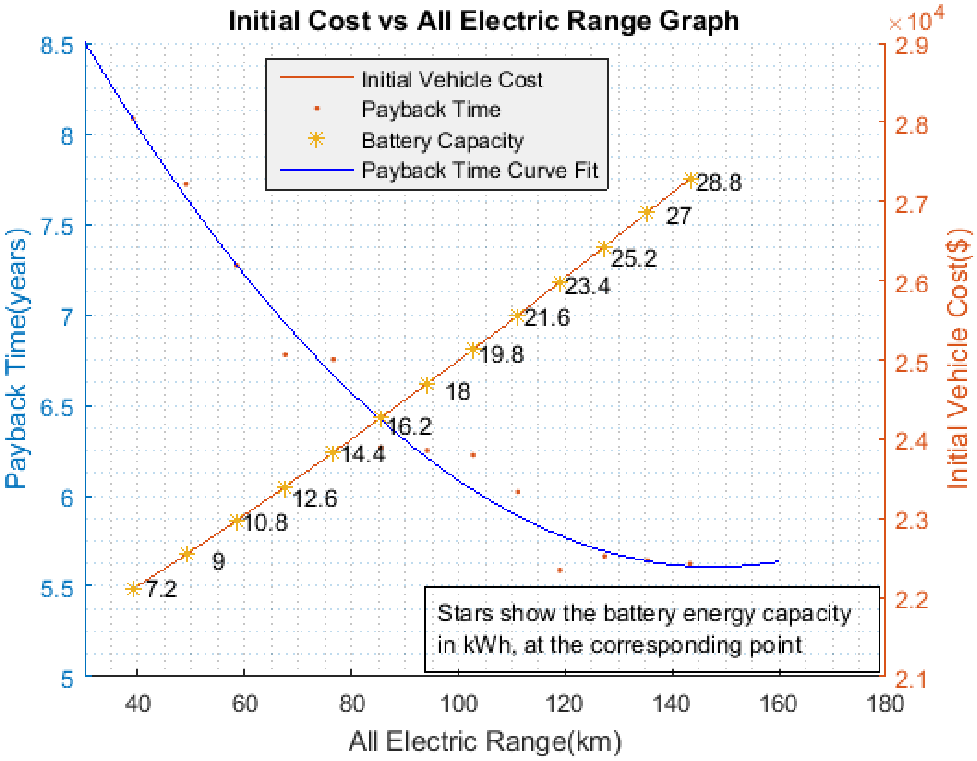


Figure 6.3. Initial Cost vs all electric range of the vehicle, in 25 NEDC cycles

- Fuel consumption versus ICE maximum power

For this case, ICE and generator maximum power ratings are changed between 27 and 62 kW. All other variables are kept constant at their nominal values, which can be seen from Table 6.4, and vehicle is simulated for 25 NEDC cycles to gather fuel consumption output in L/100km. Fuel consumption is calculated as done in previous fuel consumption calculations in this part. Results can be seen from Figure 6.4. As ICE power increases, vehicle weight increase and hence operating points for electric motor change. Initially, fuel consumption nearly does not change since highest electric motor power output requests stay in the most efficient region. However, after some point, fuel consumption increases as ICE power increases, weight of the vehicle also increases leading to utilization of electric motor in less efficient regions. At this point, it is helpful to remind that ICE uses same amount of fuel to supply the same amount of energy to the system regardless of the ICE power rating. This results from that the ICE is always operated at same efficiency i.e. maximum efficiency point and total energy requirement is same. So, input energy to ICE is same which means input fuel amount is same. Although operating point of ICE is taken as most efficient point in this part, it is a variable for optimization part. If ICE maximum power rating is changed from 35 to 30 kW, vehicle weight reduces by 30 kg and fuel consumption reduces by 0.1 L/100 km when operated at 22 kW which is the most efficient point of 35 kW ICE.

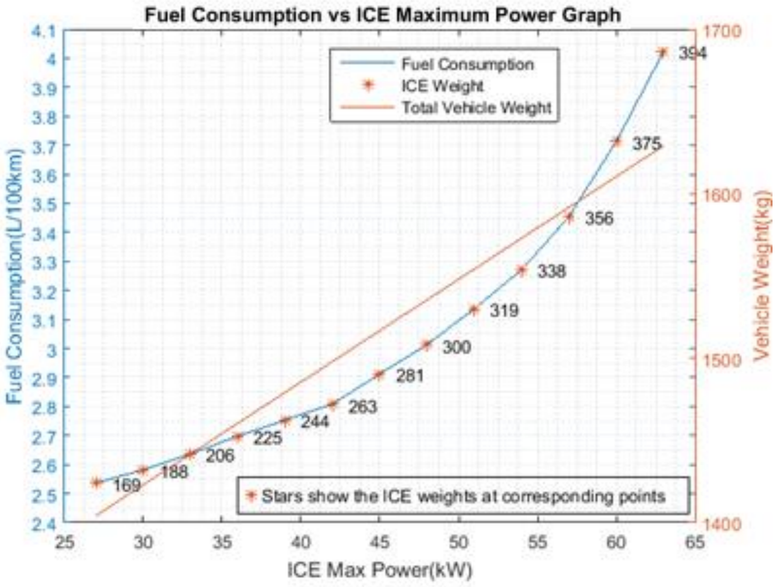


Figure 6.4. Sensitivity of fuel consumption to ICE maximum power rating, in 25 NEDC cycles

- Fuel consumption versus Vehicle mass

In this part, only vehicle mass is changed between 0.7 and 1.5 of its initial value and all other variables are kept constant at initial sizing values. Vehicle mass can not be increased too much due to maximum propulsion power limitation imposed by other components. Fuel consumption (in L/100km) is obtained by NEDC test in order to see the effect of increasing mass. Fuel consumption is calculated as done in previous fuel consumption calculations in this part. Results can be seen from the figure below, which are as expected that the fuel consumption increases as the vehicle mass increases. Conventional vehicle weight is 1190 kg with 4.4 L/100 km fuel consumption on NEDC cycle.

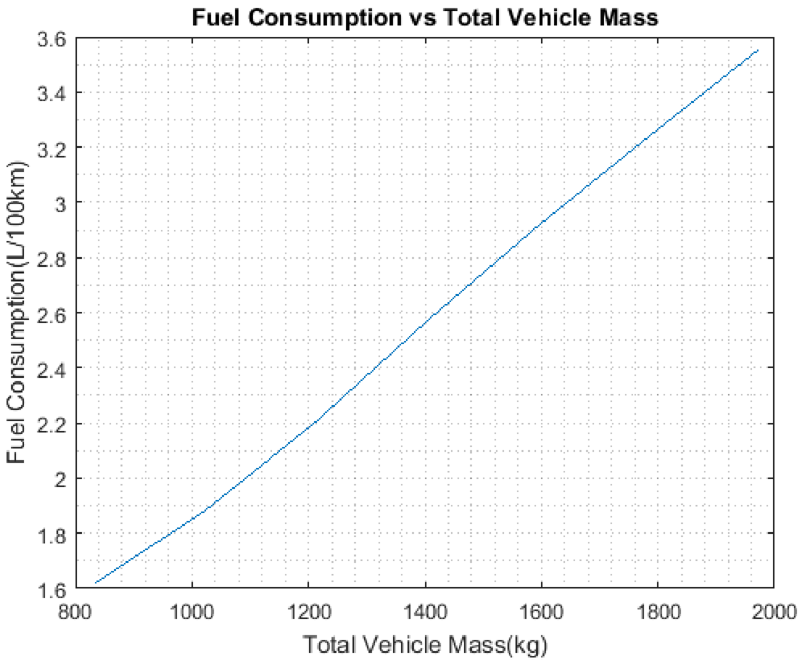


Figure 6.5. Sensitivity of fuel consumption to total vehicle mass, in 25 NEDC cycles

- Fuel consumption versus Electric motor continuous power

In this case, only power rating of electric motor is changed (maximum power and vehicle mass change accordingly) between 18 and 42kW so that its effect on fuel consumption (in L/100km) can be observed through 25 cycle NEDC test. Note that, electric motor maximum power can not be decreased too much due to power need during propulsion. All other variables are kept constant at their nominal values, which can be seen from Table 6.4. Fuel consumption is calculated as done in previous consumption calculations in this part. Results can be seen from Figure 6.6. As the motor power increases, consumption decreases initially. This is due to motor operation at more efficient regions. For example increasing electric motor from 20 kW to 40 kW increases overall electric motor utilization efficiency by 0.01. Since the vehicle weight is also increased by around 65 kg, fuel consumption stays more or the less same. If motor power is increased beyond some value, fuel consumption starts to increase again since electric motor starts to operate at less efficient regions due to the oversized electric motor.

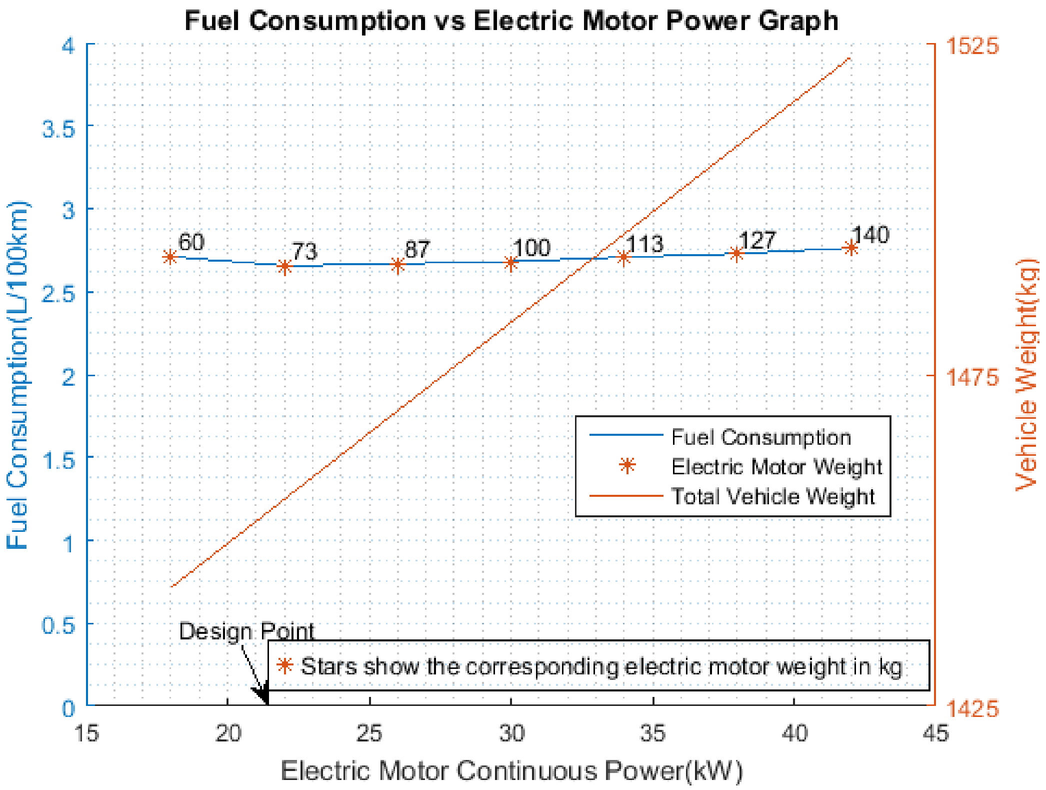


Figure 6.6. Sensitivity of fuel consumption to Electric motor power rating, in 25 NEDC cycles

- Fuel consumption versus Electric motor maximum efficiency

In this case, maximum efficiency hence the overall efficiency is changed between 0.80 and 0.98 All other variables are kept constant at their initial values, which can be seen from Table 6.4, and fuel consumption change is observed via NEDC cycle simulations. Fuel consumption is calculated as done in previous fuel consumption calculations in sensitivity analysis part. It is clearly seen from Figure 6.7 that fuel consumption is inversely related to the electric motor efficiency.

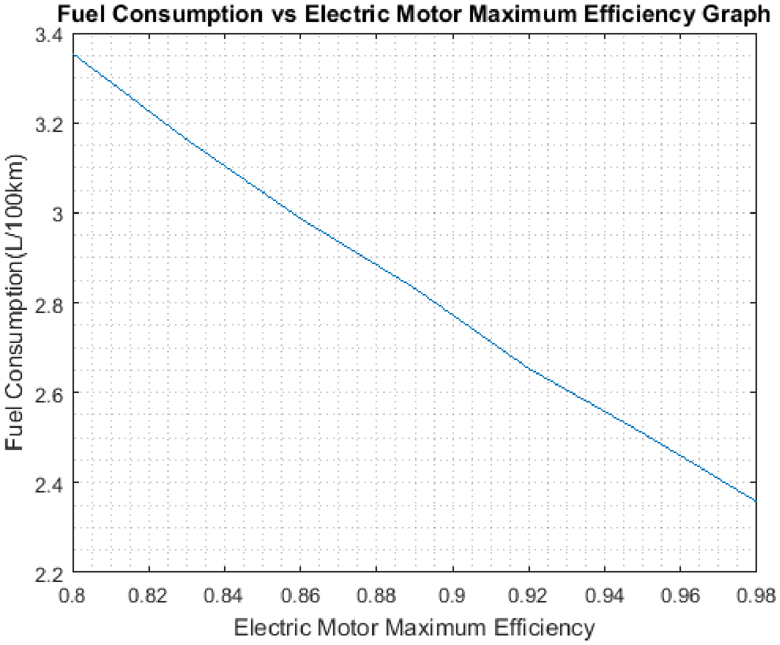


Figure 6.7. Sensitivity of fuel consumption to Electric motor maximum efficiency, in 25 NEDC cycles

6.1.6. Conclusions

To conclude the sensitivity analysis work, some comments are given in this part. For example, as it can be seen from Figure 6.2, fuel consumption decreases as the battery capacity increases due to the increased amount of initial charge in battery. It is also called to be linear, 0.077 L/100km decrease in fuel consumption per kWh of battery capacity increase. Another case in sensitivity analysis is that battery capacity vs range. As the initial cost of the vehicle is increased by increasing battery energy capacity, all electric range increases as expected. As it can be seen from Figure 6.3, all electric range increases by 5.36 km per kWh increase of the battery energy capacity. Thirdly in sensitivity analysis, vehicle mass increases fuel consumption linearly, as expected. It is seen in Figure 6.5 that each 100 kg increase in vehicle mass increases fuel consumption by 0.170 L/100km. As the fourth case, electric motor continuous power versus fuel consumption is simulated. In Figure 6.6 it is seen that when electric motor power is changed in a meaningful interval such as 18-42 kW, fuel consumption changes very slightly since utilized efficiency regions of electric motor do not change much and required energy is more or the less same. Lastly for sensitivity analysis, fuel consumption decreases linearly with increasing efficiency. As it can be seen from Figure 6.7, fuel consumption decreases by 0.055 L/100km as electric motor efficiency increases 0.01.

6.2. Optimization of the Designed Hybrid Electric Vehicle

Design process of a hybrid electric vehicle is more complex than the conventional vehicle due to the increased number of power sources and hence the increased number of design parameters. So, an optimization process should take place after choosing the initial values for design parameters. This process starts with defining the cost function, constraints and optimization variables. Then, optimization tool calculates the best ratings for optimization variables in given intervals while making the vehicle stay in the bounds of performance constraints with minimum cost function value.

6.2.1. Description of the Problem

There are many aspects of the hybrid vehicle that can be optimized such as range, running costs and initial cost of the vehicle etc. In this work, 3 cases are considered for optimization. These cases are, total cost optimization, initial cost optimization and running cost optimization. In other words, in case 1, objective function is taken as the total cost which means that addition of initial cost and running costs of the vehicle during lifetime. Objective function is only initial cost of the vehicle in case 2 and only running costs in Case 3.

Initial cost of the vehicle is calculated by subtracting original drivetrain cost from original conventional vehicle cost and adding net battery cost, supercapacitor cost, electric drive price, new ICE and gearbox prices. Net battery cost is calculated by subtracting battery scrap price from original battery cost. Running costs include lifetime charging, fuel and maintenance costs where lifetime is taken as the life of the battery pack. Motor vehicle taxes are not included and conventional vehicle initial cost is the sale price of Fiorino including all taxes in December 2017.

As in every optimization problem, there should be some limits on the optimization variables, i.e. electric motor power rating, generator and ICE ratings and battery pack energy capacity. These are called the optimization variable bounds and defined by the volumetric limitations and parametric optimization made in sensitivity analysis chapter. Lower bounds for these optimization variables are chosen according to the performance. For example, decreasing electric motor power rating too much results in insufficient traction torque and hence vehicle cannot follow the drive cycle as intended.

For battery, Li-Ion battery is used due to its higher energy density and power performance. As the electric motor, induction motor model supplied by ADVISOR is taken. Efficiency maps, maximum torque and power, vehicle mass are scaled using the base values during optimization.

Optimization variables, constraints and constants used in this work are given in Table 6.5 . On the right hand side, intervals or values for each optimization variable are seen. These are the intervals that optimization tool is allowed to change the related parameter within. Intervals for optimization variables are taken from sensitivity analysis part where physical and operational limits are considered for each design parameter. For example, ICE power rating is allowed to change between 25 and 50 kW and generator is allowed to operate between 22 and 30 kW. This lets optimization algorithm to choose a smaller ICE and operate at a bit worse efficient point but decrease the ICE size to decrease both the initial cost and weight of the vehicle. Constraints are the rules to be obeyed by the vehicle while minimizing the cost function. During this acceleration test, electric motor is able to use over torque factor defined as 1.4 before. Lastly, there are optimization constants which are design parameters in sizing process but not taken into account in optimization as variable. These are gearbox ratio and supercapacitor energy capacity. Supercapacitor is not taken as an optimization variable since it affects only the state of health (SOH) of the battery pack and there is not any calculation about SOH of battery in this work.

Table 6.5. Optimization Variables List

	Variable	**Explanation**	**Interval / Value**
Optimization Variables	mc_trq_scale	Electric motor continuous power rating	20-45kW
	ess_cap_scale	Battery energy capacity rating	7200-28800Wh
	fc_trq_scale	ICE maximum power rating	25-50 kW
	gc_operating_pwr	Generator operating power	22-30 kW
Optimization Constraints	Trace Miss	Difference between desired and achieved vehicle speed values	<3.0%
	All electric range	Distance which the vehicle can go using battery only	>50km
Optimization Constants	ess2_cap_scale	Supercapacitor energy capacity is constant	112 Wh
	gb_ratio	Gear ratio between electric motor and wheels is constant	4.44:1

Optimization algorithm takes optimization variables as continuous. However, it is hard to find or design an electric motor right at 21.4 kW. In other words, values that the optimization variables can take are discrete. Hence, results found by the optimization algorithm is to be interpreted as discrete, i.e. the closest feasible value will be taken during design and manufacturing processes.

At this point, it is beneficial to point out that if battery SOC is 0.3 and supercapacitor is emptied, and electric motor is only fed by engine/generator set, then some degradation in the vehicle performance will occur. Hence, battery might be left with some charge before turning on generator or it can be forced to discharge below minimum SOC. This shows the importance of the control algorithm also.

6.2.2. Assumptions

In this optimization problem some assumptions are made. These assumptions are given below.

- Single reduction gearbox ratio is taken as an optimization constant, 4.44:1. Efficiency of gearbox is taken to be constant at 0.97.
- ICE, electric motor, battery, supercapacitor are assumed to have scalable models according to the method given in Chapter 6.2.6.1. Their efficiency maps are assumed to be scaled when their energy capacity or power ratings are scaled.
- Electric motor is able to use over torque capability during acceleration tests.
- ICE is assumed to be able to operate the vehicle on NEDC cycle when battery is emptied.
- Generator is taken as a constant efficiency machine, i.e. 0.96 efficiency.
- Accessory power is taken as 0.

6.2.3. Cost Function

There are 4 cases to be examined for optimization chapter in this work. These cases differ according to following rules:

- Case 1: Cost function is taken as overall cost (initial cost + running costs) of the vehicle and rules in Table 6.5 are obeyed.
- Case 2: Cost function is taken as initial cost of the vehicle and rules in Table 6.5 are obeyed.
- Case 3: Cost function is taken as running costs of the vehicle during the lifetime of the battery, which is 5 years. Rules in Table 6.5 are obeyed.

Overall cost has two dimensions as running and initial costs. For the owner of the vehicle, initial cost is important but extra expenditures are also made during lifetime of the vehicle i.e. running costs. Hence, addition of running and initial costs is minimized in this work, which is the overall cost of the vehicle (Case 1). Another point here is that some effects such as time value of money, battery aging, motor vehicle taxes and tire wear are not considered.

Running costs are calculated according to the battery lifetime. According to the lifecycle graph given in battery aging part before, lifecycle of Li-Ion battery is expected to be 1500 cycles when charged and discharged at 40% DoD (0.3-0.7 SoC change). This makes around 5 years of battery life if battery is taken to be fully discharged every day with 6 working days per week. This is coherent with the lifetime data supplied by Nissan and Toyota in their websites [72], [88]. Daily usage is taken to be 200 km/day. Hence, $200\frac{km}{day} * \frac{300days}{year} * 5\ years$ = 300000 km of total battery life is expected.

6.2.3.1. Running Costs

In this part, fuel consumption, overnight battery charging cost and maintenance throughout the battery lifetime are taken as running costs. Maintenance cost of plug-in series hybrid vehicle is around 0.7 of the conventional vehicle due to the lower mechanical part wearing such as brake pads, ICE parts etc. [89]. Conventional Fiorino has 750₺ yearly maintenance cost. Accordingly, total maintenance cost of hybrid fiorino is calculated as in Equation 6.1.

$$
\begin{aligned}
&Maintenance\ cost\ (\$)\\
&= \frac{750(\frac{₺}{year})}{3.8173\left(\frac{₺}{\$}\right)} * 5\text{ years} * 0.7\left(\frac{\text{hybrid cost}}{\text{conventional cost}}\right) \qquad (6.1)\\
&= 688\$
\end{aligned}
$$

Fuel consumption cost over lifetime is calculated in Equation 6.2.

$$
\begin{aligned}
Fuel\ consumption\ (\$) &= FC\left(\frac{L}{100km}\right) * \frac{300000(km)}{100(km)} * 1.34\left(\frac{\$}{L}\right)\\
&= 4020 * FC\left(\frac{L}{100km}\right) \qquad (6.2)
\end{aligned}
$$

Lastly for running costs, overnight charging costs over the lifetime of the battery should also be included. By taking 300 workdays in a year, total charging cost of the battery from the mains is shown in Equation 6.3.

$$
\begin{aligned}
&Battery\ charging\ costs\ from\ mains\ over\ lifetime(\$)\\
&= \frac{E_{battery}(Wh)}{1000\left(\frac{Wh}{kWh}\right)} * 0.108\left(\frac{\$}{kWh}\right) * 300\left(\frac{days}{year}\right) \qquad (6.3)\\
&* 5(years) = 0.162 * E_{battery}
\end{aligned}
$$

6.2.3.2. Initial Cost

In calculation of the initial vehicle cost, following approach is used. As the initial cost, the price of the conventional vehicle plus cost of hybrid components minus cost of unused conventional components of Fiorino is taken. More clearly; cost of battery, electric motor, generator, new ICE, new single stage gearbox and supercapacitor bank are added to Fiorino price and original ICE and transmission prices are subtracted to find the hybrid vehicle cost. As the conventional vehicle cost, sale price of the Fiorino is considered including all of the taxes. New component prices are found from market and subtracted conventional vehicle components costs are calculated using the cost percentages for each component in a vehicle taken from literature[74].

Li-Ion battery scrap price is 1.3$/lb = 2.866$/kg [90]. So, net battery cost is calculated as shown in Equation 6.4. Electric motor drive and supercapacitor prices are calculated in Equation 6.5 and 6.6 according to the prices given in sensitivity analysis part. Electric motor cost parameters are taken for generator cost calculation as seen in Equation 6.7.

$$\begin{aligned} &Net\ Battery\ Cost(\$) \\ &\quad = Battery\ Cost - Battery\ Scrap\ Price \\ &\quad = \frac{Ebattery(Wh)}{3.7\left(\frac{Wh}{\$}\right)} - \frac{Ebattery(Wh)}{96\left(\frac{Wh}{kg}\right)} \\ &\quad * 2.866\left(\frac{\$}{kg}\right) = 0.24\left(\frac{\$}{Wh}\right) * E_{battery}(Wh) \end{aligned} \tag{6.4}$$

$$\begin{aligned} &\text{Electric motor drive price}(\$) = \frac{P_{motor}(kW)}{0.00745\left(\frac{kW}{\$}\right)} \\ &\quad = 134.23 * P_{motor} \end{aligned} \tag{6.5}$$

$$\begin{aligned} &\text{Supercapacitor bank price } (\$) \\ &\quad = \frac{E_{SC}(Wh)}{0.076\left(\frac{Wh}{\$}\right)} = 13.16 * E_{SC} \end{aligned} \tag{6.6}$$

$$\text{Generator price}(\$) = \frac{P_{gen}(kW)}{0.00745\left(\frac{kW}{\$}\right)} = 134.23 * P_{gen} \tag{6.7}$$

Cost of original Fiat Fiorino (in December 2017) 1.3 MJet 75hp Pop is 55400 TL [91] all taxes included. Taking TL/$ currency as 3.8173 same with the previous chapters, Fiorino costs 55400(TL)/3.8173(TL/$) = 14513 $. $/€ parity is taken to be 0.8335 from “investing.com” website for the end of December 2017 to be compatible with the TL/$ parity. Drivetrain costs about 22% of total vehicle according to the comprehensive study made by Fries et al. [74]. Then hybrid vehicle body cost is calculated accordingly in Equation 6.8.

$$\begin{aligned}\text{Hybrid vehicle body cost (\$)} &= \mathit{Vehicle\ initial\ cost} \\ &- \mathit{Original\ drivetrain\ price} \\ &= 14513\ (\$) - 14513(\$) \\ &* 0.22\left(\frac{\mathit{drivetrain\ cost}}{\mathit{total\ vehicle\ cost}}\right) = 11320\ (\$)\end{aligned} \tag{6.8}$$

$$\begin{aligned}\text{New ICE price(\$)} = 50\left(\frac{€}{kW}\right) * 0.8335\left(\frac{\$}{€}\right) * P_{newICE}(kW) \\ = 41.675 * P_{newICE}\ \$\end{aligned} \tag{6.9}$$

$$\text{New gearbox price (\$)} = 300\$ \tag{6.10}$$

New gearbox price is taken from market and assumed to be constant as it does not change with respect to gear ratio considerably (Equation 6.10) [92].

To calculate the overall cost of the vehicle, all of the initial cost and running cost components are added (Equation 6.11).

$$\begin{aligned}\mathit{Overall\ cost}\ (\$) &= 688 + 4020 * FC\left(\frac{L}{100km}\right) + 0.402 * E_{battery} \\ &+ 134.23 * P_{motor} + 13.16 * E_{SC} + 11320 + 300 \\ &= 12308 + 4020 * FC\left(\frac{L}{100km}\right) + 0.402 \\ &* E_{battery} + 134.23 * P_{motor} + 134.23 * P_{gen} \\ &+ 13.16 * E_{SC}\end{aligned} \tag{6.11}$$

Table 6.6. Default values for optimization variables

Component	**Rating**
Traction motor	21.4kW
Internal combustion engine	35kW
Battery	14.9kWh
Supercapacitor	112Wh
Gear Ratio	4.44:1

Initial sizing made with the proposed method in Chapter 4.2 resulted as seen in Table 6.6. These are the initial points for the optimization variables and starting from this point, traction motor power, ICE/Gen set power rating and battery energy capacity ratings are optimized. Others are kept constant for this work.

6.2.4. Constraints

In the optimization process, there is also a performance expectation from the vehicle. These expectations are called optimization constraints. For example, in this case, vehicle should have minimum all electric range of 50 km while maintaining the cost function as low as possible. Another performance criterion for this optimization problem is “trace miss”. Trace miss is defined as the difference between achieved and desired vehicle speeds. In other words, it is a measure of how good the vehicle followed the drive cycle input and occurs when traction power or electric motor speed is not sufficient. Trace miss is kept below 3.0% in order to make sure that vehicle is following the given drive cycle.

6.2.5. Selection of an Optimization Algorithm

In this thesis, derivative-free algorithms such as DIRECT, Simulated Annealing, Genetic Algorithm, Particle Swarm Optimization are considered. Main problem in using these algorithms is that they find the solution much slower than the gradient based algorithms.

DIRECT(DIvided RECTangles) is a deterministic global optimization algorithm where design space is divided into hypercubes and search is started by evaluating the objective function at the center of each cube. Then process continues with dividing the longest edge of the cube until termination limit or convergence is reached [85].

Simulated Annealing (SA), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are stochastic global optimization algorithms which means that problem is solved by following a random path for each search. SA algorithm is based on annealing process of metals such that atoms move freely when metals are at high temperatures. As the metal colds down, atoms move slower and try to have the most stable orientation to have lowest energy state. In a similar way, this algorithm starts by evaluating the objective function at a random point and jumps to another point and evaluates there. New point is accepted if it is better than the previous one. If temperature is high, new point may be accepted even it is worse in terms of objective function value. This method helps algorithm to overcome local minimums. Until convergence criteria is met or maximum step size is reached, this process continues. In PSO algorithm, swarm intelligence found in nature such as in ant colonies is used. In ant colonies for example, position and velocity interactions between agents result in a global behavior. In the same manner, PSO starts with initial random points called particles. These particles start moving in design space. Each point in design space is called position and moving speed is called velocity. According to the best value of objective function with respect to particle and whole group during movement, global minimum is reached [85]. Lastly, GA is the algorithm based on Darwin’s theory of natural selection. Population consists of solution sets and these solution sets are used to create new ones through crossover, mutation and natural selection. Randomly chosen solution sets consist the initial population and objective function are calculated for each set which is called fitness value. Best sets are called as parents. Some sets with lower fitness values are chosen as elite children and automatically passed to next generation. Other solution sets for next generation is created by combining the entries of a pair of parents (crossover) and randomly changing an entry in a parent (mutation). Crossover and mutation creates diversity in solution sets i.e. population and diversity helps not to stuck in a local minimum. After next generation is created using elite, mutation and crossover children, fitness values are calculated for each set and process starts again. When relative change in fitness value remains below function tolerance or maximum number of generations is reached, optimization process is finished and result is served as the global minimum [86].

Among these 3 algorithms, PSO is the slowest one and SA is the fastest[87]. Since there is not considerable speed difference between GA and SA, and GA is implemented in a stable manner by Matlab, Genetic Algorithm is chosen as the optimization solver for this work. Flowchart for GA is given in Figure 6.8 . Genetic Algorithm implemented by Matlab is used.

6.2.6. Optimization Method

In this work, Genetic Algorithm is selected as the optimization algorithm as indicated in the previous sections. MATLAB has a good implementation of Genetic Algorithm called by the function “ga()”.

To keep optimization time low, vehicle is started with 0.32 SOC battery pack and algorithm is run on 2 NEDC cycles. Pre-calculated all electric ranges for various vehicle weights are taken from lookup table and added to all electric range during optimization. At the end of the optimization, fuel consumption per day (per 200 km) is gathered by simulating the optimized vehicle through 18 NEDC cycles, starting with fully charged battery.

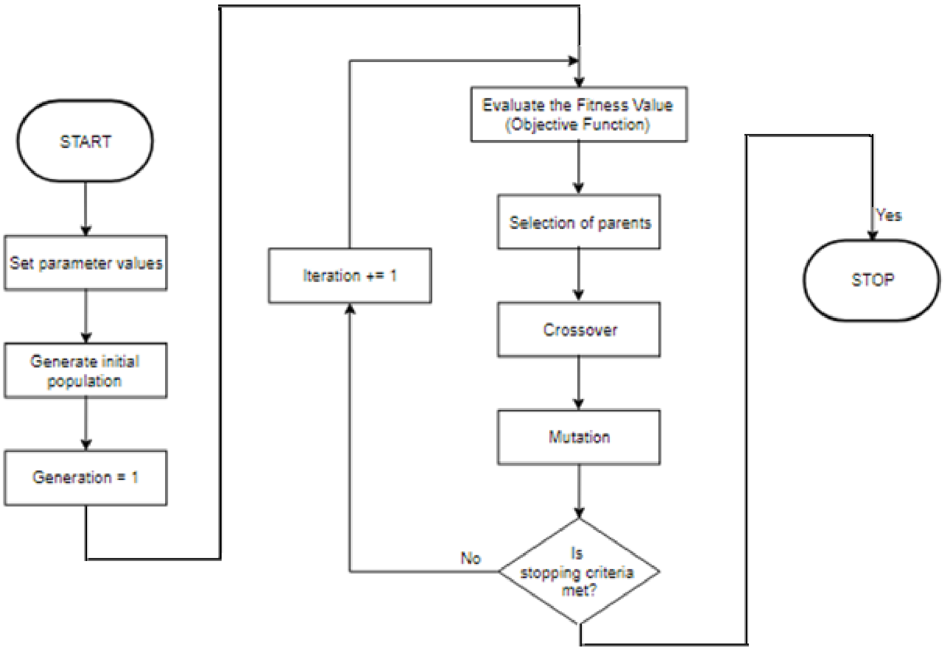


Figure 6.8. Genetic Algorithm generic flowchart

6.2.6.1. Scaling Optimization Variables

During optimization process, optimization variables are changed so that different vehicle configurations are tested in terms of constraints and objective function. And at the end, best configuration (with lowest cost function according to Appendix C.) satisfying the constraints is said to be the optimum solution. Optimization variables used are electric motor power rating and battery energy capacity in this work. Electric motor power is changed by changing the mc_trq_scale variable in MATLAB workspace in the same way with the ICE made in Chapter 4.2.2. Base value (mc_trq_scale=1.0000) for the electric motor power in our model is 45 kW. By changing the mc_trq_scale variable as 0.6000, maximum output torque curve of electric motor is moved to 0.6 of its initial value in y-axis and hence electric motor power rating is made 27 kW. And in the same way, battery energy capacity is changed using the ess_cap_scale variable in the workspace. Base value (ess_cap_scale=1.0000) for the battery energy capacity is 1800 Wh in our model. For example, making ess_cap_scale 8.0000 results in 14.4 kWh battery pack.

6.2.6.2. Hybrid Vehicle Mass Calculation

As the optimization algorithm changes electric motor power and battery energy capacity ratings, weight of these components and hence the total vehicle weight changes. Total weight of the vehicle is calculated in every step and changed for more accurate simulation. Formula for vehicle weight is given in Equation 5.1.

6.2.6.3. Fuel Consumption and All Electric Range

Fuel consumption is given as L/100km at the end of the simulation by ADVISOR. However, in some situations battery is left with some charge at the end of the simulation and fuel equivalent of this remaining charge should be subtracted from the total consumption for more meaningful fuel consumption results. For example, at the end of the simulation battery remained with 0.4 SOC. Then, required amount of fuel to charge the battery 0.4-0.3=0.1 SOC is calculated by taking fuel density as 832 g/L, fuel energy density as 10942 Wh/L and assuming that ICE operated at the most efficient point. Lastly, amount of liters found is subtracted from total fuel consumed, divided to total distance and multiplied by 100 to find the real consumption (in L/100km) of the vehicle for that drive cycle. This calculation is made to make a fair comparison of used energy for each solution. To be more clear, simulation that ends with a full battery gives high fuel consumption results although it is not the situation since remaining battery SOC would be used if the simulation would have continued.

All electric range is taken as the distance covered up to first starting of the ICE/Gen set (0.3 SOC point), after starting the drive cycle simulation with 100% charge of the battery.

6.2.7. Application of Genetic Algorithm

Flow diagram for the Genetic Algorithm implemented for optimization process is seen in Figure 6.9. In this figure, actions take place during optimization process are given in an ordered manner. As it can be seen from the figure, firstly ADVISOR is initialized. Initialization is done in “no gui” format since optimization algorithm calls advisor many times to make objective function, cost function and fitness value calculations in background which cannot be done using ADVISOR GUI.

6.2.7.1. Interfacing ADVISOR to Matlab

Commands used in ADVISOR no gui form are given below, with the explanations.

Table 6.7. Command sets used in ADVISOR no gui form

Command Set	**Explanation**
input.init.saved_veh_file='fio_hybrid_hess_RA_in' adv_no_gui('initialize',input);	Starts the model fio_hybrid_hess_RA
input.modify.param={'veh_mass','mc_trq_scale', 'ess_cap_scale'} input.modify.value={1450,0.5,1}	Adjusts vehicle mass as 1450 kg, electric motor as 22.5 kW and battery capacity as 1.8 kWh
input.cycle.param= {'cycle.name','cycle.SOCiter'} input.cycle.value = {'CYC_NEDC',15} adv_no_gui('drive_cycle', input)	Starts 15 cycle of NEDC simulation with the initialized vehicle

ADVISOR model is initialized as below, with 21.4 kW electric motor, 35 kW ICE, 15 kWh HESS pack and 112 Wh supercapacitor bank. Values seen in function are the scaling parameters in order to have desired capacity/power for the related optimization variable. For example, original internal combustion engine maximum power is 56kW and fc_trq_scale which is the torque scaling parameter for internal combustion engine is given as 0.625 hence initial ICE maximum power is 0.625x56=35kW. Optimization algorithm also uses these parameters to scale the components and find the optimum value for each. Moreover, as variables are changed, effected properties of the vehicle are also updated. For example, vehicle mass is recalculated and increased when battery energy capacity is increased.

```
input.init.saved_veh_file = 'fio_hybrid_hess_RA_in';
[error, resp] = adv_no_gui('initialize',input);
input.modify.param={'veh_mass',  'ess_module_num',  'mc_spd_scale',
'mc_trq_scale', 'ess2_cap_scale', 'ess2_module_num', 'fc_trq_scale',
'ess_cap_scale', 'gc_trq_scale'};
input.modify.value={1452,28,0.60,0.4756,1.87,20,0.625,8.5712,0.38};
[a,b]=adv_no_gui('modify',input);
```

Afterwards, Genetic Algorithm is initialized in terms of PopulationSize, Generations and StallGenLimit in MATLAB code, as below. “PopulationSize” determines number of members in a generation, “Generations” is the number of maximum generations to be created and “StallGenLimit” is the minimum number of generations for fitness function to be counted as in tolerance limits. “Nvars” is the number of optimization variables. “LB” and “UB” are the lower and upper bounds for these optimization variables, respectively. Matrices “A”, “B”, “Aeq” and “Beq” are not related to our optimization problem. “A” is linear inequality constraints matrix, “Aeq” is linear equality constraints matrix, “B” is linear inequality constraints vector and “Beq” is linear equality constraints vector. In this work, all of these matrices are not used since problem is modelled using a toolbox, ADVISOR namely, not using mathematical formula set defined by matrices.

Generation size is chosen as 20 to keep the optimization time low. If it would not converge or changes in the objective function would still be high at the end of 20 generations, generation size could be increased. Population size is taken as 10 since there are only 4 optimization variables.

```
nvars = 4;
LB =[0.4444 4 0.5 22000]';
UB =[1.000 16 1.0 30000]';

A=[];
B=[];
Aeq=[];
Beq=[];
options = gaoptimset('PlotFcns',{@gaplotscorediversity,@gaplotbestf,
@gaplotstopping},'PopulationSize',10,'Generations',20,
'StallGenLimit',10);

[X,Fval,EXITFLAG,Output]=ga(FUN,nvars,A,B,Aeq,Beq,LB,UB,NONLCON,
options)
```

Then the MATLAB algorithm automatically creates an initial population of optimization variables randomly and between upper and lower bounds for them. And this is called the first generation. First generation members are simulated in ADVISOR and constraints are checked. Suitable ones are used for fitness function evaluation and best fitting members are chosen as parents. Parents are used in mutation and crossover processes to generate next generations which are going to be called as second, third, fourth generation and so on. This next generation creation process continues until stopping criterias are met. In this case, stopping criteria are defined as the relative change in objective function and maximum number of generations.

6.2.7.2. Optimization Flowchart

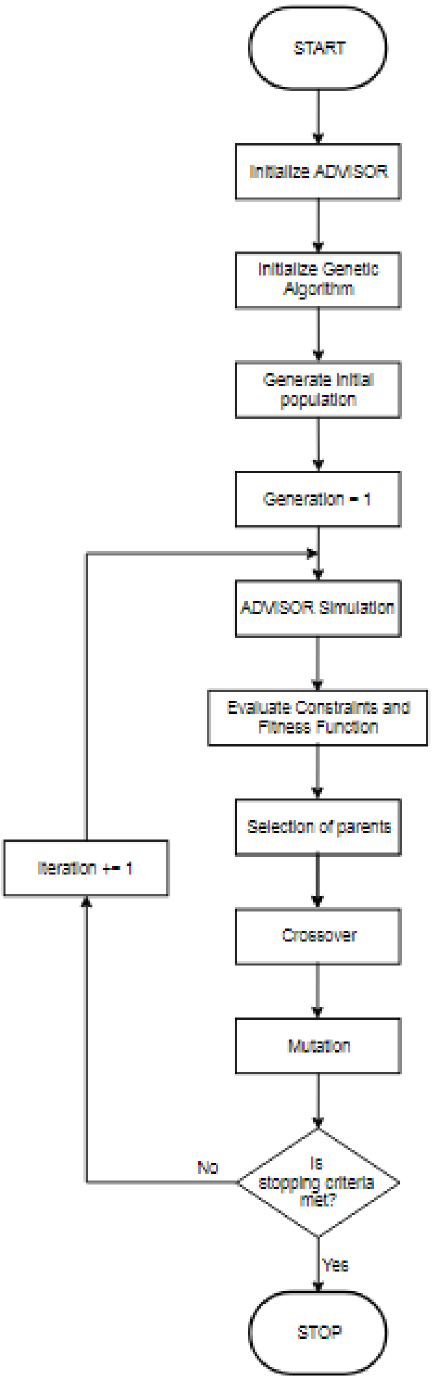


Figure 6.9. Flowchart for optimization process

6.2.8. Optimization Results

Optimization algorithm is typically found to converge in around 30000 seconds (8-9 hours) for each case and stopped due to the invariance in the fitness value and fitness of individuals as it can be seen from the results below. This means that there are nearly identical members in the optimization optimization variable groups and cost function is not changing considerably. Hence optimization decides there will be no further changes in the optimization.

Results for each cost function considered in Chapter 6.2.3 are given below. Base values of optimization variables are 45kW and 1.8kWh for electric motor and battery pack respectively.

6.2.8.1. Results for Case 1: Total Cost of the Vehicle

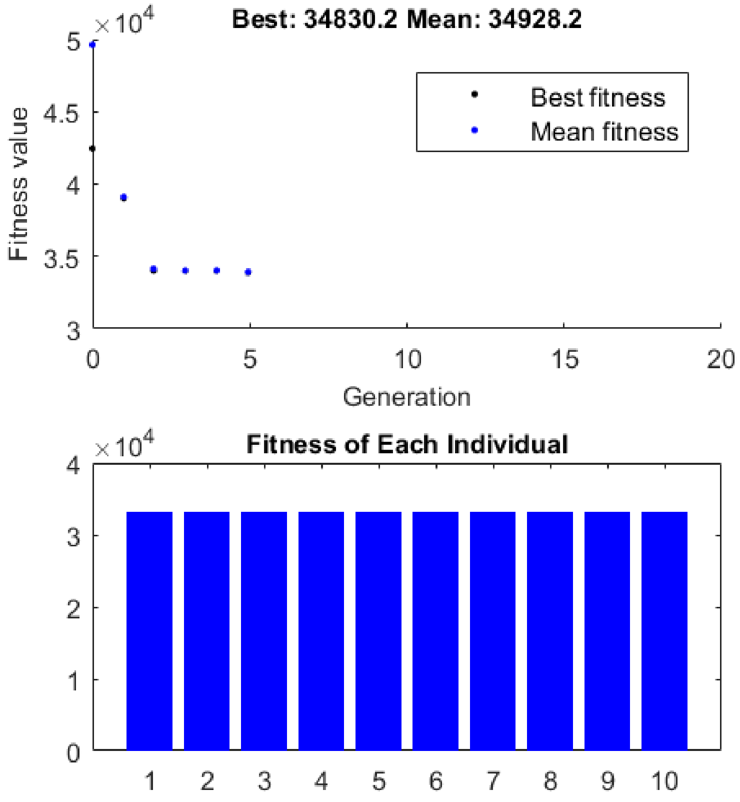


Figure 6.10. Optimization results for Case 1

For case 1, total cost of the vehicle is optimized. Optimization process resulted in 24.75 kW electric motor, 28.76 kWh battery pack and 36.4 kW ICE. Generator is selected to operate at 1520 rpm with 22 kW output power. Note that instead of operating the ICE at most efficient point, ICE is selected to be smaller and operated at a worse point by the optimization algorithm. This results from the small invariance in fuel consumption of ICE around the most efficient point. Vehicle consumes 0.4514 L/100km diesel on NEDC cycle when simulated for 200 km and has 175 km all electric range. This vehicle uses 2.17 $ electricity at the first 175 km, corresponding to 1.62 L of diesel in terms of cost. Another point for this case is that, since this vehicle makes very long distances per year, optimizing it in terms of total cost nearly means optimizing it in terms of running costs. Initial cost of the vehicle for this case is 27789$, 1.915 times the diesel Fiorino initial cost. However, 5 years running cost of hybrid vehicle is 7041 $ where it is 18670 $ for diesel Fiorino.

6.2.8.2. Results for Case 2: Initial Cost of the Vehicle

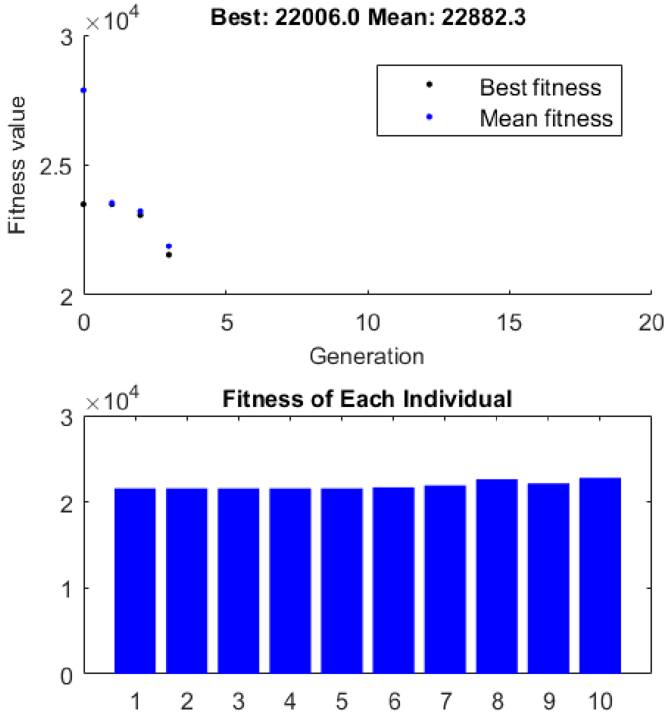


Figure 6.11. Optimization results for Case 2

For case 2, initial cost of the vehicle is optimized. Optimization process resulted in 17.40 kW electric motor, 7.90 kWh battery pack and 29.6 kW ICE. Generator is selected to operate at 2522 rpm with 22.3 kW output power. In this case, ICE is made smaller to decrease the vehicle initial cost as small as possible but operation rpm is increased to supply electric motor average power when battery is emptied. Battery pack is resulted to be 7.90 kWh which is the smallest battery satisfying minimum 50 km all electric range constraint. Vehicle consumes 3.0962 L/100km fuel on NEDC cycle when simulated for 200 km and has 52 km all electric range. This vehicle uses 0.6 $ electricity in this 200 km, corresponding to 0.45 L of diesel in terms of cost. Another point for this case is that, running costs of the vehicle increased considerably due to the dramatic decrease in the battery energy capacity. Initial cost of the vehicle for this case is 22006 $, 1.516 times the diesel Fiorino initial cost. However, 5 years running cost of hybrid vehicle is 14610 $ where it is 18670 $ for diesel Fiorino.

6.2.8.3. Results for Case 3: Running Costs of the Vehicle

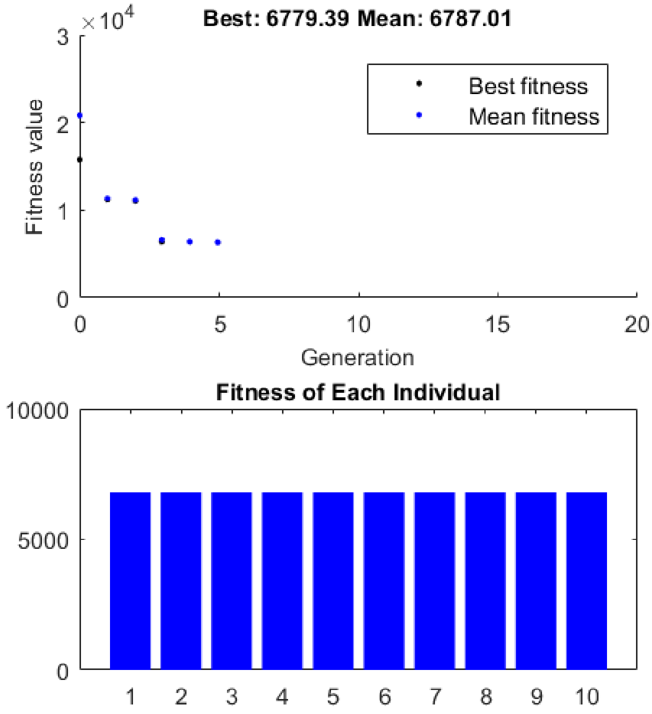


Figure 6.12. Optimization results for Case 3

For case 3, running costs of the vehicle for 5 years is optimized. Optimization process resulted in 29.6 kW electric motor, 28.75 kWh battery pack and 30.7 kW ICE. Generator is selected to operate at 2246 rpm with 22.1 kW output power. This time battery pack is increased up to the upper bound and electric motor is selected to be a bit more powerful to decrease the running costs of the vehicle. As it is seen in sensitivity analysis chapter, increasing electric motor power rating up to some point decreases fuel consumption. This is due to the utilization of electric motor at more efficient points, increasing the overall efficiency. In this case, vehicle consumes 0.3356 L/100km fuel on NEDC cycle when simulated for 200 km and has 178 km all electric range. This vehicle uses 2.17 $ electricity in this 200 km, corresponding to 1.62 L of diesel in terms of cost. Another point for this case is that, running costs of the vehicle increased considerably due to the dramatic decrease in the battery energy capacity. Initial cost of the vehicle for this case is 28192 $, 1.94 times the diesel Fiorino initial cost. However, 5 years running cost of hybrid vehicle is 6700 $ where it is 18670 $ for diesel Fiorino.

Optimization results are summarized in Table 6.8 below. Conventional Fiorino (56 kW diesel) costs 14513 $ initially and 5 years running cost is found to be 18670 $ under the same conditions.

Table 6.8. Sizing methods and optimization results comparison

Method	Electric Motor (kW)	Battery energy Capacity (kWh)	Generator Speed (rpm)	Generator Operating Power (kW)	ICE Maximum Power (kW)	Fuel Consumption (L/100km)	Initial Cost ($)	Running Costs ($)	Total Cost ($)
Conventional Method	27.9	27.10	-	38.3	-	0.9500	27674	8907	36581
Proposed Method	21.4	14.90	1500	22.0	35.0	2.0000	23870	10919	34789
Total Cost Optimization	24.8	28.76	1520	22.0	36.4	0.4514	27789	7041	34830
Running Cost Optimization	29.6	28.75	2246	22.1	30.7	0.3356	28192	6700	34892
Initial Cost Optimization	17.4	7.90	2522	22.3	29.6	3.0962	22006	14610	36616

As it can be seen from Table 6.8, maximum difference in total vehicle cost between the optimum vehicle and the vehicle sized using new approach is around 0.1%. Difference between the best case and conventional method is 5% in terms of total vehicle cost. So it can be concluded that in terms of total cost, proposed sizing method gives closer results to optimized component ratings with respect to total and running costs than the conventional sizing method results. This is mainly due to the fact that energy calculations are made directly at the wheel of the conventional vehicle and component ratings are calculated in reverse order by considering the efficiencies.

Moreover, running costs are increased around 2000$ when vehicle is sized using the proposed method instead of the conventional method. However, initial cost is decreased around 3800 $ in proposed method with respect to conventional method. Hence, total cost of the vehicle resulted to be lower in the new method.

Conventional method is better in running costs. On the other hand, proposed method gives better results in terms of initial cost and total cost of the vehicle. When the requirement for optimization after sizing is considered, proposed method seems not to need optimization since the optimization results are very close to sizing results of the new method. From this point of view, proposed method is also better in terms of the time spent for the whole sizing process.

6.3. Comparison of Conventional Vehicle and Optimized Vehicle

After optimization process, conventional vehicle and optimized vehicles are compared in terms of cumulative costs over 10 years. In this comparison, maintenance costs are distributed throughout the years and battery replacement is made for every 5 years for the hybrid vehicle. Motor vehicle taxes are not included here. Running costs and initial cost are calculated as given in Chapter 6.2.2.

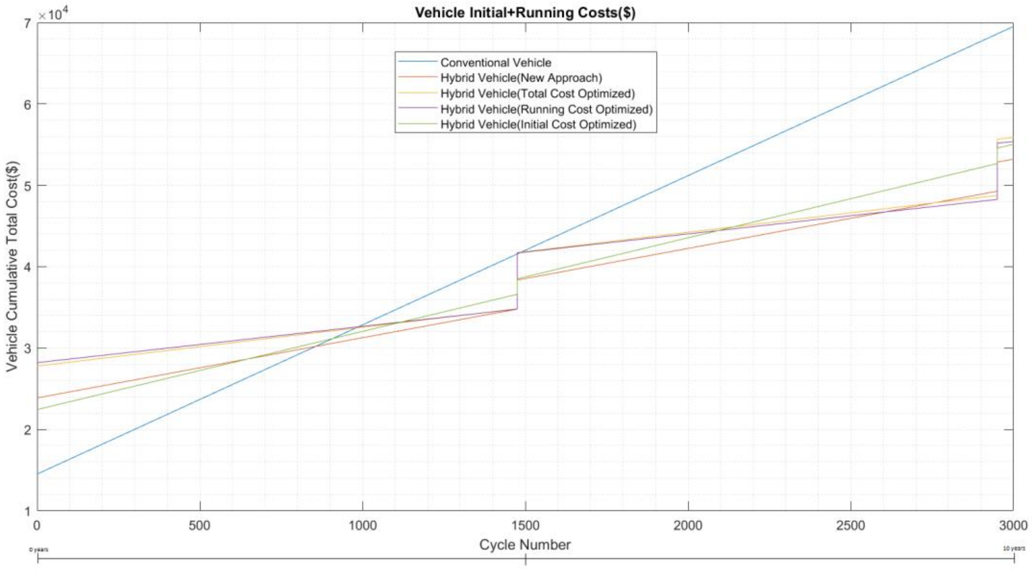


Figure 6.13. Total costs comparison of conventional vehicle and optimized hybrid vehicle

It is seen from Figure 6.13 that initial cost of the hybrid electric vehicle is higher than the conventional vehicle. However, in such cases that vehicles are used for longer distances especially under city conditions, running costs become a significant parameter that affects total costs of the vehicle. In this work, a vehicle driven for 200 km daily in urban areas is chosen and it is seen that hybrid electric vehicle in proposed approach catches up the conventional vehicle in 2.8 years (850 workdays), due to its lower running costs. At the end of 10 years period, there is more than 1.3:1 total cost ratio between the conventional vehicle and the hybrid electric vehicle, for this case. Initial cost optimized vehicle catches up the conventional vehicle in terms of initial costs in 3 years (900 workdays) and vehicle optimized in terms of total and running costs catches up in 3.3 years (980 workdays).

Another comparison to be made between optimized vehicle and the conventional vehicle is the performance of both vehicles. In Table 6.9, it is seen that fuel consumption of the hybrid Fiorino designed using proposed approach is lower than half of the fuel consumption of conventional Fiorino. Hybrid Fiorino accelerates slower than conventional Fiorino. This result is expected since, acceleration time is adjusted to be 17 s maximum in sizing. This is done in order not to increase electric motor power rating too much because there is not a need for faster acceleration ratings for a light commercial vehicle used in city conditions.

Table 6.9. Performance comparisons and return of investment between conventional and hybrid Fiorino

	Fuel Consumption (L/100 km)	0-100 kph Acceleration (s)	Return of Investment (wrt Diesel Fiorino)
Conventional Fiorino	4.40	12.5	-
Hybrid Fiorino (Proposed Method)	1.99	16.7	2.8 years
Hybrid Fiorino (Total cost optimized)	0.4514	28.1	3.3 years
Hybrid Fiorino (Initial cost optimized)	3.0962	24.8	3 years
Hybrid Fiorino (Running cost optimized)	0.3356	22.3	3.3 years

CHAPTER 7

CONCLUSIONS

The main objective of this thesis is to design a series plug-in hybrid electric vehicle with hybrid energy storage system, using the wheel energy and power output requirements on NEDC drive cycle. This vehicle is intended to be charged through mains overnight, make 200 km during the day and have at least 50 km all electric range. After the design problem is defined as an optimization problem, cost optimization process has taken process. Lastly, optimized vehicle is compared with the conventional non-hybrid vehicle and conventional sizing method in terms of cost and performance.

In this study, non-hybrid vehicle model is built firstly and then verified using the acceleration and NEDC fuel consumption simulations. Hybrid vehicle components are studied and modelled in Matlab ADVISOR. After building the reliable vehicle model, hybrid vehicle is modelled using these hybrid vehicle components. Vehicle sizing is made with the conventional method in literature firstly and then the new approach which uses the NEDC cycle energy and power requirements of the conventional vehicle. Only mass of the conventional vehicle is updated with the hybrid vehicle mass while simulating the vehicle on NEDC.

Before optimization, sensitivity analysis is made. Change of the vehicle performance with respect to hybrid vehicle component ratings are observed. Sensitivity analysis cases in this part of the study are: Battery energy capacity vs Fuel consumption, Initial cost vs All-Electric range, ICE max power vs Fuel consumption, Vehicle mass vs Fuel consumption, Electric motor continuous power rating vs Fuel consumption and Electric motor max efficiency vs Fuel consumption. There are some findings from sensitivity analysis part. For example, increasing electric motor power rating up to some point increases electric motor overall utilization efficiency, i.e. increasing electric motor from 20 to 40 kW overall efficiency increases by 0.01. This is due to operating the electric motor in better efficiency points at high power demands. Secondly, instead of putting a bigger internal combustion engine and operating it at the best efficient point, using a smaller engine operating at the same power rating but with worse efficiency increases diesel use in very small amounts but decreases the electric energy usage per km due to lowered weight.

After sizing the vehicle using two different methods (conventional method found in literature and new approach developed), an optimization problem is constructed by taking the vehicle costs into account. As an optimization method, Genetic Algorithm is chosen and vehicle is then optimized for three cases: Total cost, Initial cost and Running costs of the vehicle. As the total cost vehicle, initial cost and running costs are added. For the initial cost, vehicle price including the taxes plus the hybrid vehicle components price are considered. Hybrid components costs are calculated according to the electrical ratings of each and vehicle mass is updated as the design changes during optimization. Lastly for the running costs, maintenance costs, cost for charging the battery from mains and fuel consumption costs are considered. Running costs are calculated for 5 years which is the lifetime of the battery.

During optimization some calculations are also done at each iteration. For example, fuel consumption is updated by subtracting the fuel equivalent of the remaining energy in the battery so that a real consumption value is gathered. All electric range is taken as the distance covered up to the first start of the ICE/Gen set after starting with 100% charged battery. Vehicle mass is updated using the new ratings at each iteration.

Although putting extra components such as supercapacitors and two more converters instead of putting single battery pack without a converter seems to be more expensive at the first sight, this configuration increases battery lifetime and hence decreases the running costs. Moreover, supercapacitor lets the system capture more regenerative braking energy due to its higher charge current rating and efficiency.

Optimization results are examined and it is seen that conventional method has lower running costs. However, proposed approach has lower initial cost and the difference is higher. Hence new approach results in a hybrid vehicle with lower total cost. Total vehicle cost in proposed approach is 0.1% closer to optimum vehicle ratings. The difference between optimized vehicle and vehicle sized using conventional method is 5% in terms of total cost. Vehicle sized using the proposed approach resulted in 5% less total cost at the end of 5 years when compared with the vehicle sized using conventional approach. Moreover, initial cost of the hybrid vehicle in proposed method is 13.7 % less than the vehicle sized using the conventional method. After initial cost optimization, initial cost is lowered 6.8% more with respect to conventional method. However, running costs increases considerably then, resulting in higher total cost at the end of 5 years usage.

When running cost is optimized, battery energy capacity resulted to be high to decrease the fuel consumption. Battery capacity resulted in the same way also when total cost is optimized. This is due to the excessive amount of the distance covered in a year so that the fuel consumption has a bigger portion in the total cost calculation. However, this time when battery replacement time comes at the end of 5 years, total cost makes a big jump and catches the conventional vehicle total cost and hybrid vehicle loses the advantage when compared to diesel vehicle. Conversely, in the initial cost optimization, battery pack energy capacity, ICE rated power and electric motor size are selected to be as small as possible that vehicle has 50 km all electric range and can follow NEDC cycle. Since battery pack is resulted to be small, fuel consumption increased dramatically resulting in high running costs.

Optimized hybrid electric vehicle is compared to conventional vehicle in terms of total costs. It is seen that although the hybrid vehicle is paid more initially, conventional vehicle overtakes in around 3 years in terms of total costs. This early catch is due to the higher running costs of the conventional vehicle. Since high distances are covered by the vehicle i.e. 200 km/day, running costs become more important with respect to initial cost difference between vehicles at an earlier time.

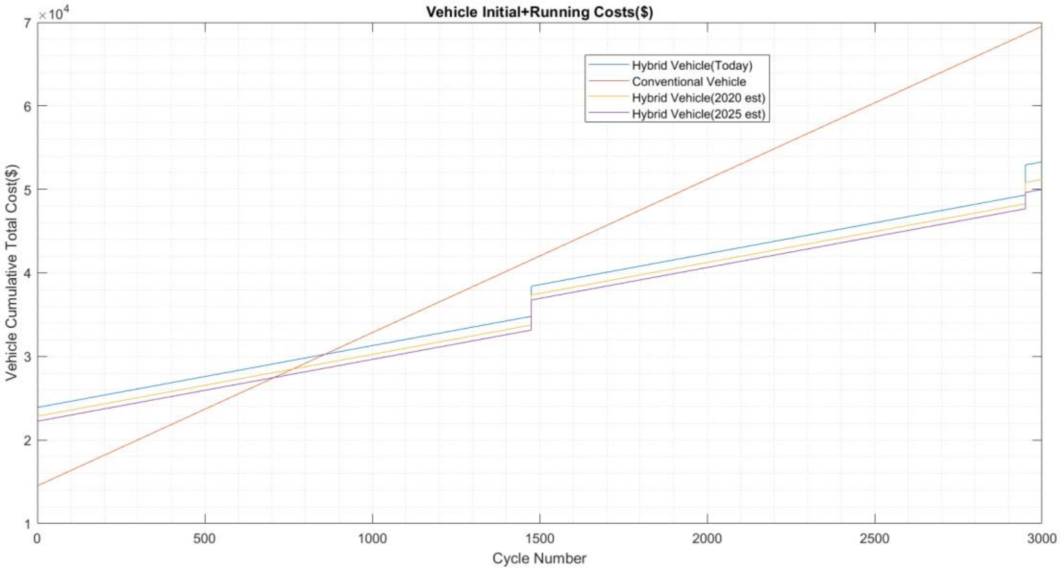


Figure 7.1. Vehicle total costs change according to future battery costs estimations

Lastly as the battery costs are decreasing, total costs are updated taking the estimated battery costs for the upcoming years, 2020 and 2025. According to a study made about future battery costs [93], it is estimated that battery pack prices are going to be around 200 $/kWh in 2020 and 160 $/kWh in 2025. In this work battery pack price is taken as 270 $/kWh and when these prices are taken into account, it can be expected that hybrid vehicle prices are going to be lower around 7% in terms of both the initial and the total cost by 2025. Moreover, catch up time of hybrid vehicle will be lower, i.e. around 2.3 years.

There are also some future works that can be done to enhance this study. These are listed below.

- State of health algorithm may be developed and used to determine the lifetime of the battery. Afterwards, effect of adding supercapacitor to energy storage system can be examined. Thus, more detailed cost analyses can be done in terms of the tradeoff between replacing the battery earlier or adding supercapacitor to the system. Moreover, some different control algorithms such as turning on the ICE during peak power can be tested to maximize the battery life.

- ICE/Gen set power rating and gear ratio can also be added as optimization variable.
- Control parameters such as depth of discharge, maximum battery power etc. may be optimized to have smaller battery pack or to increase the battery lifetime.
- Effect of temperature (especially cold weather) may be investigated. Tradeoff between heating the battery before starting under cold conditions or starting cold can be observed. Difference between heating the battery using supercapacitor in a fast manner or heating the battery slowly using its own energy can be compared.

REFERENCES

[1] C. Mi, M. A. Masrur, and D. W. Gao, *Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives*. 2011.

[2] P. Dalsjo, “Hybrid electric propulsion for military vehicles,” 2008.

[3] D. S. Cardoso, P. O. Fael, and A. Espírito-Santo, “A review of micro and mild hybrid systems,” *Energy Reports*, 2019.

[4] Y. Gao and M. Ehsani, “Parametric design of the traction motor and energy storage for series hybrid off-road and military vehicles,” *IEEE Trans. Power Electron.*, 2006.

[5] M. Ehsani, Y. Gao, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*. 2017.

[6] S. Chanda, “Powertrain Sizing and Energy Usage Adaptation Strategy,” *Univ. Akron,* 2008.

[7] G. R. Mineeshma, R. V. Chacko, S. Amal, M. L. Sreedevi, and V. Vishnu, “Component sizing of electric vehicle / hybrid electric vehicle subsystems using backward modelling approach,” in *IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2016,* 2017.

[8] C. R. Akli, X. Roboam, B. Sareni, and A. Jeunesse, “Energy management and sizing of a hybrid locomotive,” in *2007 European Conference on Power Electronics and Applications, EPE,* 2007.

[9] K. Bayar *et al.*, “Design of an extended-range electric vehicle for the EcoCAR challenge,” in *Proceedings of the ASME Design Engineering Technical Conference*, 2010.

[10] R. Bindu and S. Thale, “Sizing of hybrid energy storage system and propulsion unit for electric vehicle,” in *2017 IEEE Transportation Electrification Conference, ITEC-India 2017,* 2018.

[11] M. Porru, A. Serpi, A. Lai, G. Gatto, and A. Damiano, “Modelling, sizing and control of hybrid energy storage systems for electric vehicles,” in *Proceedings IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017.

[12] “Fiorino Combi.” [Online]. Available: http://www.fiat.com.tr/modeller/sayfalar/FIORINOCOMBI/Teknik.aspx.

[13] "FIAT Qubo specs & photos - 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019 - autoevolution." [Online]. Available: https://www.autoevolution.com/cars/fiat-qubo-2008.html#aeng_fiat-qubo-2008-13-multijet-95-hp. [Accessed: 19-Jan-2017].

[14] "Plot Digitizer." [Online]. Available: http://plotdigitizer.sourceforge.net/. [Accessed: 20-Jan-2017].

[15] "Fiat Fiorino Combi 1.3 Multijet 16V Euro 5 (man. 5) engine Horsepower / Torque Curve." [Online]. Available: http://www.automobile-catalog.com/curve/2014/1457480/fiat_fiorino_combi_1_3_multijet_16v_euro_5.html. [Accessed: 20-Jan-2017].

[16] "Fiat Fiorino Qubo 1.3 JTD Multijet 16V (75 Hp) | Technical specs, data, fuel consumption, Dimensions." [Online]. Available: https://www.auto-data.net/en/fiat-fiorino-qubo-1.3-jtd-multijet-16v-75hp-6951. [Accessed: 27-Jul-2018].

[17] "Freelander Wheels and Tyres « FreelanderSpecialist.com." [Online]. Available: https://www.freelanderspecialist.com/freelander-2/freelander-wheels-and-tyres. [Accessed: 20-Jan-2017].

[18] P. Stenner and M. Lienkamp, "100 tips to beat the New European Driving Cycle (NEDC)," 2014.

[19] "FIAT Qubo Trekking 1.3 Mjet." [Online]. Available: http://www.automobile-catalog.com/performance/2016/2259200/fiat_qubo_trekking_1_3_. [Accessed: 20-Jan-2017].

[20] "Fiorino Cargo | Cargo Vans | Vans | Fiat Professional UK." [Online]. Available: https://www.fiatprofessional.com/uk/fiorino-cargo. [Accessed: 19-Jan-2017].

[21] E. Grunditz and E. Jansson, "Modelling and Simulation of a Hybrid Electric Vehicle for Shell Eco-marathon and an Electric Go-kart," CHALMERS UNIVERSITY OF TECHNOLOGY, 2009.

[22] S. Skoog, "Power Sources for Hybrid Electric Vehicles," Lund University, 2009.

[23] Y. L. Zhou, "Modeling and Simulation of Hybrid Electric Vehicles," University of Victoria, 2005.

[24] "Batteries - energypedia.info." [Online]. Available: https://energypedia.info/wiki/Batteries. [Accessed: 10-Aug-2019].

[25] "Understanding Batteries - Spirit Energy." [Online]. Available: https://www.spiritenergy.co.uk/kb-batteries-understanding-batteries. [Accessed: 08-Jun-2018].

[26] “Battery Chemistry Chart | Battery Specifications Info.” [Online]. Available: https://www.houseofbatteries.com/battery-chemistry-chart. [Accessed: 10-Aug-2019].

[27] “Which hybrid battery is better?” [Online]. Available: https://www.thehybridshop.com/battery-conditioning/questions/which-hybrid-battery-is-better-nickel-metal-hydride-or-lithium-ion/. [Accessed: 10-May-2018].

[28] C. S. N. Shiau, C. Samaras, R. Hauffe, and J. J. Michalek, “Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles,” *Energy Policy*, 2009.

[29] M. Mruzek, I. Gajdáč, Ľ. Kučera, and D. Barta, “Analysis of Parameters Influencing Electric Vehicle Range,” in *Procedia Engineering*, 2016.

[30] *Systems Perspectives on Electromobility*. Chalmers University Press, 2014.

[31] R. Sadoun, N. Rizoug, P. Bartholumeüs, B. Barbedette, and P. Lemoigne, “Sizing of hybrid supply (battery-supercapacitor) for electric vehicle taking into account the weight of the additional Buck-Boost chopper,” in *2012 1st International Conference on Renewable Energies and Vehicular Technology, REVET 2012*, 2012.

[32] “Ricardo Electric Vehicle Component Sizing vs Vehicle Structural Weight Report | Drive Aluminum.” [Online]. Available: https://www.drivealuminum.org/research-resources/ricardo-electric-vehicle-component-sizing-vs-vehicle-structural-weight-report/. [Accessed: 08-Sep-2018].

[33] O. Barlas, “Ford Tourneo Connect Hybrid Electric Vehicle Transformation With ADVISOR,” İstanbul, 2005.

[34] “Toyota Prius Smaller Batteries.” [Online]. Available: https://www.greenoptimistic.com/toyota-prius-smaller-batteries#.WI4zBlOLTIU. [Accessed: 02-May-2017].

[35] “Battery Module NP2 | Products | Development, manufacture, and sale of a hybrid car and the battery for electric vehicles (battery) | Primearth EV Energy Co., Ltd.” [Online]. Available: https://www.peve.jp/en/product/np2/index.html. [Accessed: 10-May-2017].

[36] “Panasonic and Tesla Sign Agreement for the Gigafactory | Tesla.” [Online]. Available: https://www.tesla.com/blog/panasonic-and-tesla-sign-agreement-gigafactory?redirect=no. [Accessed: 08-Apr-2018].

[37] “Tesla Model S.” [Online]. Available: http://www.roperld.com/science/TeslaModelS.htm. [Accessed: 08-Mar-2018].

[38] “Nissan and Portugal Exploring Establishing Li-ion Battery Plant in Portugal - Green Car Congress.” [Online]. Available: https://www.greencarcongress.com/2009/03/nissan-and-port.html. [Accessed: 03-Jun-2018].

[39] “EVTV Motor Verks Store: 1 Renault Influenza Battery Packs, Lithium Battery Cells, Betterplace.” [Online]. Available: http://store.evtv.me/proddetail.php?prod=Betterplace. [Accessed: 07-Jan-2017].

[40] “Could 2017 BMW i3 Use Samsung SDI’s Planned 94 Ah Battery Cells? | CleanTechnica.” [Online]. Available: https://cleantechnica.com/2015/11/27/could-2017-bmw-i3-use-samsung-sdis-planned-94-ah-battery-cells/. [Accessed: 03-May-2017].

[41] “Looking forward to the Samsung Lithium-ion Battery Enabling 600 km Range – EMValley.” [Online]. Available: http://www.emvalley.com/news/looking-forward-to-the-samsung-lithium-ion-batteries-enabling-600-km-range/. [Accessed: 03-May-2017].

[42] “2016 Hyundai Sonata PHEV raises the bar among blended PHEVs - GM-VOLT : Chevy Volt Electric Car Site GM-VOLT : Chevy Volt Electric Car Site.” [Online]. Available: https://gm-volt.com/2015/05/22/2016-hyundai-sonata-phev-raises-the-bar-among-blended-phevs/. [Accessed: 03-May-2018].

[43] “7.2V 6500mAh Hybrid Electric Vehicle Battery.” [Online]. Available: https://www.alibaba.com/product-detail/7-2V-6500mah-Hybrid-Electric-Vehicle_60253292709.html?spm=a2700.7724838.0.0.wzxorn&s=p. [Accessed: 17-Jan-2017].

[44] “hybrid vehicle battery 48v honda hybrid.” .

[45] “hybrid vehicle battery 12V100Ah.” [Online]. Available: https://www.alibaba.com/product-detail/hybrid-vehicle-battery-12V100Ah-hybrid-TB_490442102.html?spm=a2700.7724838.0.0.wzxorn. [Accessed: 01-May-2017].

[46] “Electric Boat Hybrid Electric Vehicle LiFePO4.” [Online]. Available: https://www.alibaba.com/product-detail/Electric-Boat-Hybrid-Electric-Vehicle-LiFePO4_60477427605.html?spm=a2700.7724838.0.0.wzxorn. [Accessed: 01-May-2017].

[47] “High Rate LiFePO4.” [Online]. Available: https://www.alibaba.com/product-detail/3-3v-20ah-high-rate-lifepo4_60468482283.html?spm=a2700.7724838.0.0.wzxorn. [Accessed: 02-May-2017].

[48] “Rechargeable LiFePO4 hybrid car battery.” .

[49] “96V 100Ah Li-Ion Hybrid Car.” [Online]. Available: https://www.alibaba.com/product-detail/96V-100Ah-li-ion-hybrid-car_60410671922.html?spm=a2700.7724838.0.0.wzxorn. [Accessed: 02-May-2017].

[50] “Honda Civic NiMH.” [Online]. Available: https://www.alibaba.com/product-detail/for-honda-civic-Ni-Mh-7_60321006638.html?spm=a2700.7724838.0.0.wzxorn. [Accessed: 02-May-2017].

[51] “3-EVF-200-A-6V200A.” [Online]. Available: https://www.alibaba.com/product-detail/3-EVF-200-A-6V200A-3HR_60216560255.html?spm=a2700.7724838.0.0.wzxorn. [Accessed: 02-May-2017].

[52] S. Barcellona, M. Brenna, F. Foiadelli, M. Longo, and L. Piegari, “Analysis of Ageing Effect on Li-Polymer Batteries,” *Sci. World J.*, vol. 2015, 2015.

[53] “BU-1002a: Hybrid Electric Vehicles and the Battery – Battery University.” [Online]. Available: https://batteryuniversity.com/index.php/learn/article/hybrid_electric_vehicles_and_the_battery. [Accessed: 03-May-2017].

[54] “Battery Life and How To Improve It.” [Online]. Available: https://www.mpoweruk.com/life.htm. [Accessed: 05-Jun-2018].

[55] “Get The Straight Facts About Honda Hybrid Battery Replacement.” [Online]. Available: https://bumblebeebatteries.com/straight-facts-about-honda-hybrid-battery-replacement/. [Accessed: 19-Jul-2017].

[56] “Honda insight Battery.” [Online]. Available: http://www.insightcentral.net/encyclopedia/enbattery.html. [Accessed: 19-Jul-2017].

[57] M. Olszewski, “Evaluation of 2004 Toyota Prius Hybrid Electric Drive System,” 2005.

[58] P. Ahmad, G. Jeffrey, and K. Matt, “Ultracapacitor Applications and Evaluation for Hybrid Electric Vehicles,” in *Presented at the 7th Annual Advanced Capacitor World Summit Conference*, 2009.

[59] Murata, “Supercapacitor (EDLC) Basics (Part 1): What Is a Supercapacitor (EDLC)? | Murata Manufacturing Co., Ltd.,” 2015. [Online]. Available: https://www.murata.com/en-eu/products/emiconfun/capacitor/2015/03/24/20150324-p1. [Accessed: 10-Aug-2019].

[60] M. Pedram, N. Chang, Y. Kim, and Y. Wang, “Hybrid electrical energy storage systems,” in *Proceedings of the International Symposium on Low Power Electronics and Design*, 2010.

[61] K. Mikkelsen, “Design and evaluation of hybrid energy storage systems for electric powertrains,” University of Waterloo, 2010.

[62] M. Michalczuk, L. M. Grzesiak, and B. Ufnalski, “A lithium battery and ultracapacitor hybrid energy source for an urban electric vehicle,” *Electrotech. Rev.*, vol. 88, no. 4, pp. 158–162, 2012.

[63] A. Florescu, S. Bacha, I. Munteanu, and A. I. Bratcu, “Frequency-separation-based energy management control strategy of power flows within electric vehicles using ultracapacitors,” in *IECON Proceedings (Industrial Electronics Conference)*, 2012.

[64] X. Hu, N. Murgovski, L. M. Johannesson, and B. Egardt, “Comparison of three electrochemical energy buffers applied to a hybrid bus powertrain with simultaneous optimal sizing and energy management,” *IEEE Trans. Intell. Transp. Syst.*, 2014.

[65] “Maxwell-BoostCap-Ultra-Capacitors-3000-Farad-2-7-VDC-Lot-of-4.” [Online]. Available: http://www.ebay.com/itm/Maxwell-BoostCap-Ultra-Capacitors-3000-Farad-2-7-VDC-Lot-of-4-/302230376187?hash=item465e558efb:g:fqgAAOSwOgdYqw6j. [Accessed: 03-May-2017].

[66] “2.7V 650-3000F ULTRACAPACITOR CELLS Product Specs.” [Online]. Available: https://www.maxwell.com/images/documents/K2Series_DS_1015370_5_20141104.pdf. [Accessed: 03-May-2018].

[67] G. Lagunoff, “Automotive Hybrid Technology,” Automotive Hybrid Technology, 2008.

[68] P. Rajan, “Permanent Magnet & Induction Motors for Electric Vehicle.” [Online]. Available: https://www.telematicswire.net/articles_interviews_qa-2/articles_inhouse_invited/permanent-magnet-induction-motors-for-electric-vehicle/. [Accessed: 13-Oct-2019].

[69] C. C. Chan, “The state of the art of electric and hybrid vehicles,” *Proc. IEEE*, 2002.

[70] “Aytuğ Acar Detay.” [Online]. Available: https://www.aytugacar.com/Ansiklopedi/Modeller/Fiat/3/Qubo--Fiorino/203/Qubo-13-Multijet-5MT-(75-HP)/639. [Accessed: 27-Jun-2019].

[71] E. Figenbaum, “Can battery electric light commercial vehicles work for craftsmen and service enterprises?,” *Energy Policy*, 2018.

[72] “Hybrid Batteries | Toyota Hybrid Cars |Toyota UK | Toyota UK.” [Online]. Available: https://www.toyota.co.uk/hybrid/hybrid-faq/batteries. [Accessed: 07-Sep-2019].

[73] “Siemens Drive Motor 1PV5135-4WS14.” [Online]. Available: http://www.metricmind.com/wp-content/uploads/2011/09/1pv5135-4ws14-300V.pdf. [Accessed: 07-Jun-2018].

[74] M. Fries *et al.*, “An Overview of Costs for Vehicle Components, Fuels, Greenhouse Gas Emissions and Total Cost of Ownership Update 2017,” *Researchgate*, 2017.

[75] “Fuel Converter.” [Online]. Available: http://adv-vehicle-sim.sourceforge.net/fuel_converter.html. [Accessed: 10-Sep-2018].

[76] “1000cc suzuki F10A 465Q engine.” [Online]. Available: https://www.alibaba.com/product-detail/1000cc-suzuki-F10A-465Q-engine_729592090.html. [Accessed: 05-Jan-2017].

[77] “Diesel Engine for Generator.” [Online]. Available: https://wfcainiao.en.alibaba.com/product/1812282728-807279604/K4100D1_diesel_engine_specialized_for_generator.html?spm=a2700.icbuShop.prewdfa4cf.20.42b92696qfu7We. [Accessed: 04-Aug-2018].

[78] J. Pyrhönen, T. Jokinen, and V. Hrabovcová, *Design of Rotating Electrical Machines*. 2014.

[79] “Fiat Fiorino dimensions - Car Body Design.” [Online]. Available: https://www.carbodydesign.com/gallery/2007/12/28-fiat-fiorino-design/9/. [Accessed: 27-Jul-2018].

[80] “Yanmar 2TNV70-HGE.” [Online]. Available: https://www.yanmar.com/us/wp-content/uploads/2015/11/2TNV70-HGE-bro.pdf. [Accessed: 18-Jun-2018].

[81] “Diesel Water-cooled engines - industrial - Yanmar Industrial.” [Online]. Available: https://www.yanmarindustrial.eu/Products/Diesel-Water-cooled-industrial-engines/. [Accessed: 29-Jul-2018].

[82] “JTD Engine.” [Online]. Available: https://www.wikizeroo.org/index.php?q=aHR0cHM6Ly9lbi53aWtpcGVkaWEub3JnL3dpa2kvTXVsdGlqZXQ. [Accessed: 18-Jun-2018].

[83] “What motor oil is best for FIAT Fiorino Combis 1.3 Multijet. Motor oil by car. How much motor oil does your car holds. Motor oil catalogue.” [Online]. Available: http://oil4motor.com/en/cars-oil/FIAT/Fiorino-Combis-1.3-Multijet-(Diesel)-(2009-)/3220. [Accessed: 05-Jun-2018].

[84] “Engine oil SAE 5W-30 [SubsTech].” [Online]. Available: http://www.substech.com/dokuwiki/doku.php?id=engine_oil_sae_5w-30. [Accessed: 08-Jun-2018].

[85] W. Gao and C. Mi, “Hybrid vehicle design using global optimisation algorithms,” *Int. J. Electr. Hybrid Veh.*, 2007.

[86] “How Genetic Algorithm Works.” [Online]. Available: https://www.mathworks.com/help/gads/how-the-genetic-algorithm-works.html. [Accessed: 06-Mar-2019].

[87] M. Panda, “Performance Comparison of Genetic Algorithm, Particle Swarm Optimization and Simulated Annealing Applied to TSP,” *Int. J. Appl. Eng. Res.*, vol. 13, no. 9, pp. 6808–6816, 2018.

[88] “Nissan starts new program to replace old LEAF battery packs - Electrek.” [Online]. Available: https://electrek.co/2018/03/26/nissan-leaf-battery-pack-replacement-program/. [Accessed: 10-Oct-2018].

[89] B. Propfe, M. Redelbach, D. J. Santini, and H. Friedrich, “Cost analysis of plug-in hybrid electric vehicles including maintenance & repair costs and resale values,” *World Electr. Veh. J.*, 2012.

[90] “Lithium-Ion Battery Scrap Price $US / Lb United States, North America, Electronics Scrap Prices.” [Online]. Available: https://www.scrapmonster.com/scrap-prices/north-american-electronics-scrap/lithium-ion-battery-scraps/344/1/1. [Accessed: 21-Sep-2018].

[91] “Fiat Fiorino Fiyat Listesi 2018-Kasım 2017-11-01 - YeniModelArabalar.com.” [Online]. Available: https://www.yenimodelarabalar.com/fiat-fiorino-fiyat-listesi-2018-kasim-2017-11-01-31186.html. [Accessed: 07-Oct-2018].

[92] “high efficiency electric vehicle gearbox.” [Online]. Available: https://www.alibaba.com/product-detail/high-efficiency-electric-vehicle-gearbox_60579426386.html?spm=a2700.7724857.normalList.21.1ffe3683YwxP41&s=p. [Accessed: 10-May-2019].

[93] B. Nykvist and M. Nilsson, “Rapidly falling costs of battery packs for electric vehicles,” *Nat. Clim. Chang.*, 2015.

[94] “REGULATION (EC) No 715/2007 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and mai,” 2007.

[95] “Emission Test Cycles: ECE 15 + EUDC / NEDC.” [Online]. Available: https://www.dieselnet.com/standards/cycles/ece_eudc.php. [Accessed: 07-Mar-2017].

[96] “ECE Regulation - Addendum 82: Regulation No. 83 : Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements,” 2011.

APPENDICES

A. Fiorino Properties

Parameters for the Fiorino model in the simulation are as in Table 0.1. In this table, general properties are given and engine properties are shown in Figure 0.1 and Figure 0.2. Since the exactly same parameters with the Fiat Fiorino are used in the simulation, model can be interpreted as realistic [70].

Table 0.1. General Properties[70]

C_d	0.31
A_f	$2.04m^2$
Mass	1190kg
Wheel Size	185/65R15
Drivetrain Ratios (final drive included)	13.93 7.96 5.2 3.67 2.74

In Figure 0.1, Brake Specific Fuel Consumption map is given. This data is converted to fuel consumption map(g/s) to be used in the fuel consumption calculation with the help of the engine torque and speed.

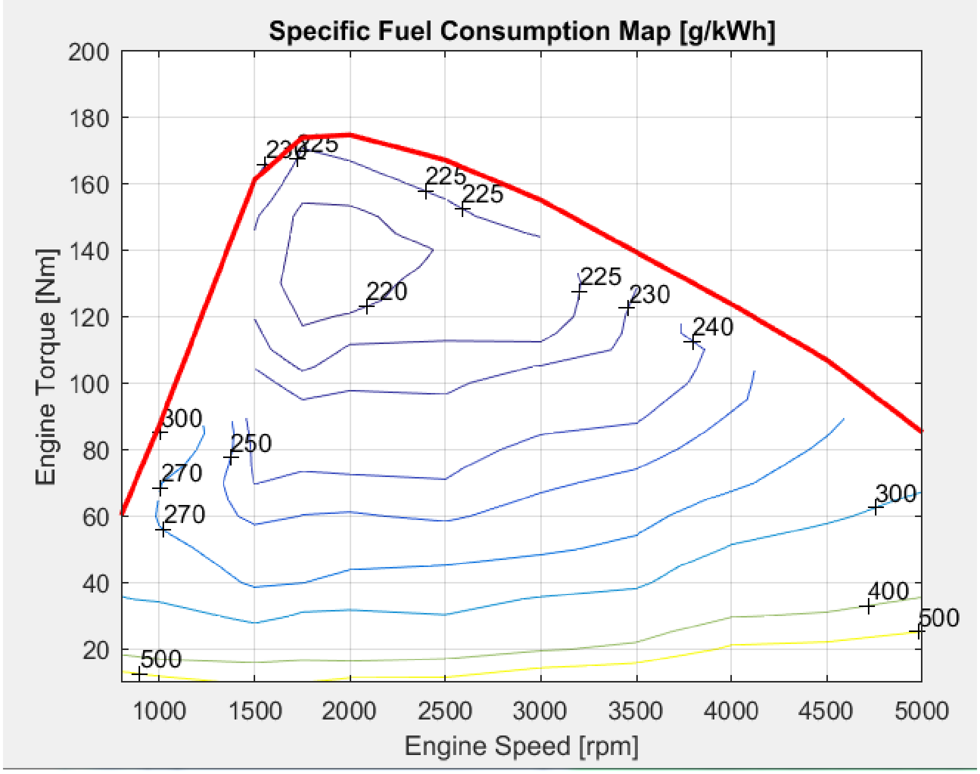
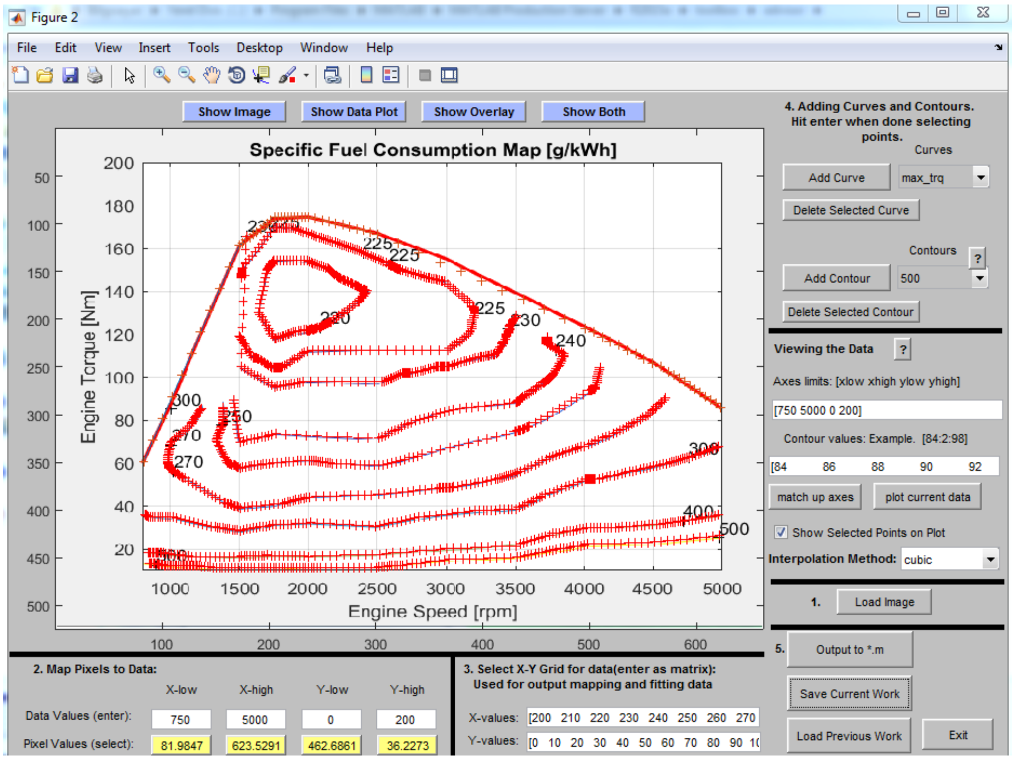


Figure 0.1. BSFC map for Fiat Fiorino 1.3 Multijet 75 hp engine

BSFC map given in Figure 0.1 is digitized using the fuel map tool in ADVISOR and dataset in Figure 0.2 is obtained. Then ADVISOR converts this dataset into the form which is directly used in fuel consumption and performance calculations, namely Fuel Efficiency Map. The Fuel Efficiency Graph which can be seen in Figure 0.3, defines the engine in terms of torque, power and fuel consumption with respect to engine rpm.



4. Adding Curves and Contours. Hit enter when done selecting points.

Curves: max_trq

Contours: 500

Axes limits: [xlow xhigh ylow yhigh]

[750 5000 0 200]

Contour values: Example. [84:2:98]

[84 86 88 90 92

☑ Show Selected Points on Plot

Interpolation Method: cubic

2. Map Pixels to Data:

	X-low	X-high	Y-low	Y-high
Data Values (enter):	750	5000	0	200
Pixel Values (select):	81.9847	623.5291	462.6861	36.2273

3. Select X-Y Grid for data(enter as matrix): Used for output mapping and fitting data

X-values: [200 210 220 230 240 250 260 270

Y-values: [0 10 20 30 40 50 60 70 80 90 1(

Figure 0.2. Digitized values for the BSFC map in ADVISOR

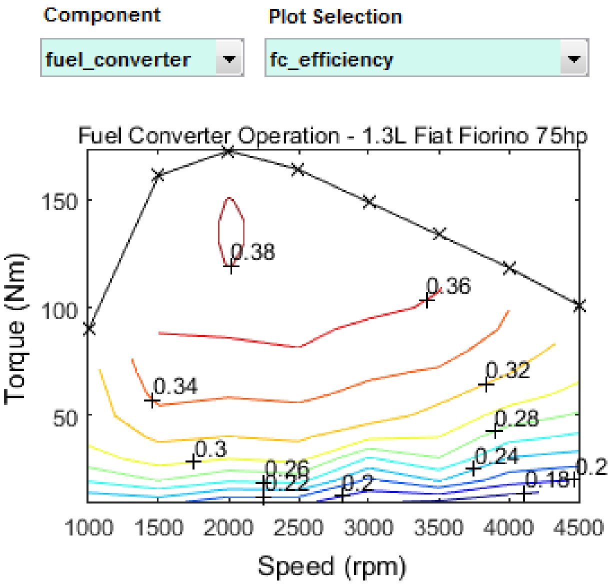


Figure 0.3. Fuel efficiency map created by ADVISOR

In Figure 0.4, horsepower and torque versus engine speed map is given for Fiat Fiorino 1.3 Multijet 75 hp. Maximum engine torque and power that can be achieved for a particular engine speed are calculated using the data extracted from this graph. These are then used in shifting gears and calculating the acceleration of the vehicle.

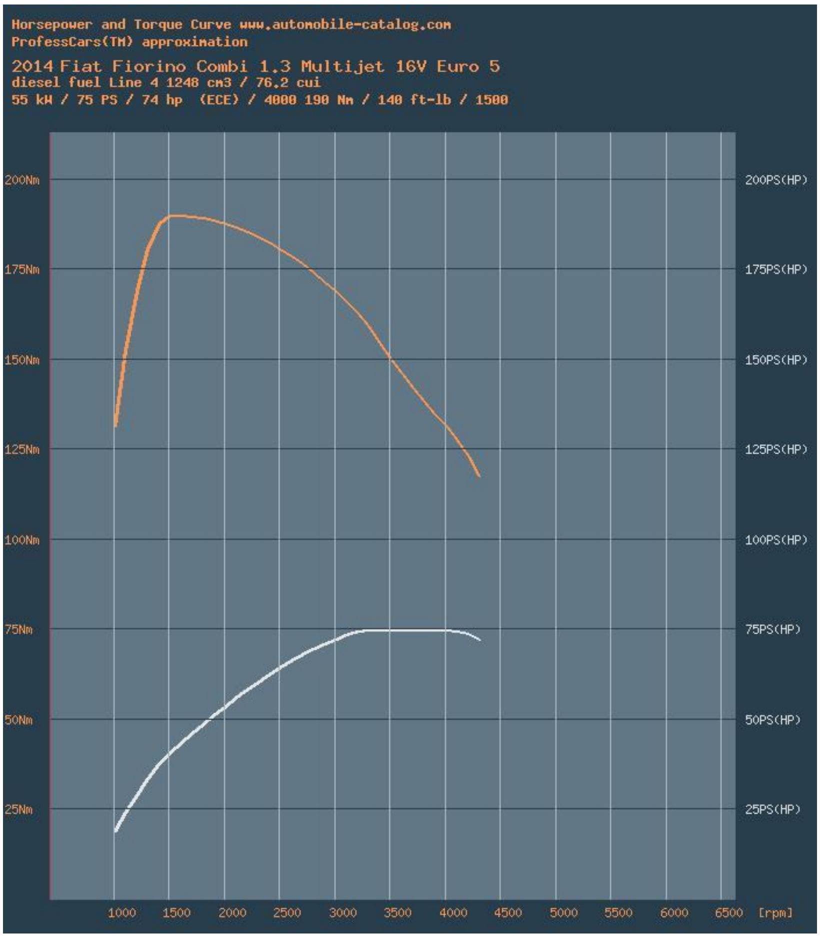


Figure 0.4. Torque hp curve for Fiat Fiorino 1.3 Multijet 75 hp [15]

In Table 0.2, maximum engine power data vs engine speed are seen which are obtained by digitizing the FIAT’s announced performance curve in Figure 0.4. Table 0.3 shows the maximum engine torque and power values vs engine speed which are obtained by digitizing the datas from the BSFC map given in Figure 0.1. When Table 0.2 and Table 0.3 are compared, it is obvious that datas are different and maximum engine power is obtained as 68 hp which is 74 hp theoretically.

To sum up, maximum torque is 190Nm and maximum power is 75hp for Fiat Fiorino 1.3 Multijet 75hp engine, as FIAT announced. However, these values are found to be 175Nm and 68hp from the BSFC map. Hence, this difference may be one of the main causes of the error in the fuel consumption simulation since it changes the torque and power to be produced at an engine speed for same amount fuel.

Table 0.2. Engine datas given by FIAT

Engine Speed (rpm)	Engine Power (hp)
1452	38
1705	46
1957	52
2457	63
2767	69
2970	71
3274	74
4061	74
4306	72

Table 0.3. Engine datas calculated from BSFC map

Engine Speed (rpm)	Engine Torque (N.m)	Engine Power (kW)	Engine Power (hp)
750	61	4,8	6,4
1452	162	24,6	33,0
1703	174	31,0	41,6
1958	175	35,9	48,1
2454	168	43,2	57,9
2764	160	46,3	62,1
2972	156	48,6	65,1
4522	107	50,7	67,9
5001	86	45,0	60,4

B. New European Drive Cycle

NEDC test is The New European Driving Cycle which is used for EU type approvals of emissions and fuel consumption for light duty vehicles. NEDC cycle does not represent the real world driving conditions, it is only a driving cycle speed pattern that is used to standardize tests and get reproducible results for CO_2 emissions and fuel consumption of a passenger car or a light commercial vehicle in Europe. These parameters are determined by using NEDC cycle according to Regulation (EC) No 715/2007 of the European Parliament and of the Council [94].

There are two segments in NEDC testing procedure, Urban Driving Cycle and Extra Urban Driving Cycle namely. UDC represents city driving conditions and EUDC represents aggresive high-speed driving conditions. As a result, NEDC consists of 4 cycles of UDC and 1 cycle of EUDC which can be seen from Figure 0.5. This test is made on the dynamometer, so that the slope of the road is taken as 0 for simulation purposes [95]. However, standards define the road as follows:

“The road shall be level and sufficiently long to enable the measurements specified in this appendix to be made. The slope shall be constant to within ±0.1 percent and shall not exceed 1.5 percent.” [96].

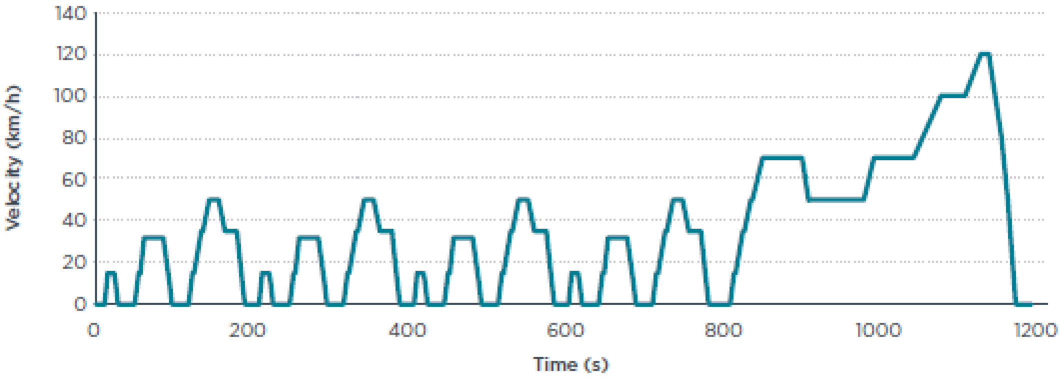


Figure 0.5. Drive cycle for NEDC test[95]

C. Costs Used in Calculations

Throughout the thesis, costs given in the following table are used. References for the values are given in the related chapters.

Table 0.4. Costs of the components used in cost function

Item	Value
Dollar	3.8173 ₺
Euro	1.1998 $
Diesel Fuel	1.34 $/L
Electricity	0.108 $/kWh
Battery	270.27 $/kWh
Battery scrap	2.866 $/kg
Maintenance (Diesel Fiorino)	196.47 $/year
Maintenance (Hybrid Fiorino)	137.53 $/year
Supercapacitor	13.16 $/Wh
Electric Motor	134.23 $/kW
Generator	134.23 $/kW
Internal Combustion Engine	41.675 $/kW
Diesel Fiorino (including taxes)	14513 $
Removed components from Diesel Fiorino	3193 $
Hybrid Vehicle Body (including taxes)	11320 $
Single Stage Gearbox	300 $