İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

MODELLING, DESIGN, SIMULATION AND ANALYSIS OF RANGE EXTENDED ELECTRIC VEHICLE

M.Sc. Thesis by
Ersin Hasan DOĞRUGÜVEN

Department : Mechanical Engineering

Programme : Automotive Engineering

Thesis Supervisor: Prof. Dr. Metin ERGENEMAN

JUNE 2011

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

MODELLING, DESIGN, SIMULATION AND ANALYSIS OF RANGE EXTENDED ELECTRIC VEHICLE

M.Sc. Thesis by
Ersin Hasan DOĞRUGÜVEN
(503081731)

Date of submission : **06 May 2011**
Date of defence examination: **09 June 2011**

Supervisor (Chairman) : **Prof. Dr. Metin ERGENEMAN (İTÜ)**
Members of the Examining Committee : **Prof. Dr. Cem SORUŞBAY (İTÜ)**
Assoc. Prof. Muammer ÖZKAN (YTÜ)

JUNE 2011

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

MENZİLİ ARTTIRILMIŞ ELEKTRİKLİ ARAÇLARIN MODELLENMESİ, TASARIMI, BENZETİMİ VE ANALİZİ

YÜKSEK LİSANS TEZİ

Ersin Hasan DOĞRUGÜVEN
(503081731)

Tezin Enstitüye Verildiği Tarih : 06 Mayıs 2011
Tezin Savunulduğu Tarih : 09 Haziran 2011

Tez Danışmanı : Prof. Dr. Metin ERGENEMAN (İTÜ)
Diğer Jüri Üyeleri : Prof. Dr. Cem SORUŞBAY (İTÜ)
Assoc. Prof. Muammer ÖZKAN (YTÜ)

HAZİRAN 2011

FOREWORD

I would like to express my deep appreciation and thanks for my advisor Prof. Dr. Metin ERGENEMAN for his valuable guidance and comments during my thesis study and thesis topic orientation; Dr. Orhan Atabay for the literature support; my family for their non-ending support during my life; my project manager Dr. Aysen Daloglu Petan, vice managers Mehmet Potur and Murat Güncan for their understanding during my master education; and my colleague Berkin Birol for helping me at style arrangements. And I would also thank myself for my hard work during my master study and quite-deserved grades.

Lastly, I would like to share my math teacher word, which is the light of my life understanding.

"You might not able to overcome all the math problems, however moral is more important."

May 2011 Ersin Hasan DOĞRUGÜVEN

El.-Electronics (Control) Engineer

TABLE OF CONTENTS

Page

ABBREVIATIONS

DOD	**:** Depth of Discharge
ECE	**:** Economic Commission for Europe
EUDC	**:** Europen Urban Driving Cycle
FTP	**:** Federal Test Procedure
HWFET	**:** Highway Fuel Economy Test
ICC	**:** Istanbul City Cycle
LiIon	**:** Lithium-Ion
NEDC	**:** New European Driving Cycle
NiMH	**:** Nickel Methal Hydrid
NYCC	**:** New York City Cycle
PI	**:** Proportional Integral
PID	**:** Proportional Intergral Derivative
REX	**:** Range Extender (Engine)
REXE-Van	**:** Range Extended Electric Van
REXEV	**:** Range Extended Electric Vehicle (MAEA)
SOC	**:** State of Charge
US06	**:** Supplemental Federal Test Procedure

LIST OF TABLES

Page

LIST OF FIGURES

Page

MODELLING, DESIGN, SIMULATION AND ANALYSIS OF RANGE EXTENDED ELECTRIC VEHICLE

SUMMARY

The important part of today's transportation is on the overland and overland vehicles use fuel from petroleum sources. The negative effect of green house gasses and rising oil price have oriented automotive sector to find alternative energy sources. Because of being environment friendly, capable of recovering brake energy, operating quietly, smoothly, high efficiently and therefore requiring less operating energy and cost, automotive sector have started mass production of different kinds of hybrid vehicles, in spite of relative higher production cost. Electric vehicles with range extender are vehicles equipped with a downsized engine without having a mechanical link to the wheels and, according to the vehicle architecture, one or more electric machines to drive the vehicle. Hence, the engine operates at full load points, also high efficiency points, and supplies power to electric motor and/or battery.

In this work, forward power flow using nonlinear single track model and backward power flow of a parametric vehicle are built and compared using Matlab Software. In common simulation models, several parameters should be entered again, if the system is desired to be performed under different conditions or with different vehicle parameters. There are some special softwares used in automotive sector which offer the user to enter simulation parameters such as vehicle mass or air drag coefficient using an interface including dialog or textboxes to simulate different kind of vehicles in a simple and user friendly way. However, these software are relative expensive. To be able to change simulation parameters in a quick and simple way, an interface program in Matlab is developed. In the following part, simulations are run in different test cycles to analyze power and and energy demands. Considering these results, different types of range extender engines are researched and chosen to use in the simulation. Like range extender engine, goal oriented electric machine and battery systems are investigated. Because of rapid changing technology, the related data in papers and books can differ and therefore data from different sources are given which are then crossed and as much as possible, manufacturer data are used to approach to a real system. After that, it is studied on the potential of eliminating the transmission using appropriate differential ratio by comparing both torque supply - demand and power supply - demand of the investigated system and driving conditions. The results are applied to the model and verification of the evaluated system is realized.

Later on, all the related parameters are updated by using user interface program and look-up tables and the model is simulated for different test cycles including both city and highway cycles; simulation results such as battery energy, fuel consumption and driving costs are discussed. In the last section, a conventional light duty vehicle is converted to a REXEV. Having modelled and simulated the vehicle, results are compared with the conventional vehicle.

MENZİLİ ARTTIRILMIŞ ELEKTRİKLİ ARAÇLARIN MODELLENMESİ, TASARIMI, BENZETİMİ VE ANALİZİ

ÖZET

Günümüz ulaşımının önemli bir ksmı karayollarında gerçekleştirilmekte ve karayolu araçları petrol kaynaklı yakıtlar kullanmaktadır. Sera gazlarının olumsuz etkisi ve artan petrol fiyatları otomotiv sektörünü alternatif enerji kayanakları aramaya yönlendirmiştir. Çevre dostu olması, fren enerjisini geri kazanabilmesi, sessiz, düzgün rejimli, yüksek verimli çalışabilmesi, böylece daha az çalışma enerjisine ve maliyetine gerek duyması sebebiyle otomotiv sektörü, farklı mimarilere sahip hibrit araçların seri üretimine başlamıştır. Menzili arttırılmış elektri araçlarda içten yanmalı motor küçültülmüş olup bu motor ile tekerlekler arasında mekanik bir bağlantı bulunmamaktadır. Bu görevi farklı mimari seçeneklerine gore bir veya daha fazla elektrik motoru üstlenmiştir. Bu sayede, içten yanmalı motor tam yük bölgesinde ve yüksek verim noktalarında çalışıp elektrik motoruna veya bateriye güç sağlamaktadır.

Bu çalışmada, parametrik bir araç için ileriye doğru güç akışı yöntemiyle doğrusal olmayan tek izli araç modeli ve geriye doğru güç akış modeli Matlab ortamında kurulmuş ve bu iki yöntem karşılaştırılmıştır. Alışılagelmiş benzetim modellerinde, araç farklı şartlarda veya farklı araç parametreleriyle yapılmak istenen yeni simülasyonlar için bir çok parameter tekrar elle girilmelidir. Bunun yanında, kullanıcı arayüzlerine sahip, araç özelliklerini daha kolay girebilme imkanları sunan, özel yazlılımlar da bulunmaktadır. Ancak bu yazılımlar göreceli olarak oldukça pahalıdır. Bu çalışmada, benzetim parametrelerini kolay ve hızlı bir şekilde değiştirebilmek için kullanıcı arayüzü sağlayan bir program tasarlanıp gerçeklenmiştir. İlerleyen bölümde, tasarlanan benzetim farklı test çevrimlerinde koştulup güç ve enerji analizi yapılmıştır. Bu çıktıları göz önünde bulundurarak, farklı menzil arttıcı motor seçenekleri araştırılıp incelenmiş ve benzetim için simülasyona eklenmiştir. Benzer şekilde amaca yönelik elektrik makinesi batarya sistemleri incelenmiştir. Teknolojinin hızlı değişim göstermesi sebebiyle makaleler ve kitaplardaki veriler birbirlerinden farklı olabilmektedir; bu sebeple gerçek bir sisteme yakınsayabilmek için birden çok kaynaktan bilgiler alınıp bunların karşılaştırılmasına olanak sağlanmış, mümkün mertebe üretici verilerinden yararlanılmıştır. Daha sonra, elektrik araç için vites kutusunun kaldırılması potansiyeli, test çevrimleri ve performans kısıtları kriterlerine gore, moment arz-talep ve güç arz-talep ilişkilerini değerlendirerek tartışılmıştır. Sonuçlar modele ugulanmış ve elde edilen sistemin gerçeklenemsi yapılmıştır.

Sonraki aşamada, ilgili parametreler oluşturulan kullanıcı arayüzü program vasıtasıyla güncellenmiş, benzetimde kullanılan tablolar güncellenmiştir. Benzetimler şehir içi ve şehir dışı çevrimlerini içeren farklı test çevrimlerinde koşturulmuştur; batarya enerjisi, yakıt tüketimi ve sürüş maliyeti tartışılmıştır. Son kısımda ise konvansiyonel ticari bir araç MAEA'a dönüştürme tasarımı yapılmış, modelleme ve benzetimi tamamlanıp sonuçlar konvansiyonel araç ile karşılaştırılmış.

1. INTRODUCTION

The motivation of hybrid vehicles in comparison with conventional vehicles is mainly improving of fuel consumption, emissions and also comfort and performance. Especially, fuel economy plays a major role considering decreasing petroleum reserves and increasing energy necessity with the developing and growing world. Other significant point of internal combustion engine vehicles is emission affects on environment pollution. Three way catalysts, particulate matter filters etc. are from exhaust gas after treatment systems, stratified charge, common rail fuel injection etc. are methods reducing emissions. Although there is a very important development considering early systems, these methods have certain limitations.

As long as renewable energy is not used in fully cycle from manufacturing process to operating, claiming a zero emission vehicle is not a real approach. Neither hybrid nor full electric vehicle concepts are zero emission vehicles, since the source of battery charging energy is usually from petroleum sources. On the other hand, efficiency of electric machines and systems are relative high and idle operation elimination brings an advantage. A further point is comfort that is successfully offered by hybrid and electric vehicles thanks to smooth operation of electric machines. Another feature of electric machines is their short time high torque and power potential, which affect the performance positively.

1.1 Purpose of the Thesis

The purpose of this study is investigating the potential of hybrid electric vehicle architecture with range extender. Vehicle models and an interface program are built for model simulations; a midsize family car concept is chosen to redesign REX hybrid vehicle. Researching actual technologies and concepts in hybrid vehicles is another objective. Having constituted the models, elements included in the topology are searched and chosen. State of art of related technologies and fuel economy and manufacturing costs are discussed considering today’s and near future’s requirements.

2. HYBRID POWERED VECHICLES

Hybrid vehicles have at least two energy sources, such as battery and conventional fuel such as gasoline or diesel or fuel cell and conventional fuel. The main configurations of hybrid vehicles and electric vehicles with range extender are defined in fallowing.

2.1 Hybrid Vehicle Configurations

Energy flow of the hybrid vehicle defines the hybrid configuration, namely series, parallel, series-parallel.

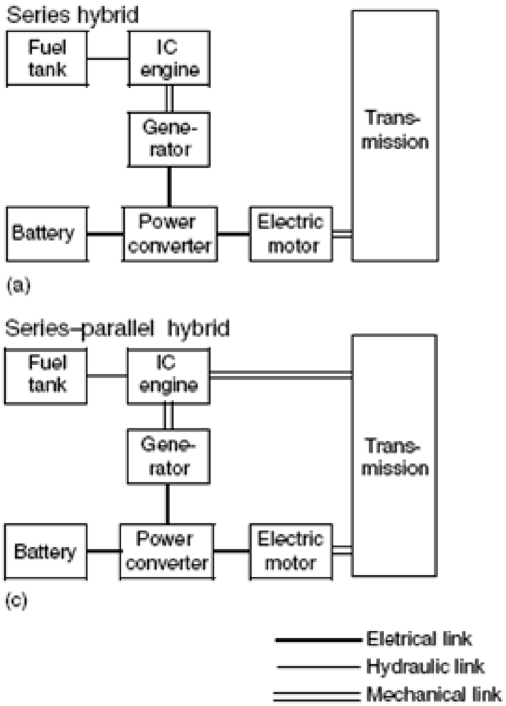


Figure 2.1 : Classification of Hybrid Vehicles (Ehsani et al, 2005).

In series architecture, engine and battery power the vehicle together. Main advantage of this configuration is that engine is decoupled from driven wheels, hence it can be operated within its maximum efficiency region. The disadvantage is conversion of mechanical power first in electric and then from electric in mechanical power. Chevrolet Volt is one of the series hybrid vehicle examples. This configuration has the following operation modes:

- Full electric: The battery supplies the whole energy demand.
- Full engine: Similar to full electric, the engine is the only power source.
- Hybrid: The power supply is both battery and engine.
- Regenerative braking: The brake energy is used to charge the battery pack.
- Battery charging: The engine charges the battery without supplying power for traction.
- Engine traction and battery charging: The engine-generator supplies power to charge the batteries and to propel the vehicle.
- Engine and traction machine as generator operating: The battery is charged by the engine and traction machine.

In parallel drive train, electric motor and engine are coupled to the wheels mechanically; therefore, the power from both sources could be transferred to the wheels together. Since the engine and electric machine should be coupled efficiently so that performance and driveability maintains, control of this configuration is complex. Honda Insight is one of the parallel hybrid vehicle examples. This configuration has the following operation modes:

- Full electric: Battery supplies the whole energy demand.
- Full engine: Similar to full electric, the engine is the only power source.
- Hybrid: The power supply is both battery and engine.
- Regenerative braking: The brake energy is used to charge the battery pack.
- Battery charging: The engine charges the battery via rotating negatively for electric machine and electric machine absorbs this power operating as generator.

Series-Parallel architecture has series and parallel power flows. It is a system of motors and/or generators includes power split device couples making available the engine to recharge the battery pack. Similar to series configuration, it has the ability to generate electricity from engine's surplus power. And like parallel hybrids, engine and electric motor can be coupled to transfer power to the wheels. A relative more complex control strategy is needed in that type configuration. Toyota Prius is a well-known series-parallel hybrid vehicle.

Figure 2.2 : Hybrid Vehicles, left Volt, middle Insight, right Prius

2.2 Electric Vehicle with Range Extender

The REX electric vehicle is actually a series hybrid vehicle. However, there is a concept confusion that the engine in series hybrid vehicles does just generate electricity for the battery. Although, there are some concepts at which the engine just charges the battery, such a limitation is not true since there are other operating modes such as engine traction and battery charging mode as explained in series hybrid architecture part. To solve this confusion Lotus engineers defines full series hybrid (FSHV) and range extended electric vehicles. FSHV achieves the maximum speed on the engine alone while it is achieved by REX electric vehicle using engine and battery. Range extender supplies a second and necessarily lower maximum speed, the charge-sustaining speed.

Figure 2.3 : REX Electric Vehicles, left Opel Ampera, right Lotus Proton

General expectations indicate production of electric vehicles with integrated Range Extender will be increase and mainly implemented for use in urban areas (Atzwanger et al, 2010). While there are in use range extended electric vehicles like Opel Ampera or concept vehicles like Lotus Proton Emas, many automotive manufacturers like BMW plan range extender configuration for future their electric vehicles (Url-1).

Table 1.1 : Opel Ampera Specifications

E-Motor	
Power	150 hp, 112 kW
Torque	273 lb-ft, 368 Nm
Battery	16 kWh Li-ion
ICE	1.4 L gasoline
Power	80 hp, 60 kW

The price of a sample REXEV Opel Ampera is given in different countries below. Opel Ampera is the European version of Chevrolet Volt with same specifications mentioned above.

Table 1.2 : Opel Ampera Price

Opel Ampera Net Price in Germany (16% VAT)	$61,200/42,900€
Opel Ampera Base Price in Germany	$49,352/36,050€
Opel Ampera Net Price in U.K. (£5,000 government grant)	$47,300/£28,995
Chevrolet Volt in USA	$41,000/22,100€
Equivalent-Size Astra	$29,150/20,000€

3. VEHICLE MODELLING

The simulation programs used for vehicle power flow analysis can be run backward or forward flowing mode. In the backward model, it is assumed that the vehicle can perform the given velocity profile and according to this, the forces and speeds at the related parts are calculated.

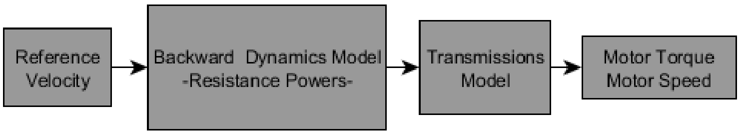


Figure 3.1 : Backward Flow Vehicle Model.

In the forward simulation model, there is a driver model evaluated with PID or PI controller. Gas pedal, brake pedal and clutch are controlled by the driver model to decrease the failure between the reference and evaluated speed (Boyalı, 2008).

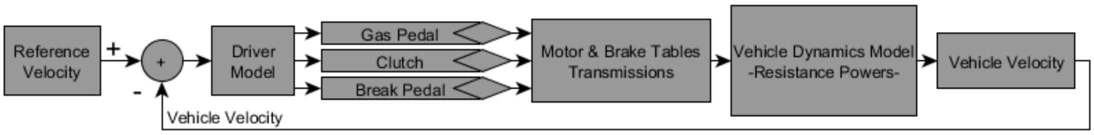


Figure 3.2 : Forward Flow Vehicle Model.

In this work, forward power flow using nonlinear single track model and backward power flow of a parametric vehicle are built. Afterwards, the models are compared to select an appropriate method for analysing hybrid vehicle with chosen architecture.

3.1 Quasi Forward Simulation Model including Nonlinear Single Track Model

In this section, a forward model is built that includes nonlinear single track model. Since the pedal maps could not get for the vehicle to be designed, the model is built without them. According to the difference, named error in control discipline, the driver applies toque to the wheels. During hybrid vehicle modelling, some additional components such as electric motor-generator and battery should be considered additionally to the conventional vehicle modelling.

The gross vehicle dynamics and tyre/wheel dynamics are to be calculated for a simulation of vehicle dynamic performance. These can both be captured by simplified lumped mass models and might include single wheel, two wheels or four wheel models for concerning as well as acceleration/breaking analysis (Gillespie, 1992). The motorway systems have been designed as straight as possible, and the steering forces to change lanes have relatively small effect and act in small periods compared to much larger longitudinal forces, therefore the lateral forces can be neglected during power flow analysis. A race car simulation would however need lateral dynamics, since acceleration, braking and cornering dynamics are much more coupled and essential to produce a realistic model, hence a full four wheel model is considered for the purpose of the vehicle power and energy analysis. (Short et al, 2004).

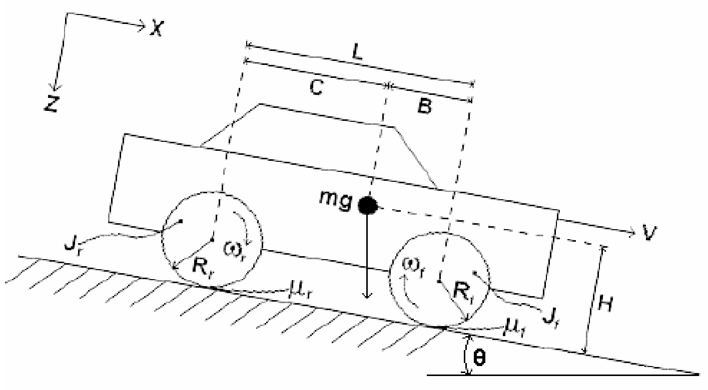


Figure 3.3 : Shematic of Two Wheel Model (Short et al, 2004).

3.1.1 Mathematical Model of a Vehicle and Matlab Implementation

For mathematical modelling, firstly equations of motions are described. The forces about X-axis are proportional to the normal force about Z at the contact region of tyre and road. The summation of the reaction forces at the rear and front contact points gives the total force. Hence, the velocity can be obtained by using the evaluated force.

$F_{x_i} = u_i F_{z_i}\,,\ i = r, f$	**(3.1)**
$F_{x_T} = 2F_{x_f} + 2F_{x_r}$	**(3.2)**
$a = \dfrac{-F_{x_T} + gsin(\theta) - \mathrm{Fd(V)}}{Cr\ m}$	**(3.3)**

where the F represents the force in N, a the velocity change in m/s^2, u the adherence coefficient, g the gravity in N/kg, Cr the rotating mass coefficient and m the mass of the vehicle in kg.

Here, F_{x_T} is evaluated in (3.1), gsin(θ) is gradient term and Fd(V) is the drag force. To obtain F_{x_T}, the equation in (3.1) should be solved, and to get that, the load distrubution at each wheel should be calculated first.

$F_{z_f} = mg\left(\dfrac{C}{L}\right)\cos(\theta) + \dfrac{H}{L}\cos(\theta) - ma\dfrac{H}{L}$	**(3.4)**
$F_{z_r} = mg\left(\dfrac{B}{L}\right)\cos(\theta) + \dfrac{H}{L}\cos(\theta) - ma\dfrac{H}{L}$	**(3.5)**

In these equations, both static and dynamic load terms are represented by the first and second terms of the right hand side, respectively. During braking the load transferred to the front axle, and during accelerating, it is transferred to the rear axle. For a 1200 kg vehicle, dynamic load transfer in ECE-15 city cycle is given below.

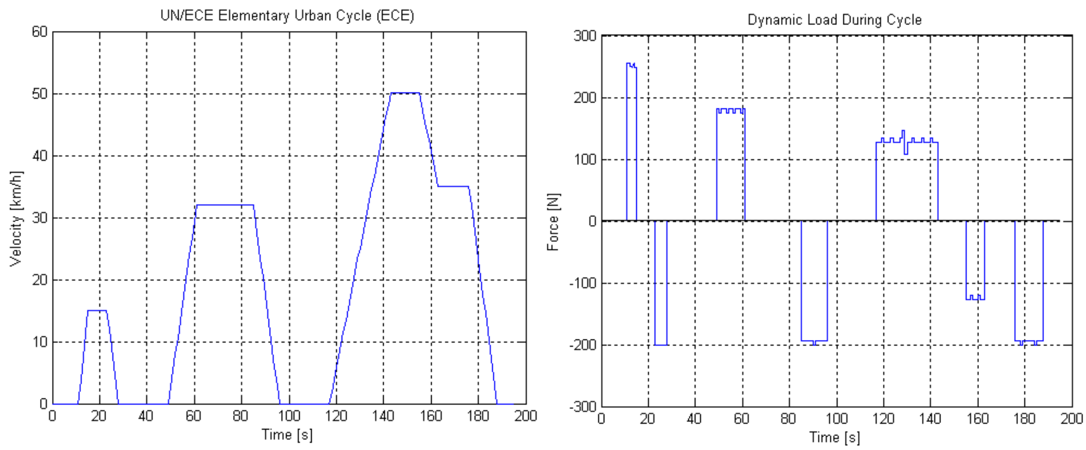


Figure 3.4 : ECE-15 Velocity Profile and Dynamic Load Transfer

Another term in the equation of motion is drag forces which are aerodynamic and rolling resistance forces.

$Fa = 0.5cwApV^2$	**(3.6)**
$Fr = mgfr$	**(3.7)**
$Fd = Fa + Fr$	**(3.8)**

where cw is the aerodynamic resistance coefficient, A the frontal area in m^2, p the air density in kg/m^3 , V the relative velocity of air.

For a more accurate picture of the force needed to accelerate the vehicle one should also consider the force making the rotating parts turn faster. The rolling mass coefficient used in (6.1) represents the effect of rotating parts. The inertia of the rotating parts is reduced to wheels by using kinetic energy equations.

$0.5\, m_{eq}V^2 = 0.5\, J_p\, w_p^2 + 0.5\, J_{ds}\, w_{ds}^2 + 0.5\, J_t w_t^2 + 0.5\, mV^2$	**(3.9)**
$w_p = w_t i_g i_d$	**(3.10)**
$V = w_t R$	**(3.11)**
$m_{eq} = Cr\, m = m + \frac{1}{R^2}.\left(J_p\left(i_g i_d\right)^2\right) + (J_{sd}/(i_d)^2) + J_t$	**(3.12)**

where Jp defines the propulsion inertia, Jsd the differential shaft inertia, Jt the total wheel inertia, Jd the differential inertia, ig gearbox transmission ratio, id differential ratio, w the rotational velocity (Boyalı, 2008).

After examined the gross vehicle dynamics, the interaction between the tyre and road that produces the tractive forces are to be considered. The force transfer coefficient µ is dependent on the slip ratio. Although mant different parameters can affect the friction coupling,it is best described in terms of the wheel slip ratio.

$s_i = (V - w_i R\,)/(max(V, w_i R))$	**(3.13)**

If the slip ratio is zero, neither brake nor motor torque is applied to the wheels. The ratio +1 and -1 represent either the locked or the spinning wheel.

The Pajecka Magic Tyre model is generally used for describing the relationship between the slip ratio and tyre friction. This model is defined as following:

$u_i(s_i) = Dsin(Carctan(Bs_i - E(Bs_i - \arctan(Bs_i))))$	**(3.14)**

More than 40 constants which are experientially determined are used in the above simplified equation. B,C,D and E are then calculated from these constants.

Pacejka Coefficients				
Surface	B	C	D	E
Dry Tarmac	10	1.9	1	0.97
Wet Tarmac	12	2.3	0.82	1
Snow	5	2	0.3	1
Ice	4	2	0.1	1

Figure 3.5 : Equivalent Model Parameters (Short et al, 2004).

For normal or wet road conditions the relation of tyre friction and slip is figured at Matlab environment using the above parameters.

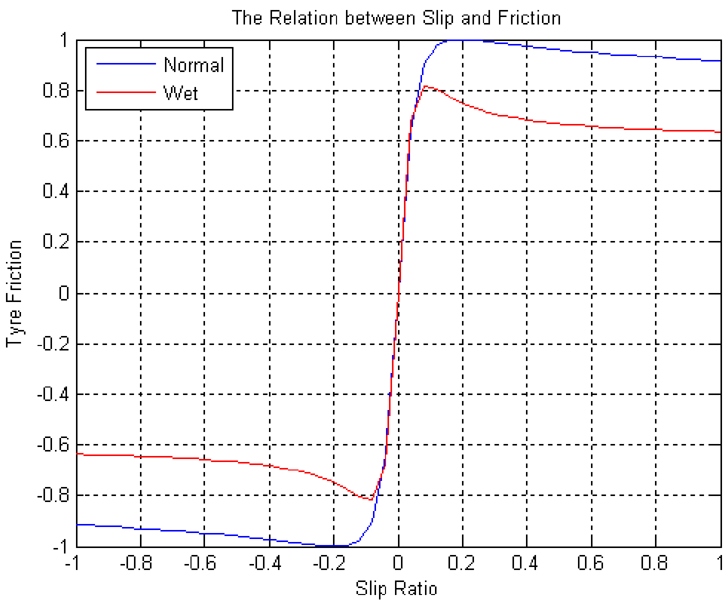


Figure 3.6 : Friction – Slip Characteristics.

The next step is obtaining wheel dynamic equations that give wheel acceleration which is used in slip ratio.

$\dot{w}_i = (T_{p_i} - T_{r_i} - T_{b_i})/(J_i)$	**(3.15)**
$T_{r_i} = R_i F_{x_i}$	**(3.16)**

where T_{p_i} is propulsion torque at the wheel, T_{b_i} wheel brake torque and T_{r_i} is the reaction torque on the wheel due to the tyre tractive force.

Having defined equations of motion, drive line equipments should be modelled. The gearbox model includes gear ratios for related velocities and efficiencies at this ratios. In a similar manner, the differential is modelled.

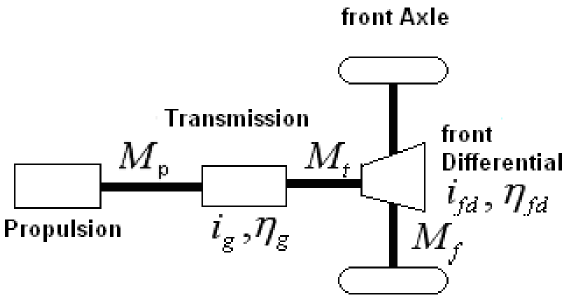


Figure 3.7 : Drive Line Parts.

The next step is obtaining wheel dynamic equations that give wheel For a front wheel drive vehicle with a single propulsion system having the driveline including a gearbox and a differential, driveline parts' relations can be seen at following equations.

$M_f = n_{fd} M_t i_{fd}$	**(3.17)**
$M_t = n_g M_p i_g$	**(3.18)**

where M_f is the front wheel torque, M_p the electric motor or engine propulsion system torque, M_t the differential shaft torque, i_g gear ratio, i_{fd} front differential ratio, n_{fd} and n_g front differential and gearbox efficiencies, respectively.

The battery equivalent model gives the battery state of charge SOC, efficiency, capacity, power and energy. For the equations below the subscript "int" stays for internal.

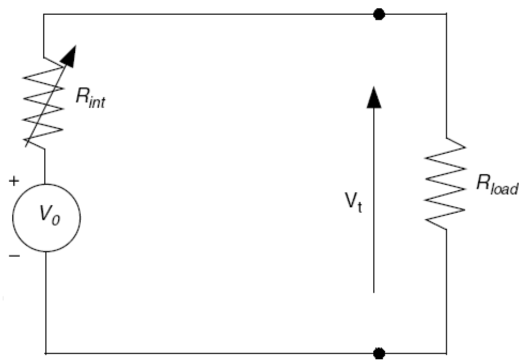


Figure 3.8 : Battery Model.

$P_{bat_{int}} = V_o(SOC(t))I(t)$	**(3.19)**
$P_{bat} = P_{bat_{int}} - I(t)^2 R_{int}(SOC(t), sign(P_{bat}))$	**(3.20)**
$P_{bat_{int}} = V_o(SOC(t))I(t)$	**(3.21)**
$P_{bat} = P_{bat_{int}} - I(t)^2 R_{int}(SOC(t), sign(P_{bat}))$	**(3.22)**
$SOC(t) = \frac{Q(t)}{Q_0} + SOC_0$	**(3.23)**
$Q(t) = \int I(t)dt + Q_0$	**(3.24)**
$n_{bat} = \frac{P_{bat_{int}}}{P_{bat}} = \frac{V_0 I(t)}{V_0 I(t) + I(t)^2 R_{int}}$	**(3.25)**
$W_{bat} = \int P_{bat}(t)dt + W_{bat_0}$	**(3.26)**

For determining motor and generator efficiencies during simulation, look-up tables using interpolation-extrapolation are built in matlab simulink. The efficiency of a electric machine in motoring mode is the ratio of the applied electrical power to the resultant mechanical power. Below, power-speed character and motoring efficiency map including controller of a 75 kW electric machine is given.

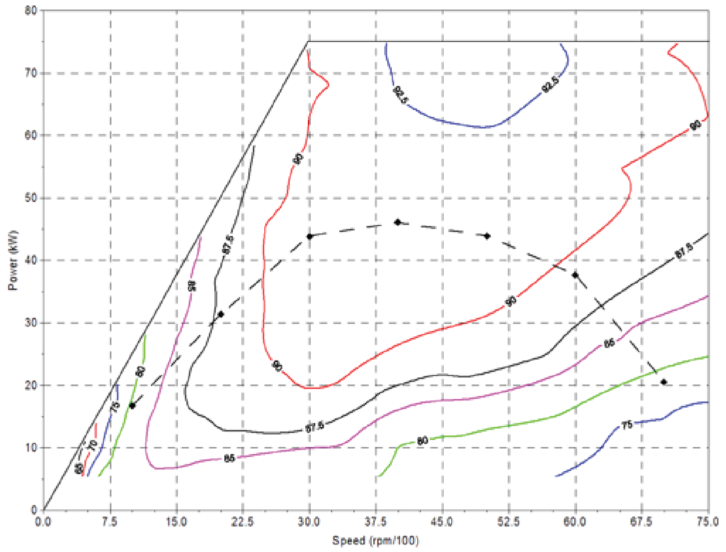


Figure 3.9 : Motoring Efficiency Map including Controller.

In this parts, the references (Short et al, 2004) and (Boyali, 2008) have been utilized.

In fallowing part, the Matlab implementation is given.

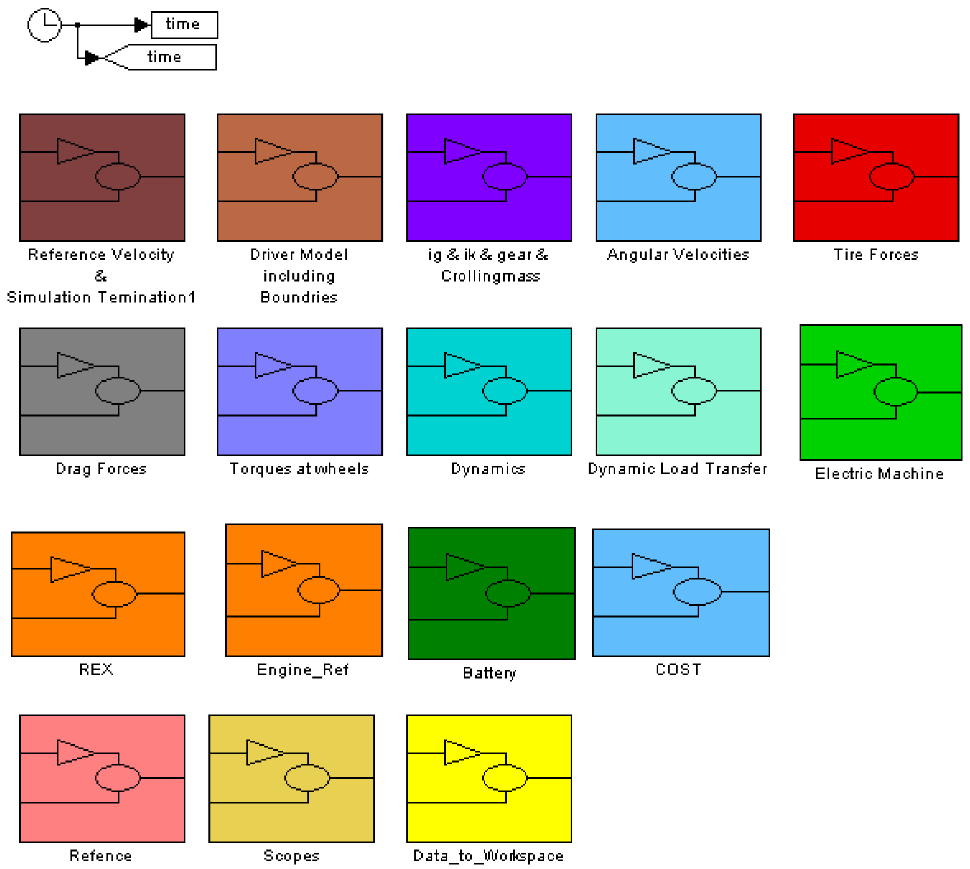


Figure 3.10 : Overall View of Forward Simulation Model Blocks.

The overall view of the blocks can be seen above.

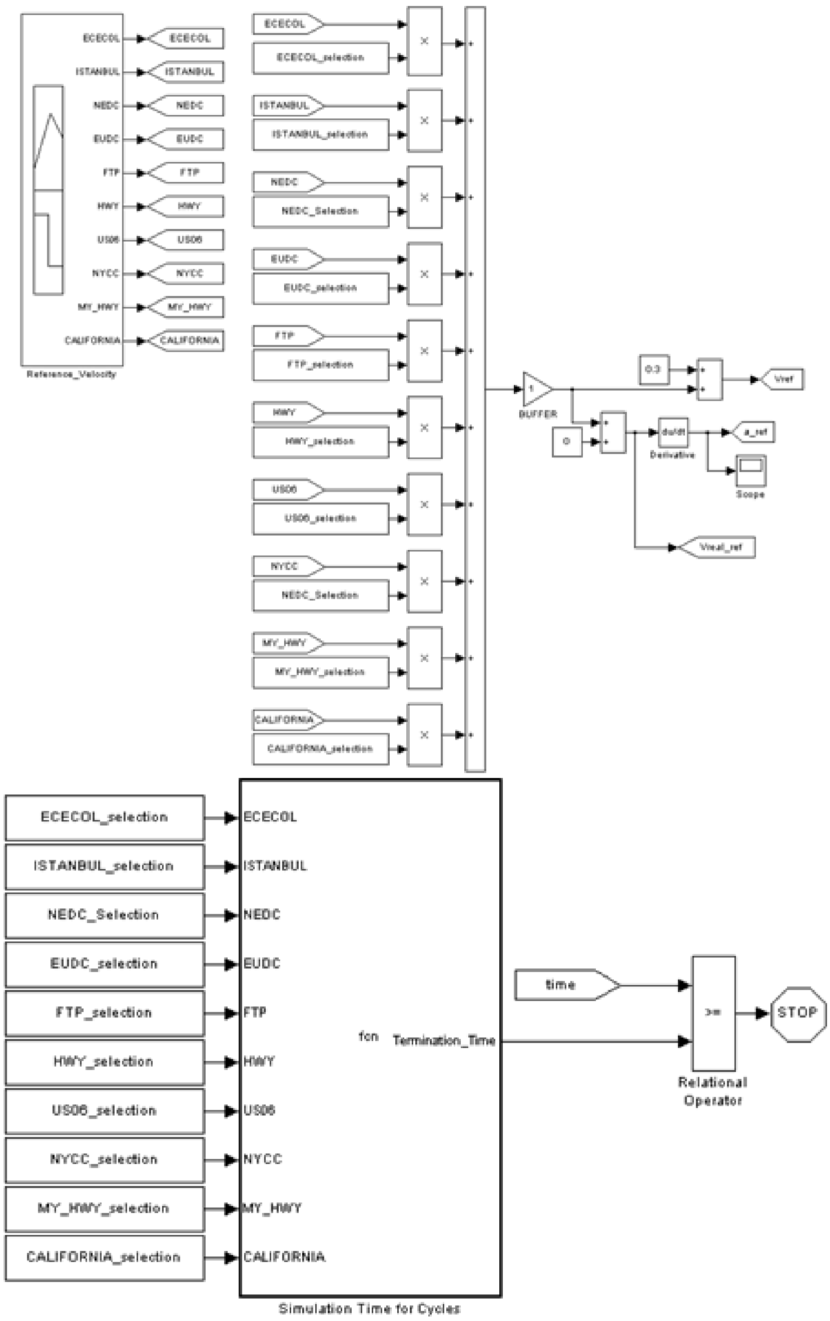


Figure 3.11 : Reference Velocity Block.

In the reference velocity block, the 10 drive cycles allowing further cycles implementation can be choosen, hence the modeled vehicle can be run in the desired cycle and the related results can be analysed. This block is so configured that there is no need to enter the simulation stop time at each drive cycle, it controls and stops the simulation according to the drive cycle automatically.

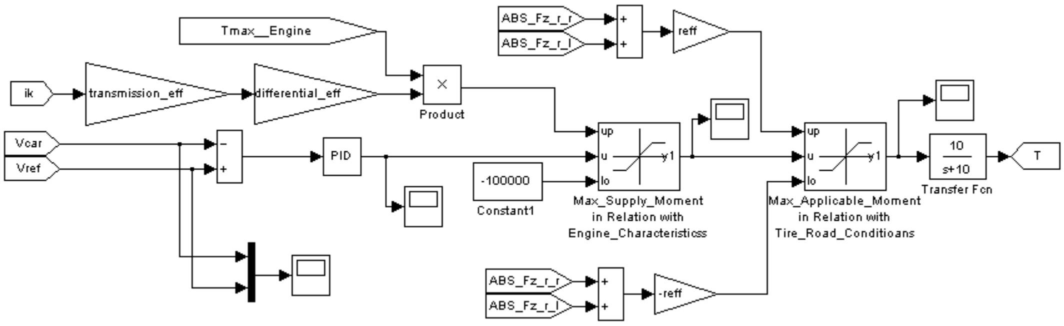


Figure 3.12 : Driver Model Block.

As stated before, the model block includes a PI or PID controller reacting according to the error or difference between the desired speed and real speed. There are also some constraints in this block. The first one is the maximum motor torque. In case the driver model produced a higher torque demand that cannot be supplied by the motoring system at the related speed, the torque applied is then the maximum torque at this speed. The further constraint is derived from the maximum adhesion coeffient showed in the previous parts. The maximum braking and accelerating torque is bounded according to maximum allowed linear force apply to the road. Both constraints are designed as dynamical considering to motor speed and dynamic load transfers, respectively.

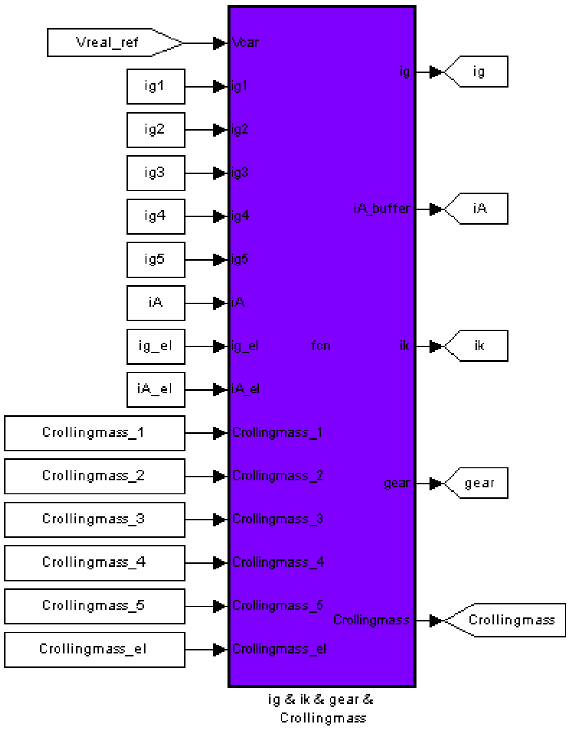


Figure 3.13 : Driveline Ratios and Rolling Mass Coefficient Block.

For determing transmission ratio, differential ratio and rolling mass coefficient, the actual velocity is needen. By using the actual velocity and gear number, the predetermined gear and transmission ratios and also rolling mass coefficients, the outputs of the block are calculated in the embedded Matlab Function which is also widely used in other blocks.

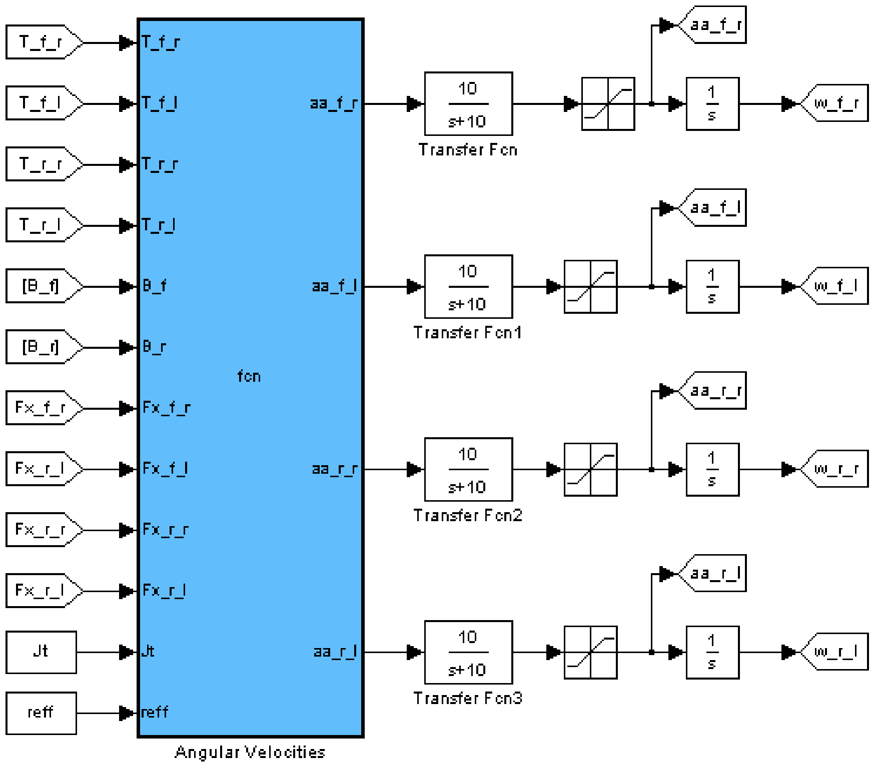


Figure 3.14 : Anglular Accelerations and Velocities Block.

The above figure shows the angular accelerations and velocities. Similarly in some other blocks, a trasfer function is used for accelerte the simulation and solve the simulation problems in Matlab. One having used simulink is similiar to such an error: “Trouble solving algebraic loop containing 'algebraicloop_problem/Sum1' at time 0. Stopping simulation. There may be a singularity in the solution. If the model is correct, try reducing the step size (either by reducing the fixed step size or by tightening the error tolerances)”. The effect of the transfer is very small can be accepted as a delay of the system and there can be neglected. For instance, if the input is 1, the output reaches to 70% of the input in about 120 miliseconds.

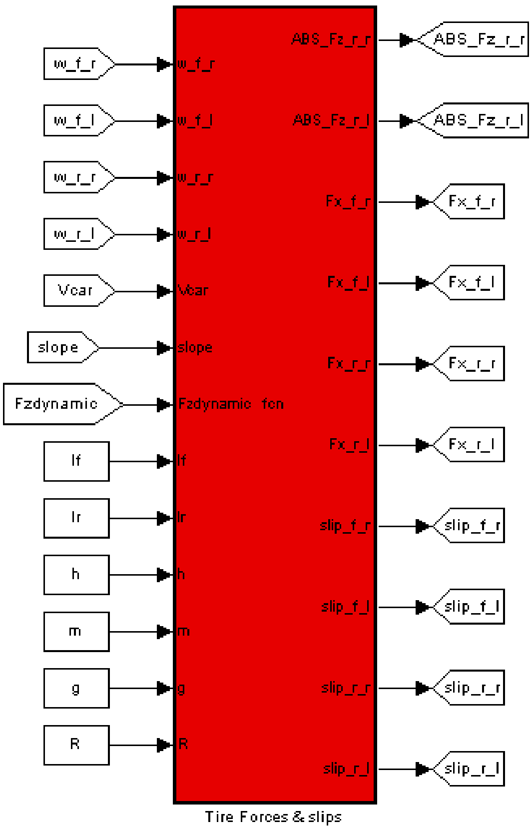


Figure 3.15 : Tire Forces and Slip Calculations Block.

The inputs and outputs of the tire force and slip calculations block is shown above.

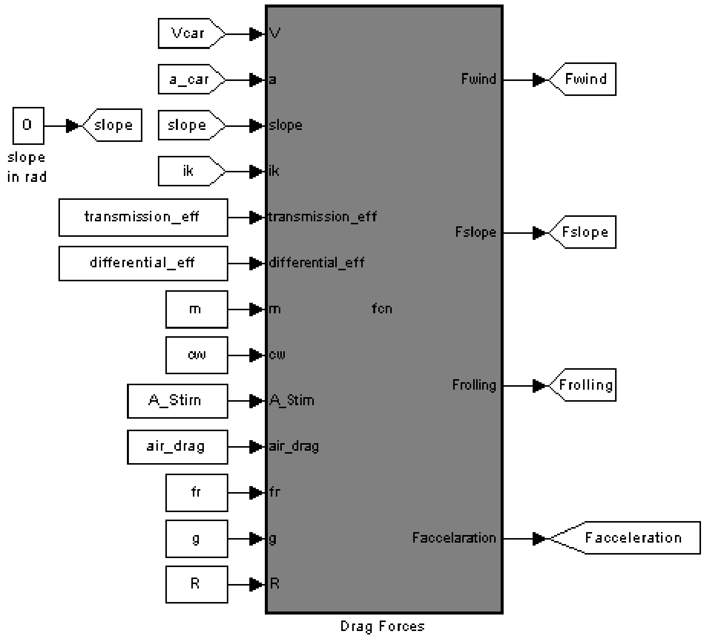


Figure 3.16 : Drag Forces Block.

According to the previously given formulas, the drag forces acting on the vehicle are obtained in the above embedded function block.

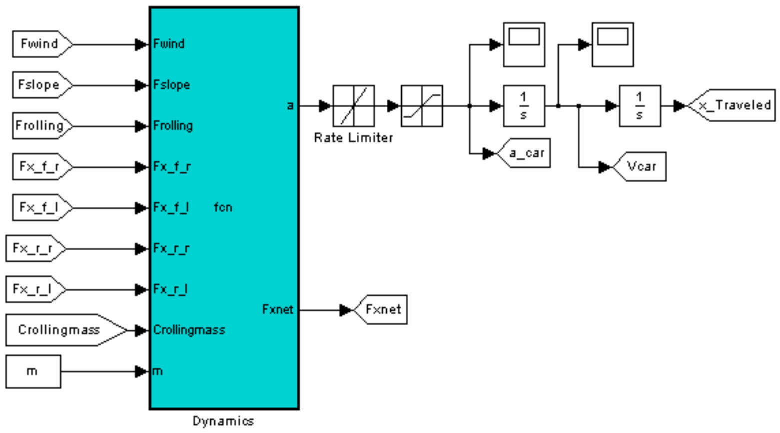


Figure 3.17 : Dynamics Block.

There are also some constraints in the dynamics block to prevent high instant acceleration rates in case of high positive or negative forces acting on the vehicle. In this block, the vehicle velocity and travelled distance are obtained by integrating the acceleration and velocity, respectively, and adding the initial values that can be entered in the integration functions as well.

The motoring and generating efficiencies are calculated using lookup-up tables by the method interpolation - extrapolation. Since there is not a continuous data available, the speed is parted to converge the real speed.

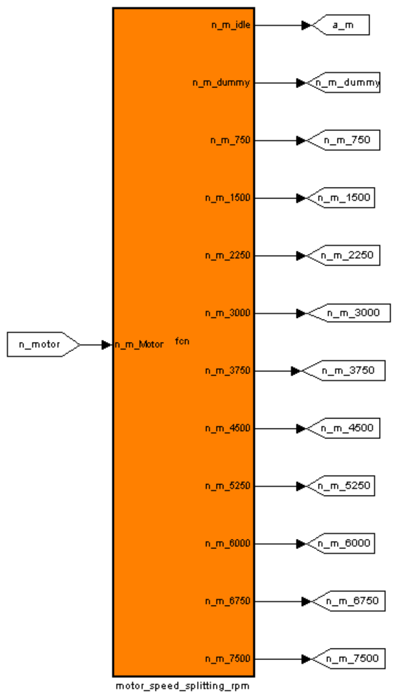


Figure 3.18 : Motor Speed Parting Block

In the block, two outputs are get true, others false, the aim here is to get a better convergence that will be stated in the following part. A view of the code is below:

```
..
if n_m_Motor>6750
   n_m_6750=1;n_m_7500=1;
   elseif n_m_Motor>6000
   n_m_6000=1;n_m_6750=1;
…
```

Below, the motoring efficiency calculation block is given. The generating efficiency block is built in a similar way. Two efficiency values are summed and then divided by 2 to get the mean of them. For instance, if the motor speed is 6400 rpm, efficiencies at 6000 and 6750 rpm is summed and then divided by 2.

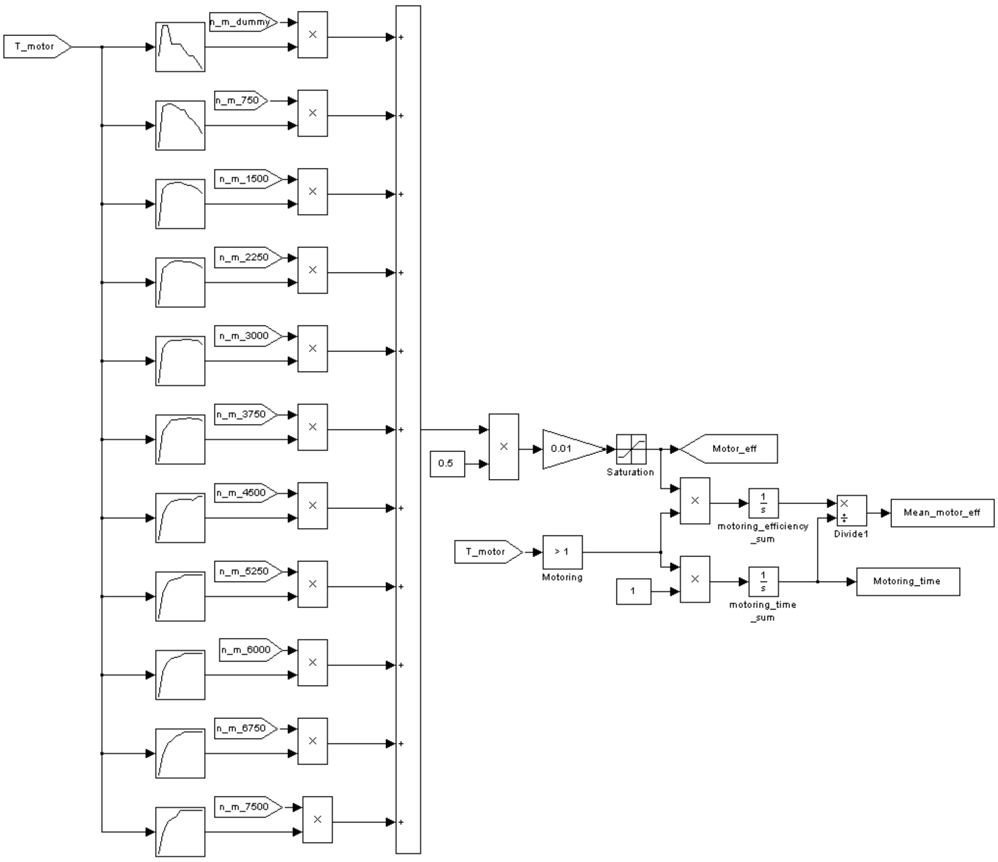


Figure 3.19 : Motoring Efficiency Block.

To evaluate the mean efficiency at the end of the simulation, the motoring time is also calculated via a comparing function that makes its output true in case motoring torque is positive.

The fallowing parts describe torque, speed, power and energy at the wheels and electric machine. Since the motor and generator blocks are very similar to each other, is convenient to describe one of them.

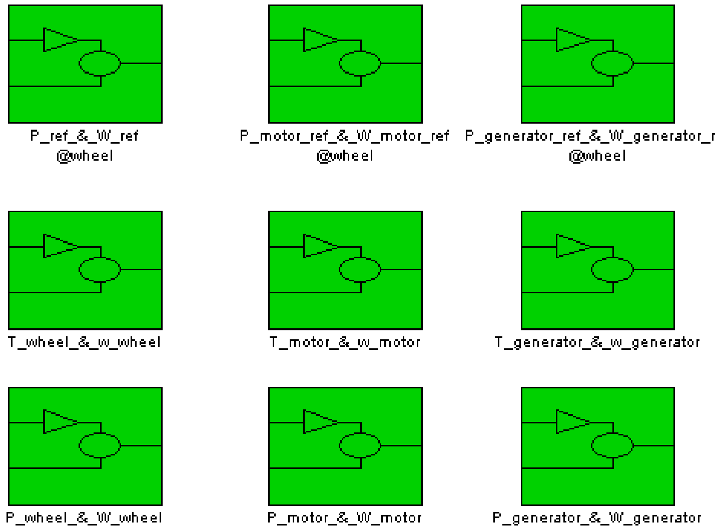


Figure 3.20 : Blocks used for Torque, Speed, Power and Energy

Firstly, the power and energy at wheels are calculated, these are potential magnitudes.

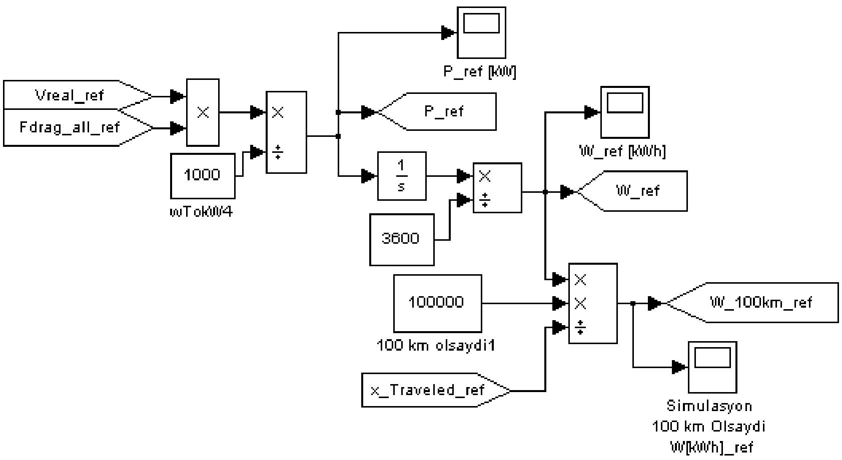


Figure 3.21 : Power and Energy at the Wheels.

By using a switch, motoring and generating powers and energies can be filtered.

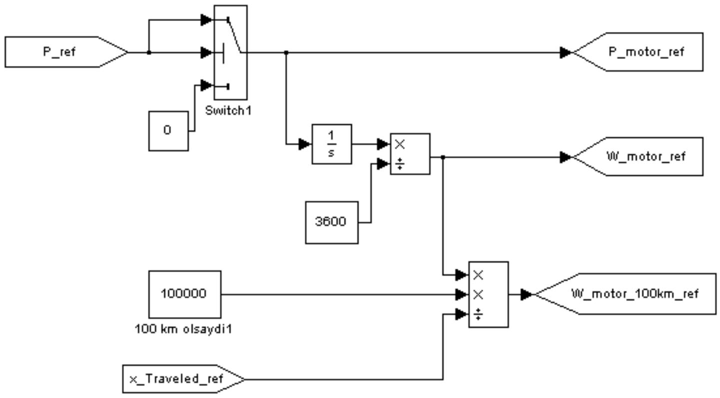


Figure 3.22 : Motoring Power and Energy at Wheels.

The motor toque and speed including constraint block and power calculation block can be seen below.

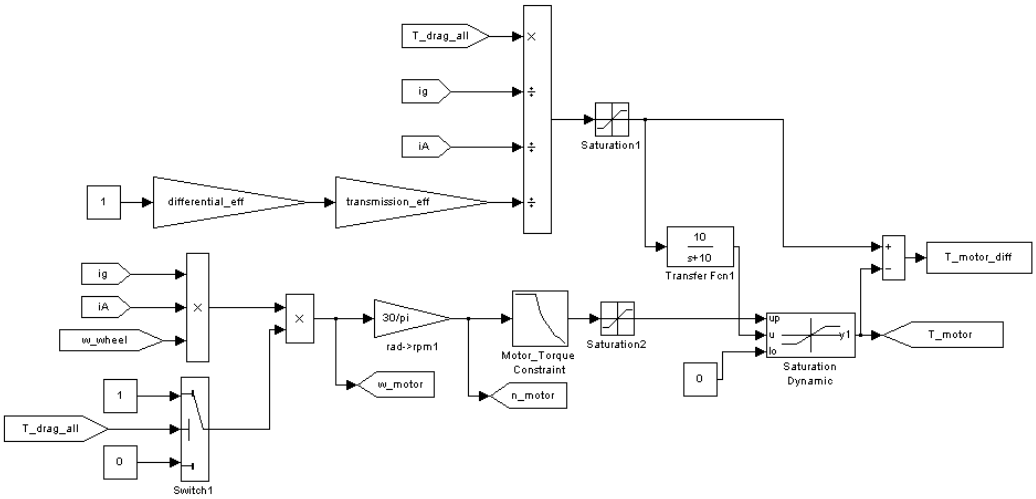


Figure 3.23 : Motor Torque and Speed.

Having evaluated motor speed and torque, the power is calculated by multiplying angular velocity and torque and dividing the result by the motor efficiency to include the controller and motor efficiency.

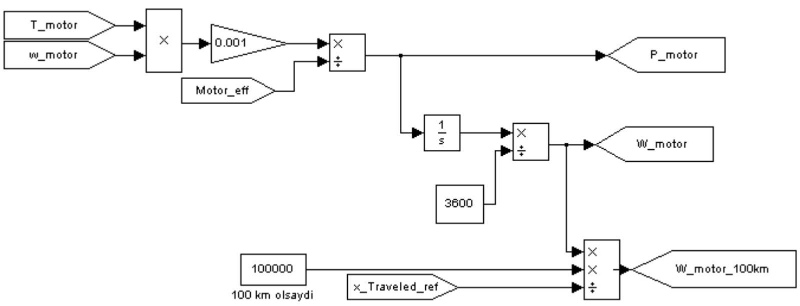


Figure 3.24 : Motor Power.

In the Range Extender Motor Block, according to obtained range extender power fuel consumption of is evaluated. Since the fuel consumption is in gram, it is converted to liter to get fuel consumption in liter and if desired in lt/km or lt/100 km.

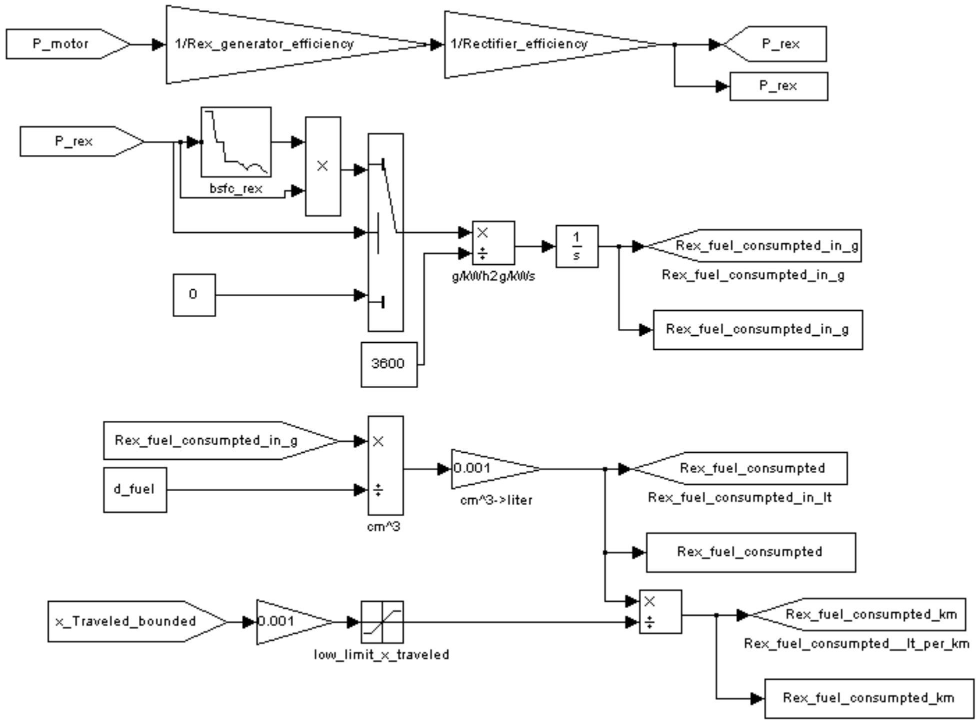


Figure 3.25 : Range Extender Engine Block.

SOC, battery current, power and energy are obtained in the Battery Block considering efficiencies of REX, rectifier, converter, battery charging and discharging.

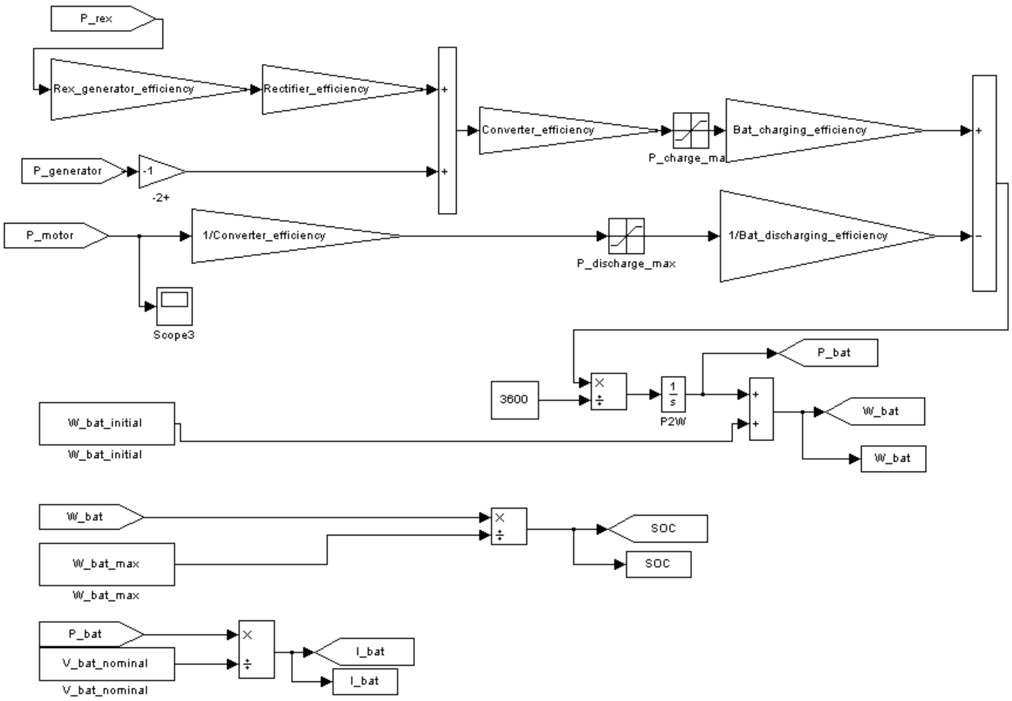


Figure 3.26 : Battery Block.

In the cost block, the consumpted electricity is obtained according to actual fuel cost. To give a better idea, the block does not calculate only the consumpted electric energy cost, but also the cost before and after taxes, namely value added tax, and these values per km. Line charger efficiency is also considered during the cost calculation.

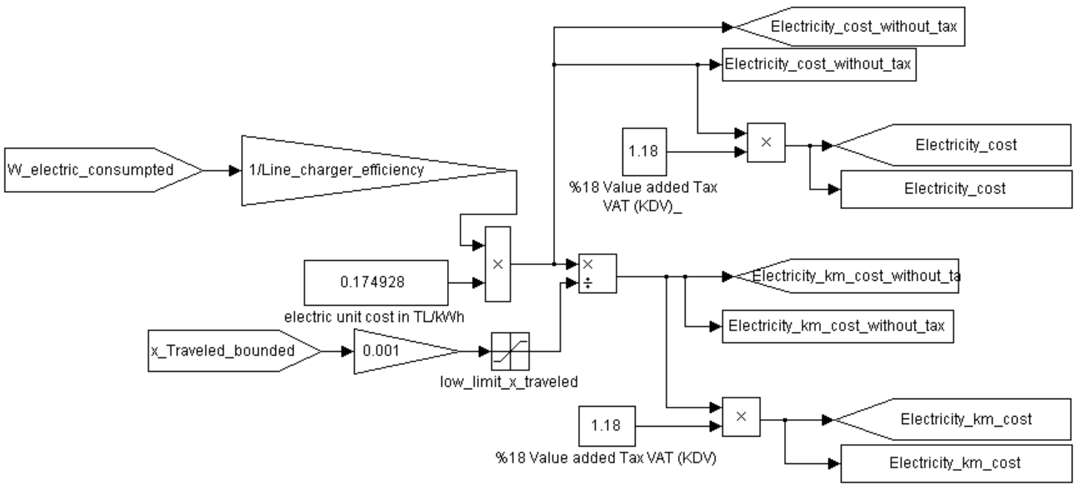


Figure 3.27 : Comsumpted Electricity Cost Block

According to obtained range extender operating point, fuel consumption of is evaluated. Since the fuel consumption is in gram, it is converted to liter to get it in liter and if desired in lt/km or lt/100 km.

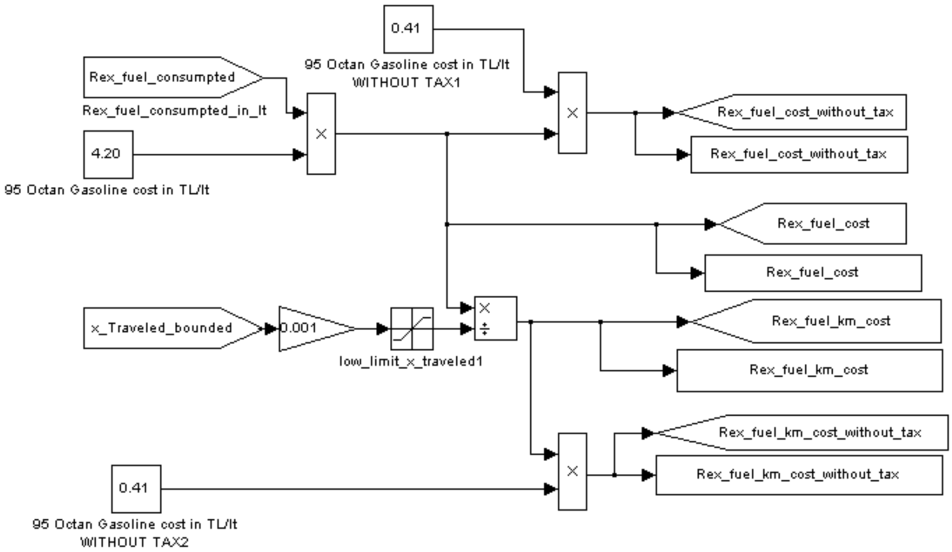


Figure 3.28 : REX Fuel Cost Block.

The scope block enables observing determined parameters during and after simulation run. With the block named as “Data to Workspace”, parameters to analyse are sent to workspace in Matlab, hence these can be recorded if required.

3.2 Backward Simulation

In backward simulation model, the blocks used in forward simulation model are utilized. The blocks “Driver Model”, “Anglular Velocites”, “Tire Forces”, “Torques at Wheels”, “Dynamics” are removed. The overall figure of the blocks can be seen below.

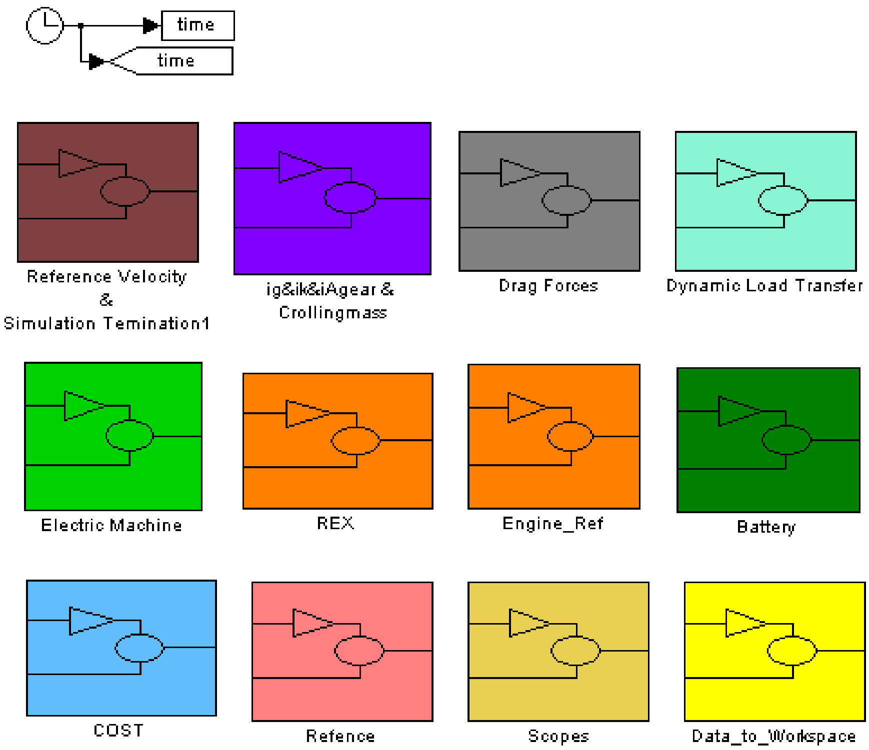


Figure 3.29 : Overall View of Backward Simulation Model Blocks.

3.3 Comparison of Backward and Forward Simulation

Backward-facing approach does not use a driver behaviour. The force required to accelerate the vehicle is computed from the reference speed. This force is then translated into the torque by the components considering efficiencies at that points. The linear velocity is likewise translated into rotational velocity. In this method tractive power flow is calculated backwards, till required energy use, fuel or electric, is calculated.

In the forward flow simulation, in accordance with the velocity error resulted by the difference of the reference and actual velocity of the vehicle, appropriate throttling and braking commands via an controller, namely via driver model, are applied. The torque is translated from throttle command supplied by the propulsion system resulting an energy usage. The propulsion torque is delivered to the transmission model and then to the wheels by computing gear and differential ratios and efficiencies. The provided tractive force produces a change in the vehicle velocity computed taking account the rotational inertias in the drive train.

The forward simulation model is generally used for performance investigations, control algorithm studies whereas backward model is often utilized at the fields having the targets fuel economy and component sizing (Url-2). The forward flow simulation approach is more likely to the real life behaviour, however its disadvantage is long simulation time. Since the backward simulation model is a fast method that allows analysing the results in case of a change in the model and appropriate for energy analysis, it is chosen as a more appropriate method in the thesis, considering power and energy analysis being the main issues of the thesis. On the other hand, the model used in the thesis is not a 100% backward simulation, since it contains constraints such as maximum motor /generator torque at the instant speed, maximum battery energy etc. to converge real vehicle operation conditions. A comparison of the models in consideration of energy analysis is described in the following figure for a midsize family car in Istanbul cycle.

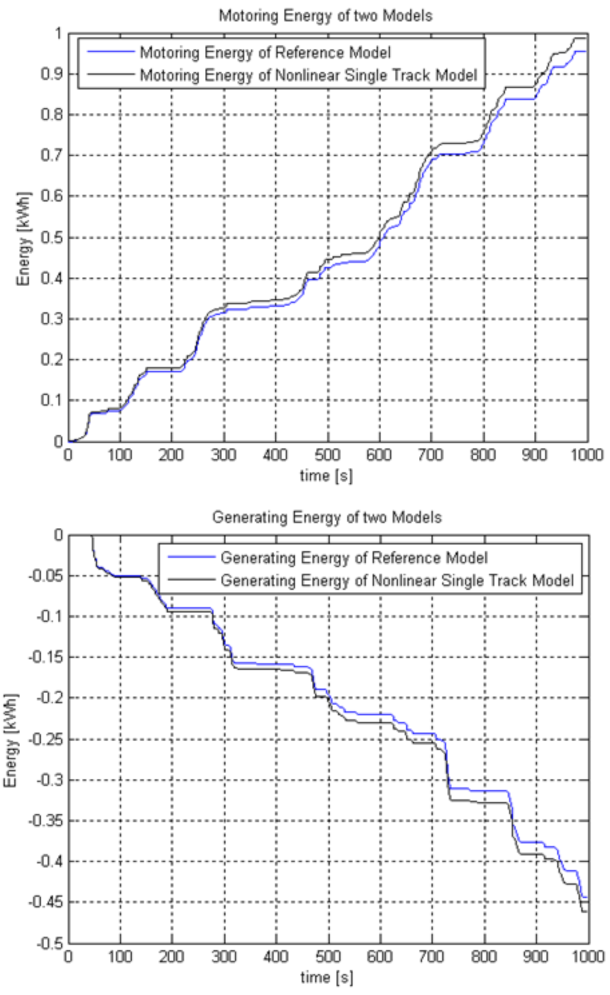


Figure 3.30 : Energy Comparison for Backward and Forward Simulations

4. MATLAB M-FILE BASED USER INTERFACE PROGRAM

In the simulation models, several parameters should be entered again, if the system is desired to be performed under different conditions or with different vehicle parameters. There are some special softwares used in automotive sector which enables selecting directly a vehicle or offer the user to specify simulation parameters such as vehicle mass, air drag coefficient, tire characteristics, transmission ratio mechanism, powertrain configuration etc. using an interface including picture boxes, dialog boxes or text boxes to simulate different kind of vehicles in a simple and user friendly way. However, these softwares are relative expensive and some universities around the world build their own simulation programs including or specified in vehicle simulation. To be able to change simulation parameters in a quick and simple way, an interface program in Matlab enabling permanent improvements is developed during the thesis study.

The program consists of several list, input dialog and message boxes, which operates in a sequential order. These boxes have already an initial value, namely a default value. First, the program offers the user to select a vehicle in about ten vehicles. Increasing the number of vehicles in the database helps to select an appropriate vehicle selection. In the list, there are small family cars like Lotus Proton Emas, mid-size family cars like Chevrolet Volt, Toyota Prius, Fiat Linea, light duty vehicles like Ford Transit Connect, Vans like For Transit Van and bus type vehicles. First step seems as fallowing:

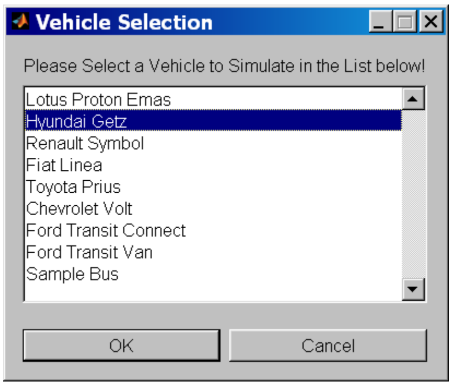


Figure 4.1 : Vehicle Selection List

After the user has selected the vehicle, the parameters required for the simulation are shown to the user with the purpose that the user could check and also change these if desired. The parameters are gear ratios, differential ratio, transmission and differential efficiency. As stated on the input dialog box, the prefix "C_" stands for the conventional and "E_" for the electric propulsion vehicle. There should be made a distinction between electric and conventional vehicle, since electrical vehicles does not use conventional gear box systems. The program allows to both architecture, one should just enter the right value in the right box and do not need to pay attention for the irrelevant box, since the vehicle architecture is asked in further steps . For instance, if the user wants to simulate a electric vehicle, he or she needs to enter just the last three boxes. Since the vehicle designed in the thesis has not a gearbox, only one transmission ratio is asked to the user. Rolling mass coefficients are also computed at each gear number. In case of a single step transmission, one rolling mass coefficient is entered in the related box.

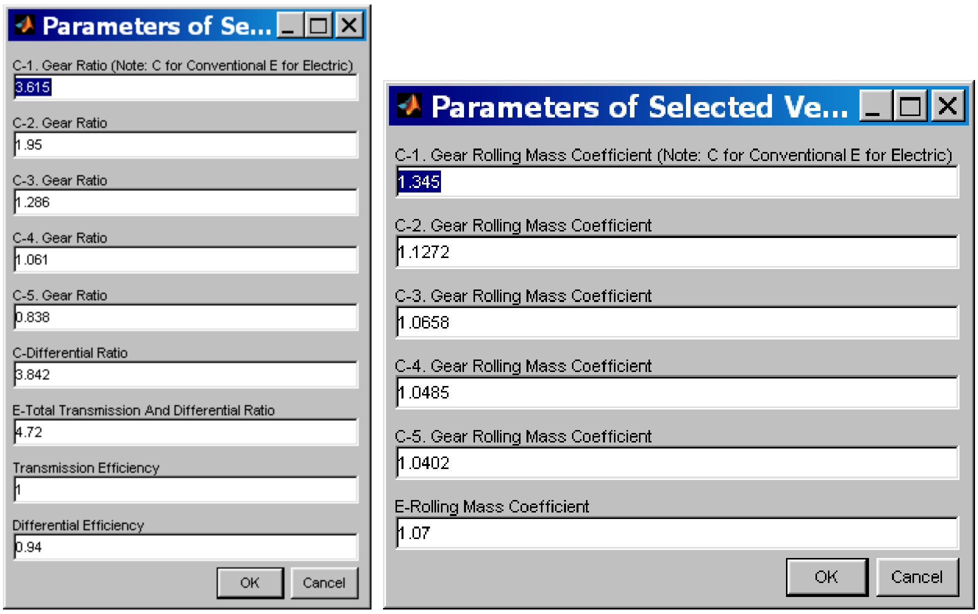


Figure 4.2 : Driveline and Rolling Mass Parameters.

In the fallowing, parameters used for resistance forces, tire specifications and some metrics to calculate centre of vehicle mass are asked. The units are in SI and given in brackets.

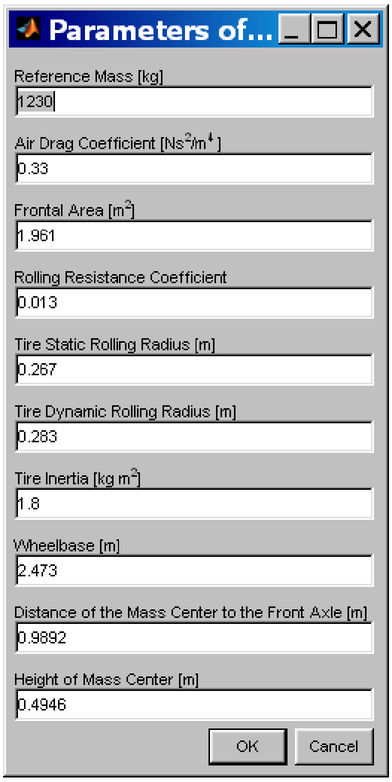


Figure 4.3 : Resistance Force Parameters, Tire Specifications and Metrics.

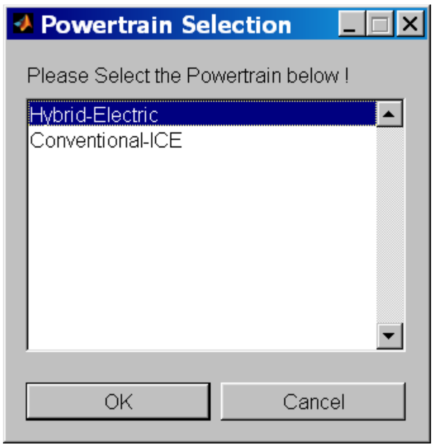


Figure 4.4 : Powertrain Selection.

According to the selected powertrain, the model built in simulink sets and resets some parameters such as gear ratios, rolling mass coefficients etc. Here, some mean electric efficiencies such as rectifier, converter and REX generator efficiencies are also defined. However, the electric machine motoring and generating efficiencies changes in a wide region according to the speed – moment operating point, therefore it is modelled in simulink according with look-up tables. On the other hand, REX generator operates at high loads and in a relative restricted area.

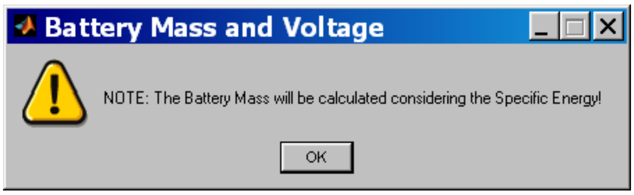


Figure 4.1 : Informing The User The Battery Mass Calculation Method

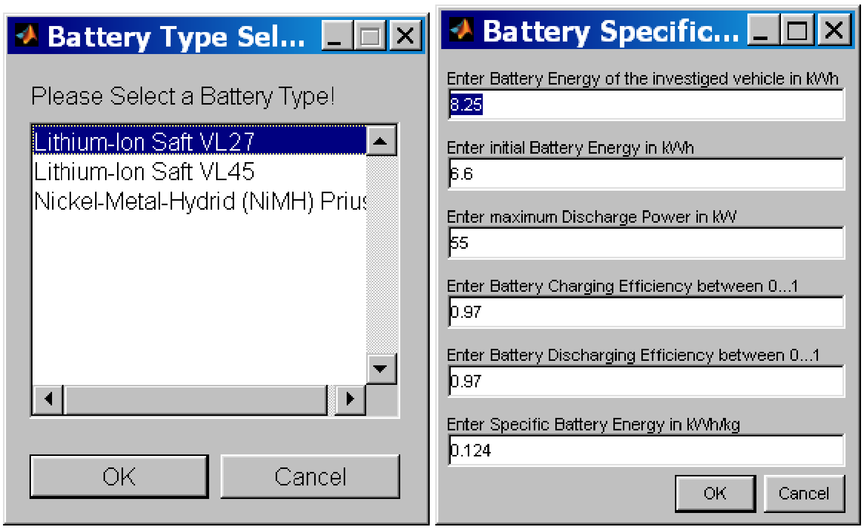


Figure 4.2 : Battery Type Selection and Battery Specifications.

At the next step, the masses of the electric propulsion system parts are evaluated. Lithium-Ion and Nickel-Methal-Hydrid battery types are from the most popular battery types. Although new generation hybrid vehicles such as Lotus Proton Emas, Chevrolet Volt and Audi A1-etron prefer Lithium-Ion, Toyota uses Nickel-Methal-Hydrid battery system in the hybrid vehicles. After the user has selected the battery type, default battery specifications such as default total energy, initial energy, charging, discharging efficiencies and specific energy are provided in the textboxes taking into account of the selected battery type.

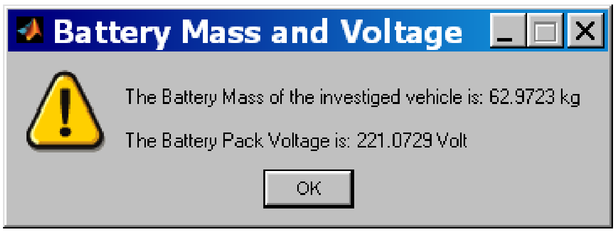


Figure 4.3 : Battery Mass and Voltage Displaying Message Box

A message box appears with the battery pack mass and voltage to give the user a feedback. The battery weight is calculated using selected battery energy and battery specific energy.

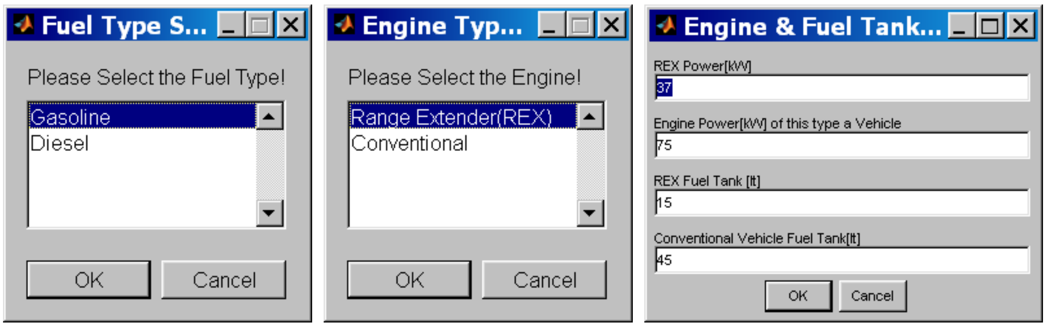


Figure 4.4 : Engine and Fuel Tank Mass Calculations

Since the engine and fuel tank have significant impact on the vehicle total weight, these are also included in the program. According to the fuel type and Tank Volume, fuel mass is computed. The gravimetric power density of a sample gasoline and diesel engine for a midsize family car are taken as gravimetric power density parameter. On the other hand, REXs are their own design and their power density is relative higher in comparison with the conventional ones. Lotus Range Extender Engine's specific weight is used for REX selection, which is 37 kW, naturally aspirated, 56 kg weighting, cost effective and has two valves per cylinder combustion system (Url-3). For conventional gasoline engine, Hyundai Alfa 1.4 naturally aspirated, 71 kW, 112 kg, and for diesel engine Hyundai U-ENG 1.5D, VGT aspiration, 82.5 kW, 140 kg are used to evaluate specific weight (Url-22). Other weight parameters such as automatic transmission, starter motor and its battery, electric machine weight, REX generator, electric machine controller, and other power electronics units like rectifier and converter are also included in the program to approach to a realistic vehicle mass.

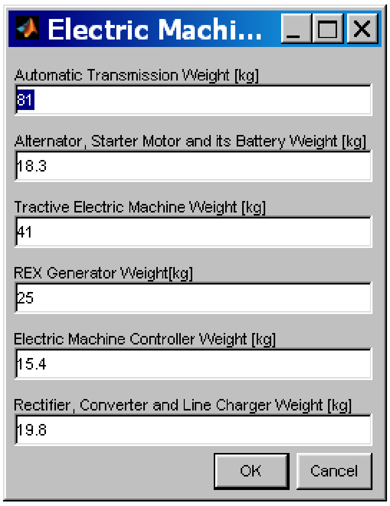


Figure 4.5 : Transmission, Electric Machines and Electronic Units Masses

The last dialog box in the interface program is driving cycle selection. With this feature, a desired driving cycle can be tested in the simulation and there is no need to enter the simulation duration each time in case of changing the driving cycle.

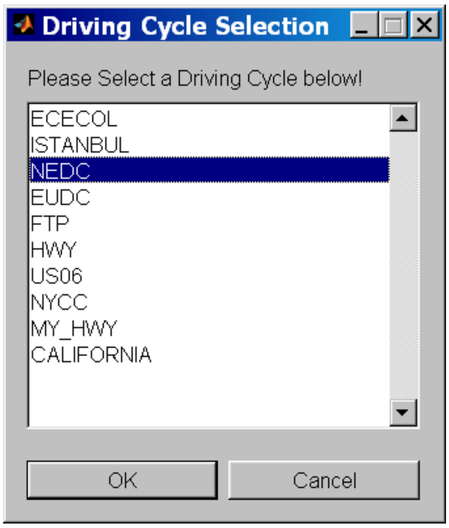


Figure 4.6 : Drive Cycle Selection

There are ten cycles including city cycles like Ececol, New York City, California, extra urban cycles like EUDC, highway cycles like HWY or My_HWY, or high performance cycles, also with high acceleration rates like US06. These cycles are to be studied in the fallowing chapter more detailed.

5. POWER AND ENERGY ANALSIS FOR DIFFERENT TEST CYCLES

Driving cycles are defined using velocity-time tables. The track covered is divided in time-steps. The acceleration rate is assumed to be constant; hence the velocity during a time step is a linear function of time. Since velocity and its change are known for each time point, the required and recoverable mechanical power and energy as a function of time (Url-20). For tests of emissions and fuel consumption rates, driving cycles are used.

Today, motor vehicles are equipped with large power engine with excess city driving power demands, for instance a midsize family car has 60 kW-80 PS engine, although the city driving power demands are much lower. The high power demands are needed on the highway with high velocities and acceleration demands. In this part, different test cycles are handled, so that the power and energy demands are compared which help the design criteria of a vehicle.

Power train and drive line components differ in conventional and hybrid vehicles. A heavy convention engine, automatic transmission, a 45 or 60 lt fuel tank and also starter motor with its battery are not needed in the REX electric vehicles. Instead, a relative small range extender engine with a relative small fuel tank, it's generator, electric machine for traction and regeneration, it's control unit and other power electronics units such as inverter and converter with their , and finally the battery pack are placed in the vehicle. For a simulation run by Obrist Engineering, a contributes automotive technology improvements to compare hybrid vehicle with 125 kW engine and 8-12 kWh Li-Ion battery and conventional vehicle with 2.0 TDI 125 kW engine, the weights are assumed to be the same, as 1550 kg, for an Audi A6. Hence, the cycle power and energy demands of a conventional and REX Electric vehicle could be accepted as the same.

During the simulations, reference mass is considered as stated in regulations. Reference mass is means the unladen mass of the vehicle increased by a uniform figure of 100 kg. Unladen mass means the mass of the vehicle in running order without driver, passengers or load, but with the fuel tank 90 per cent full and the usual set of tools and spare wheel on board (United Nations Emission Regulations No 83, 2008). The vehicle run in the simulation is 1230 kg, its rolling coefficient 0.013, drag coefficient 0.33, front area $1.961m^2$, typical for Hyundai Getz, the combination of drag coefficient and area, namely drag area is $0.65m^2$. To compare the drag area with Toyota Prius with a drag coefficient of 0.25, drag area of $2.55m^2$, combined 0.64 or with Honda Insight having combined drag area of $0.474m^2$, the vehicle can be assumed as an average family car, taking into account the weight and rolling resistance coefficient as well. Larminie and Lowry (2003) analyse the rolling mass coefficient for an 800 kg electric vehicle having a 30 kW motor and finds this coefficient 5% and mention that the inertia of the motor will not be known in most cases, a reasonable approximation is to simply increase the mass by 5% for the rolling mass coefficient. For the worst-case scenario, the rolling mass coefficient in the simulations is assumed 1.07, also 7% increase of the mass. In the simulations below, limitations caused by the electric machine maximum generative power, its controller, and battery specifications are neglected. However, considering the city cycles where the most regeneration potential is available, the regenerative powers are not so high, that the regeneration system limits it. The regenerative energy is fully utilized if deceleration rate is less than 0.2 g and optimal feel series braking method is applied for greater deceleration rates. This technique is explained in more detail in the battery energy consideration chapter.

In this part, wheel power and energy demands will be studied. The efficiencies and hence actual demands will be handled in the next chapters to size the components.

The interface designed is also used in that part. After the selection of the vehicle and test cycle, the simulation is run and the maximum power demand, energy demand, both cycle and per km, recupable energy, both cycle and per km, and finally net energy, both cycle and per km, are displayed via a message box on the screen which updates its name and data with respect to the to the last run simulation. For ECE -15, the message box can be found in fallowing, however it was not showed each time, rather than, a data table is provided with respect to related test cycle.

5.1 ECE-15

ECE 15 (Economic Commission for Europe) cycle represents urban driving and is an characterised by low vehicle speed. The velocity, power and energy characteristics are shown below:

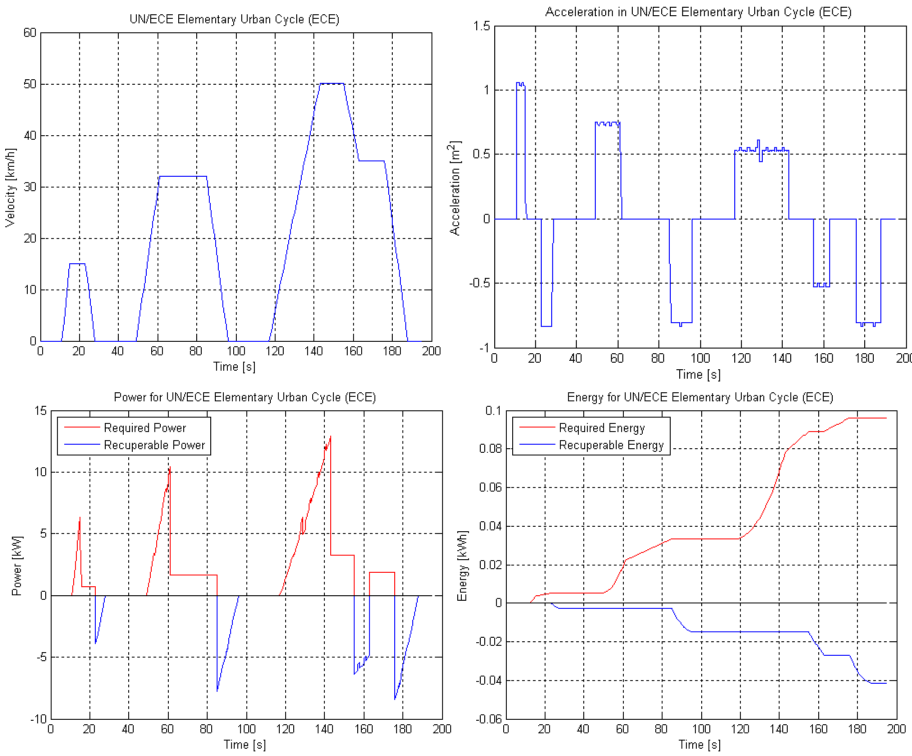


Figure 5.1 : Velocity, Acceleration, Power and Energy in ECE-15

The related message box seems as fallowing:

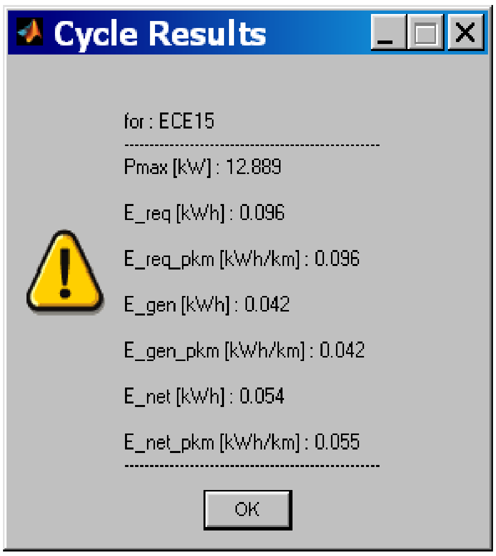


Figure 5.2 : Message Box Showing Test Cycle Results for ECE.

The table below shows the simulation results for the selected vehicle as a compact list which is, considering efficiencies of related parts as well, significant for sizing of equipments such as maximum power of drive train, battery energy etc. The abreviations t_total, t_tot, x, V_ave, V_max, E_req, E_reg, E_net mean total time, standing time, distance, average and maximum velocity, required energy, regenerative energy and net energy, respectively.

Table 5.1 : ECE-15 Characteristics and Results

	unit	ECE15
P_max	kW	12.889
E_req	kWh	0.096
E_req	kWh/km	0.097
E_reg	kWh	0.042
E_reg	kWh/km	0.042
E_net	kWh	0.054
E_net	kWh/km	0.055

5.2 NYCC

NYCC (New York City Cycle) represents low average speed with long standing times, a typical New York driving condition.

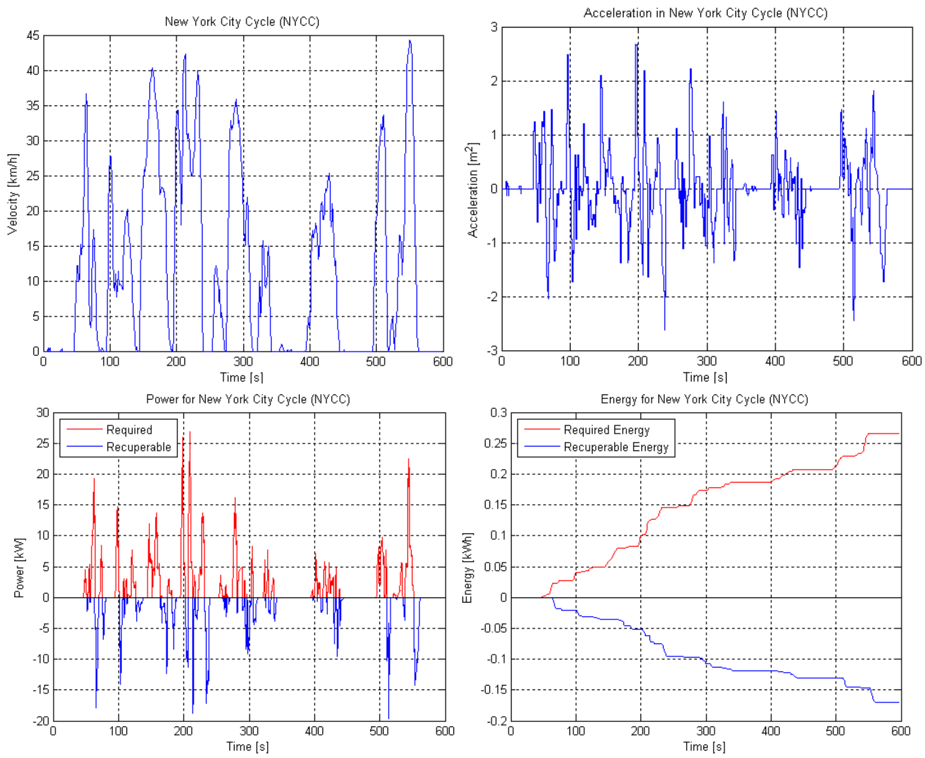


Figure 5.3 : Velocity, Acceleration, Power and Energy in NYCC

Table 5.2 : NYCC Characteristics and Results

	unit	NYCC
P_max	kW	26.878
E_req	kWh	0.265
E_req	kWh/km	0.141
E_reg	kWh	0.166
E_reg	kWh/km	0.088
E_net	kWh	0.099
E_net	kWh/km	0.053

5.3 ICC

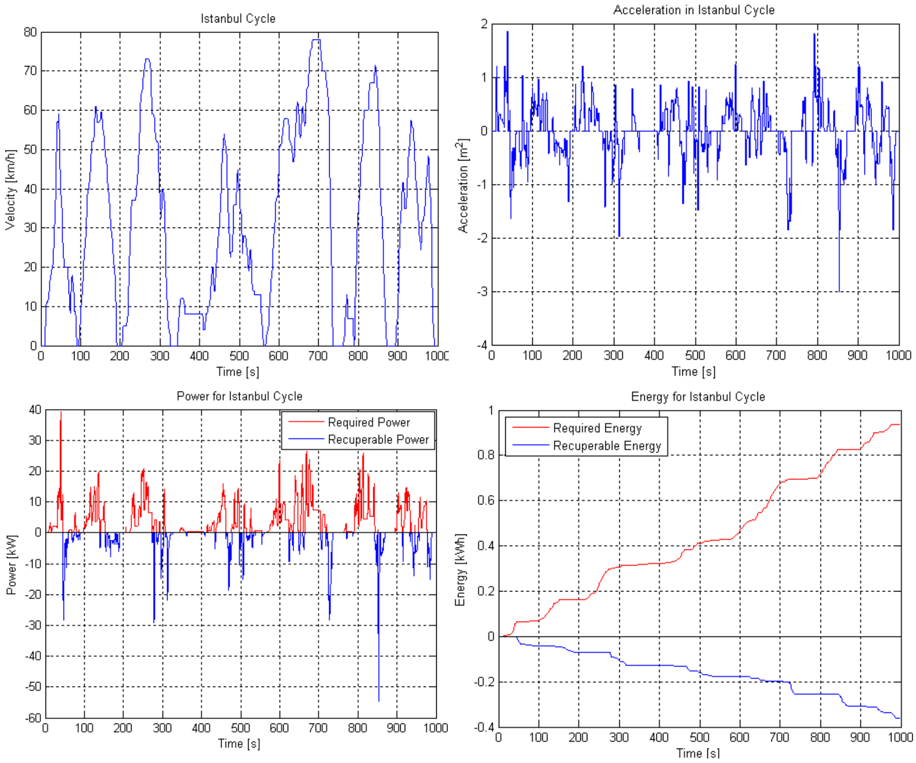


Figure 5.4 : Velocity, Acceleration, Power and Energy in ICC

Table 5.3 : ICC Characteristics and Results

	unit	ICC
P_max	kW	39.228
E_req	kWh	0.938
E_req	kWh/km	0.109
E_reg	kWh	0.357
E_reg	kWh/km	0.042
E_net	kWh	0.580
E_net	kWh/km	0.067

Istanbul City Cycle is similar to the NYCC; it has higher velocities and less standing time.

5.4 NEDC

NEDC (New European Driving Cycle) consists of four ECE 15 cycles followed by EUDC cycle. It is also known as the MVEG-A cycle.

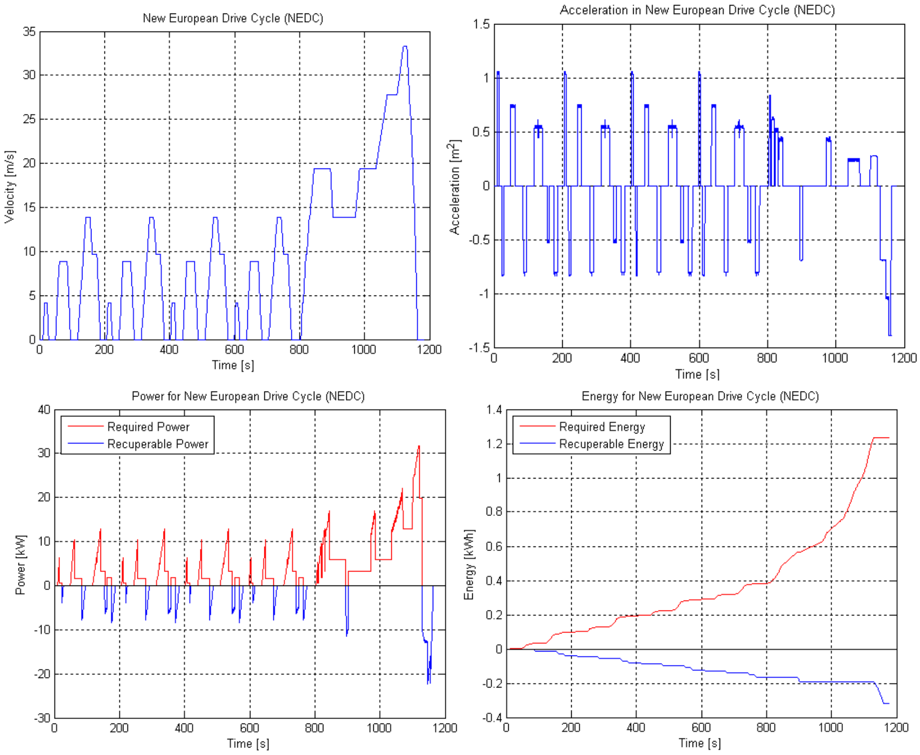


Figure 5.5 : Velocity, Acceleration, Power and Energy in NEDC

Table 5.4 : NEDC Characteristics and Results

	unit	NEDC
P_max	kW	31.760
E_req	kWh	1.234
E_req	kWh/km	0.113
E_reg	kWh	0.319
E_reg	kWh/km	0.029
E_net	kWh	0.916
E_net	kWh/km	0.084

5.5 FTP-75

The FTP 75 (Federal Test Procedure) is the FTP 72 with an extra third phase. This phase is identical to the first phase of the FTP 72 but is executed with a hot engine. FTP-72 has been developed to describe an urban route. The cycle consist of a cold start phase. This phase is followed by a transient phase with many speed.

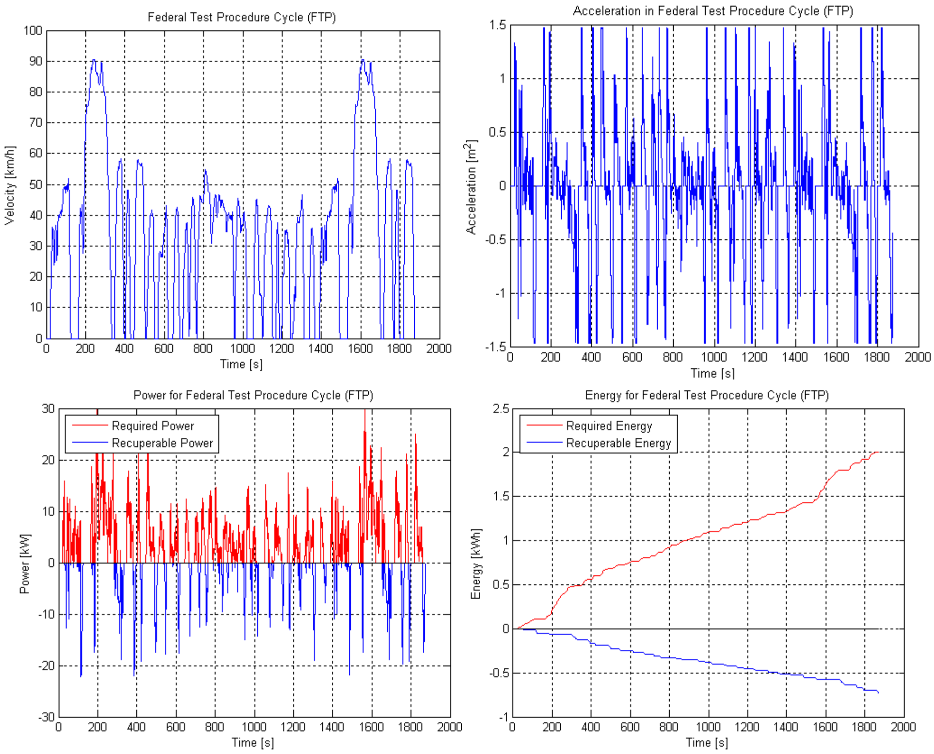


Figure 5.6 : Velocity, Acceleration, Power and Energy in FTP-75

Table 5.5 : FTP Characteristics and Results

	unit	FTP75
P_max	kW	29.716
E_req	kWh	2.000
E_req	kWh/km	0.113
E_reg	kWh	0.737
E_reg	kWh/km	0.042
E_net	kWh	1.263
E_net	kWh/km	0.071

5.6 US06

The US06 Supplemental Federal Test Procedure (SFTP) was developed to address the shortcomings with the FTP-75 test cycle in the representation of aggressive, high speed and/or high acceleration driving behaviour, rapid speed fluctuations, and driving behaviour following start-up (www.dieselnet.com/standarts/cycles).

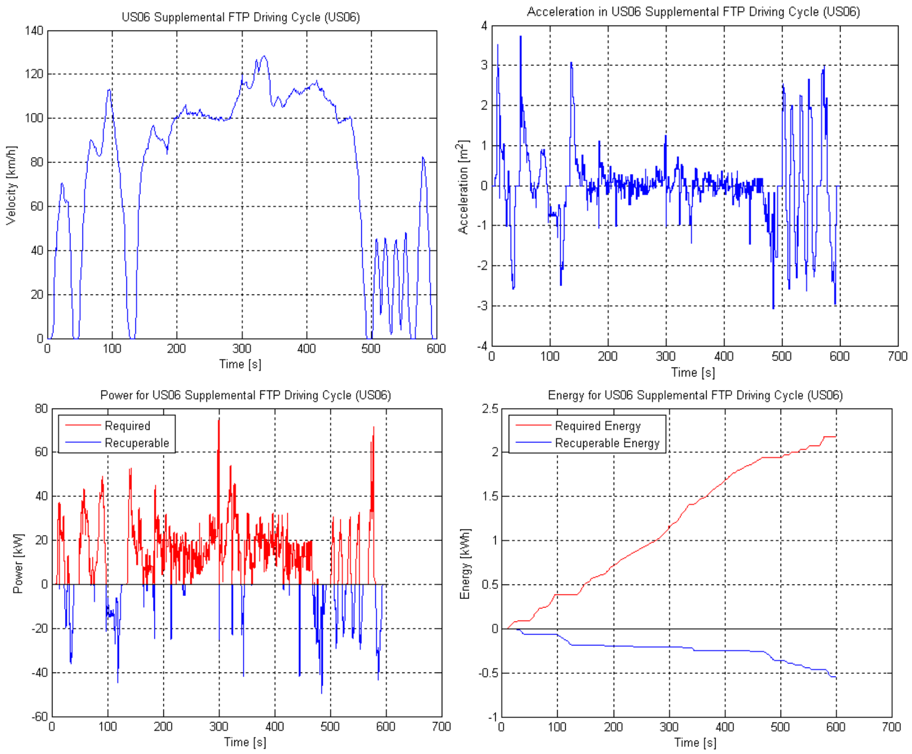


Figure 5.7 : Velocity, Acceleration, Power and Energy in US06

Table 5.6 : US06 Characteristics and Results

	unit	US06
P_max	kW	74.623
E_req	kWh	2.179
E_req	kWh/km	0.170
E_reg	kWh	0.494
E_reg	kWh/km	0.039
E_net	kWh	1.685
E_net	kWh/km	0.132

5.7 HWYFET

HWFET (Highway Fuel Economy Test) represents fuel economy driving pattern.

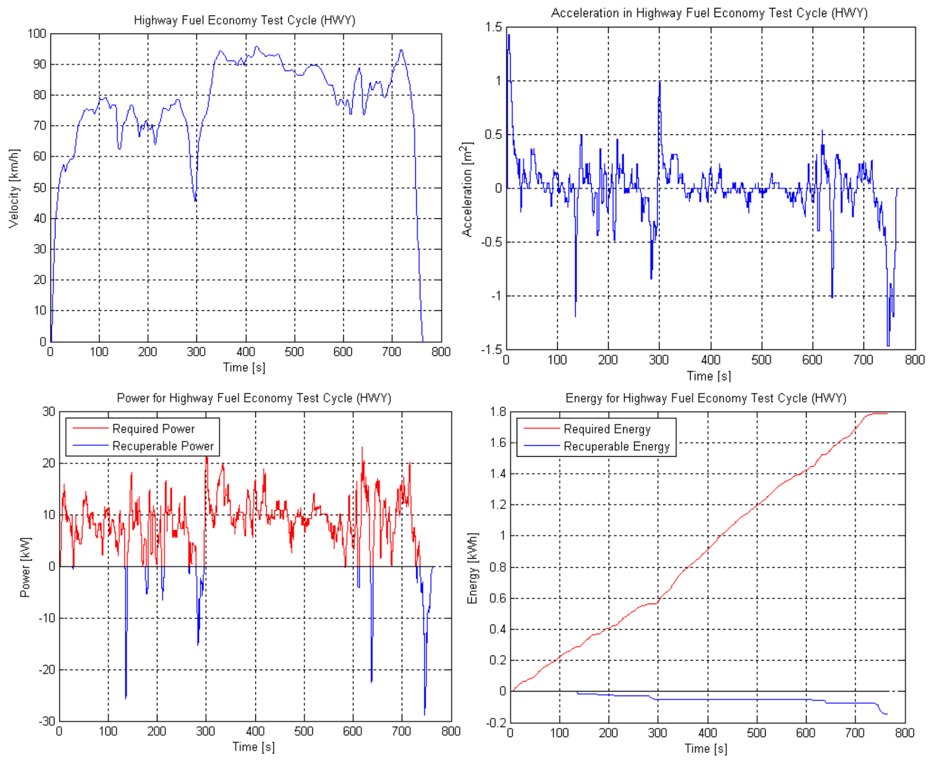


Figure 5.8 : Velocity, Acceleration, Power and Energy in HWYFE

Table 5.7 : HWYFET Characteristics and Results

	unit	HWYF
P_max	kW	24.456
E_req	kWh	1.783
E_req	kWh/km	0.011
E_reg	kWh	0.143
E_reg	kWh/km	0.009
E_net	kWh	1.640
E_net	kWh/km	0.100

The table below shows that the maximum power demand is 74.7 kW in US06, it fallows to 40 kW in ICC. However, studying carefully the graphs, this is clear that these power demands are not needed continuously, but for small periods, obviously under 30 seconds. The electric propulsion units are able to provide high peak powers and torques for a limited time, for instance 30-90 seconds, and the batteries as power sources could also provide high current for small periods. Consequently, the limited high power periods of electric units match the cycle demands, almost perfectly. For component sizing, there will be also other considerations, where also short period - high demand relation will be thoroughly investigated. The least maximum power demand occurs with 12.9 kW in ECE-15.

Table 5.8 : Different Cycles Characteristics and Simulation Results

	Unit	ECE15	NYCC	ICC	NEDC	FTP75	US06	HWY
t_total	s	195	598	999	1180	1874	596	765
t_tot	s	45	186	101	241	241	13	1
t_tot	%	23.08	31.10	0.10	20.42	12.86	2.18	0.13
x	km	0.95	1.90	8.60	11.02	17.79	12.89	16.50
V_ave	km/h	23.87	16.63	31.00	42.24	34.20	79.62	77.70
V_max	km/h	50.07	44.45	78.00	120.09	91.09	128.91	96.32
P_max	kW	12.889	26.878	39.228	31.760	29.716	74.623	24.456
E_req	kWh	0.096	0.265	0.938	1.234	2.000	2.179	1.783
E_req	kWh/km	0.097	0.141	0.109	0.113	0.113	0.170	0.011
E_reg	kWh	0.042	0.166	0.357	0.319	0.737	0.494	0.143
E_reg	kWh/km	0.042	0.088	0.042	0.029	0.042	0.039	0.009
E_net	kWh	0.054	0.099	0.580	0.916	1.263	1.685	1.640
E_net	kWh/km	0.055	0.053	0.067	0.084	0.071	0.132	0.100

Another interesting point is the cycle energy demand per km. Considering optimal feel series braking method for regenerative braking, the city energy demand per km is 0.053 kWh/km in NYCC and 0.055 kWh/km in ECE. Although ICC and NEDC possess extra urban driving periods, the net energy requirements are also at that cycles relative low, 0.067 kWh/km and 0.084 kWh/km respectively.

The data used in tables for the total time t_total, the standing time t_tot, the average and the maximum velocity V_ave and V_max are taken from the work of Barlow published in 2009.

6. REXEV DESIGN CONSIDERATIONS

In the previous chapter, many driving test cycles have been run to give an idea for component sizing. Nevertheless, real world requirements differ somewhat from those of given cycles where neither maximum velocity nor maximum grade are involved . Some studies have indicated that in hilly conditions and sporting manner driving conditions, the power outputs are still very low, in the region of 15 kW. (Turner et al, 2011). In the fallowing part, power and tractive force demand of the vehicle that is to be designed as electric vehicle with REX will be investigated more deeply.

The vehicle parameters that will be used in fallowing are the same with in the previous chapter used one except the vehicle mass. The unladen mass of the selected vehicle is 1130 kg, for the reference weight that is necessary to match the standard requirements, 100 kg has been added. In this part, instead of 100 kg, 140 kg is added to the unladen mass considering two passenger are travelling in the car. Furthermore, to approach the real world conditions, hotel loads comprising infotainment and cooling or heating systems are also estimated to be up to 2- 3 kW for a luxury vehicle (Turner et al, 2011).

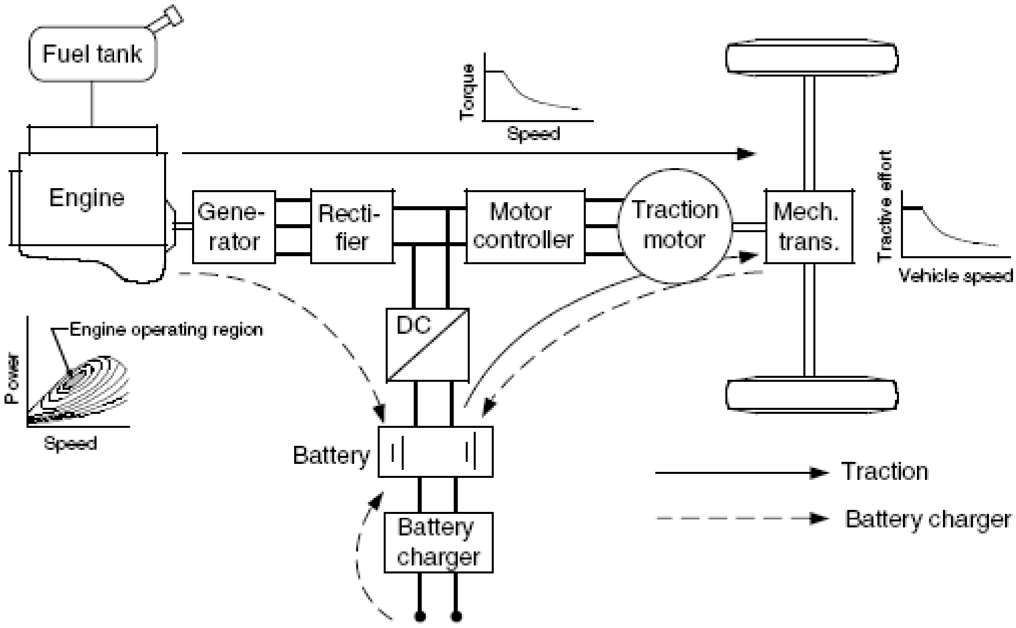


Figure 6.1 : Configuration of REX Electric Vehicle (Ehsani et al, 2008)

The figure above shows the configuration of and REX Electric Vehicle. The traction motor, engine-generator and battery compose the drivetrain, hence these are to be sized.

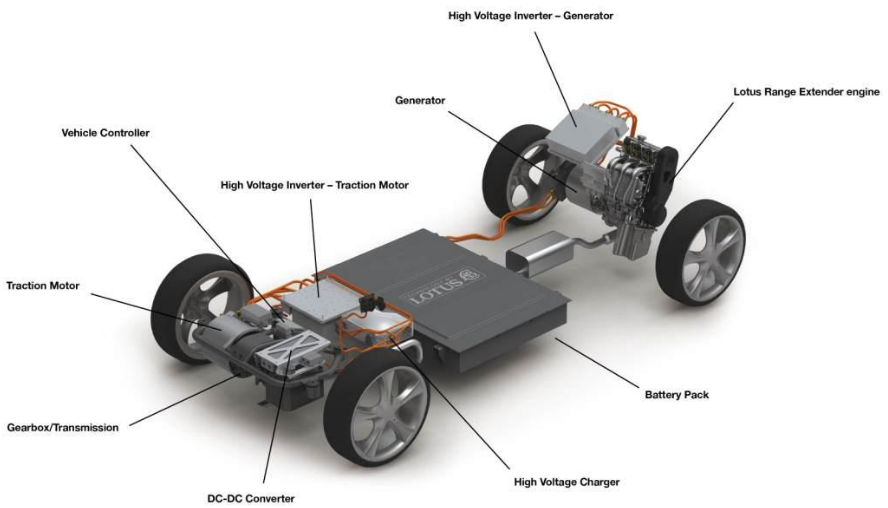


Figure 6.2 : Lotus Proton Emas Drive Train (Url-3)

6.1 Traction Motor Sizing

Electric machine is the propulsion unit of the range extended electric vehicle. The permanent magnet machine is preferred for today's hybrid electric vehicles, since it provides high torque density, potentially wide constant power range, and relatively small required inverter rating. It can be designed for a theoretically infinitely wide constant power range, only practically limited by thermal and mechanical factors. (Parra et al, 2009). In fallowing electric machine sizing constraints such maximum speed, gradeability and acceleration performance will be investigated. A remarkable point is that having considered the resistive force demands a vehicle without a gearbox will be aimed.

6.1.1 Top Speed

In Turkey, tempo limit on highways is 120 km/h, in European countries, there is an allowed maximum speed of 130 km/h and on some highways in Germany, there is no tempo limit. Therefore, continuous top speed between 130-140 km/h will be aimed during the sizing.

In analyses, the program presented before is utilized which accelerates the simulations. First, the parameters are taken from the selected vehicle and the default parameters windows are displayed. The first step can be seen below; the default parameter windows are illustrated in the previous chapters.

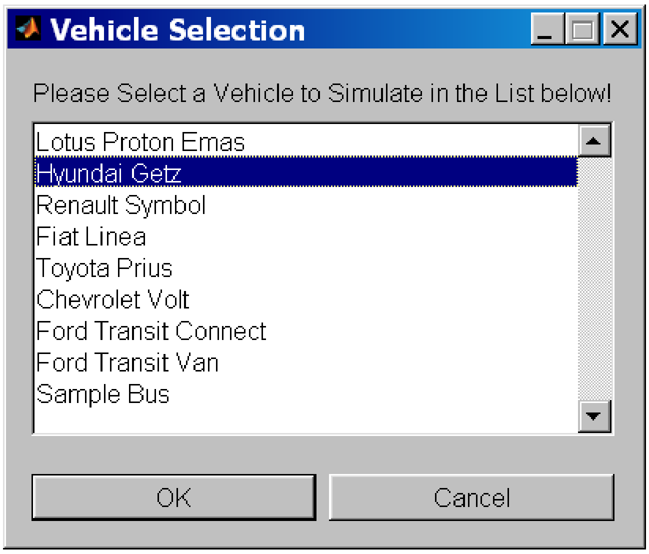


Figure 6.3 : Vehicle Selection

After that, speed limitation option will be provided which is added for the analysis to be able to allow a clearer view over the graphs. These steps are also provided for acceleration and hill climbing performance analyses.

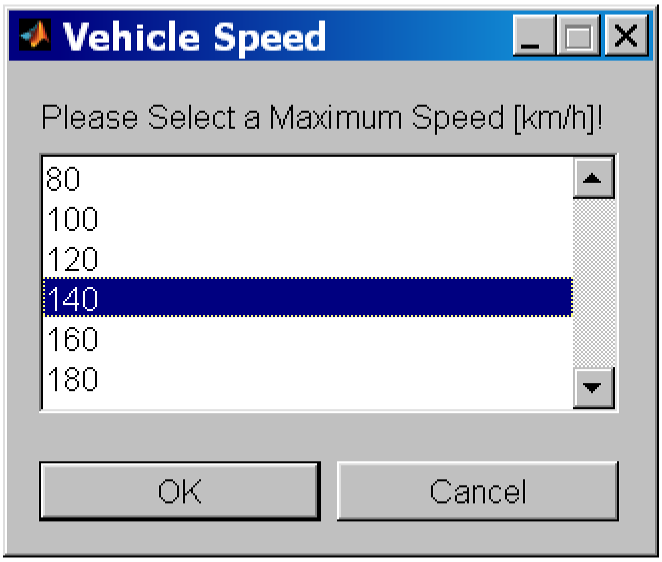


Figure 6.4 : Speed Limitation Selection Window

According to the user selections, the graphics are provided as seen below.

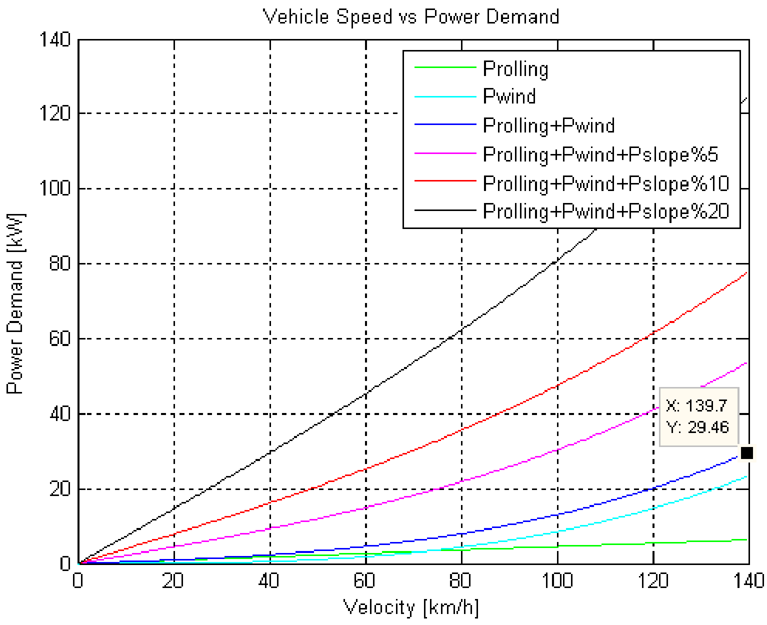


Figure 6.5 : Vehicle Speed vs. Power Demand.

The figure above shows the required rolling, wind and hill climbing power of the vehicle with specifications given above. The power need on a flat highway while driving at about 140 km/h is calculated as 29.46 kW. Considering a 0.94 differential efficiency, it becomes 31.34 kW which means the traction motor should provide that much power for a constant 140 km/h speed on the highway.

6.1.2 Acceleration Performance

The acceleration is a key performance indicator, though there is no standard measure used (Larminie and Lowry, 2003). A widely used performance parameter for a vehicle is the required time to accelerate from 0 to 100 km/h. In the United Kingdom and United States, the velocity range is 0 and 60 mph, which is equal to 97 km/h or 27 m/s. Acceleration figures are found from simulation or testing of real vehicles. For IC engined vehicles this is done at maximum power, or ‘wide open throttle’. Similarly, for electric vehicles performance simulations are carried out at maximum torque (Larminie and Lowry, 2003).

Since the electric machine operates almost noiseless, the accelerating feeling for the driver is more influential comparing to conventional cars, which is also an advantage for marketing of vehicles with electric propulsion systems. Bugatti Veyron Super Sport car is the fastest car with the 2.4 s verified time (bugatti.com.) which means it is faster than an object at frictionless free fall for which it would take 2.83 s to reach 100 km/h. However, for a midsize family car it takes 10-15 seconds to reach 100 km/h. For instance, for Renault Symbol it is 12.5 (Url-5/), Hyundai Getz 11.2 s for manual, 13.9s for automatic transmission (Url-6), Fiat Linea 14.6 s (Url-8), Toyota Prius 11 s (Url-7), Lotus Proton Emas REX electric vehicle 14s (http://www.goauto.com) and Opel Ampera REX electric vehicle 9s (Url-9). The acceleration is one of the important points for vehicle marketing strategies. A vehicle for which it takes 20 s to accelerate 100km/h would not a desired one. This parameter is decided to be below 11-12 seconds for the vehicle in this work. The mean 0-100 km/h acceleration should be 2.778, 2.525 and 2.315 m/s^2 for 10, 11 and 12 seconds, respectively. However, because of the electric machine torque-speed characteristics, the acceleration at low speeds will be higher and it will decrease gradually.

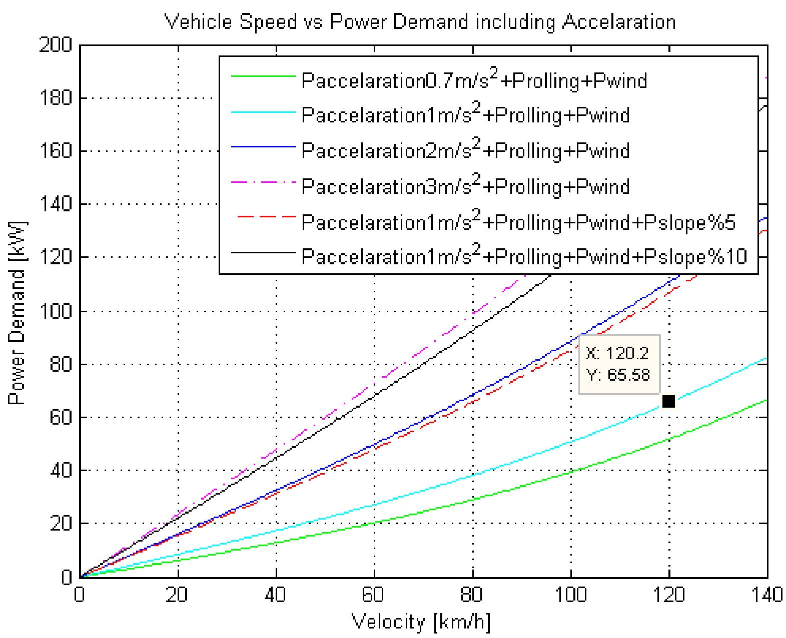


Figure 6.6 : Vehicle Speed vs. Power Demand including Acceleration.

Another point for performance is acceleration need while driving at constant speed on the highway, also for passing other vehicles. The figure above describes this situation. Because the road could also be inclined, slope values are also considered. While driving at 120 km/h, the power demand for 1 m/s^2 acceleration rate is 65.58 kW, and this rate at 140 km/h becomes 82 kW, for 0.7m/s^2 this would be 66.36 kW.

6.1.3 Hill Climbing Performance

Torque characteristics of the propulsion unit determined the maximum gradeability of the vehicle. According to the statistics published by Turkish General Directorate of Highways, the maximum incline on highways is 10%, on urban roads 15% and on rural land 22%. In this work, a 30% slope is aimed to achieve considering worst case scenarios.

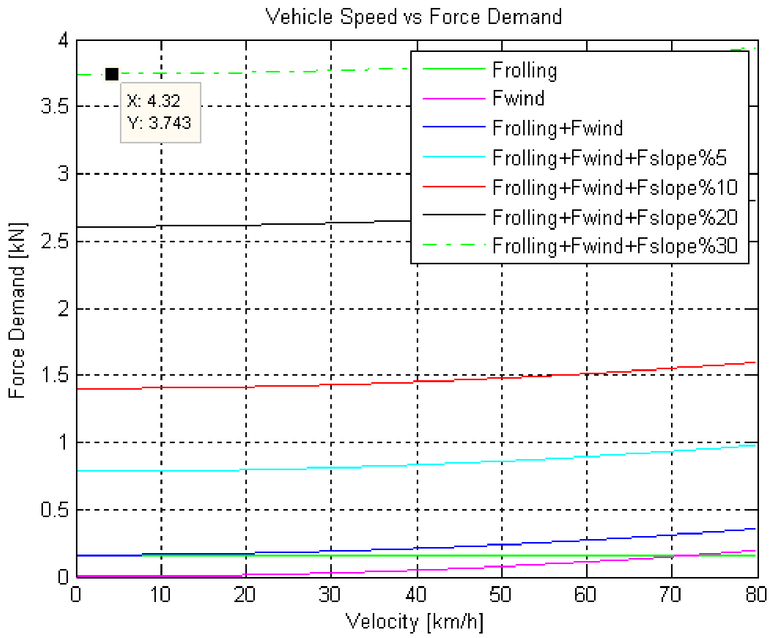


Figure 6.7 : Vehicle Speed vs. Force Demand for Different Slope Levels.

The hill climbing performance figure indicates for a 30% slope level, the force demand at the wheels is 3.743 kN, dividing by 0.94, an efficiency from motor to wheel, it becomes 3.968 kN. Again this torque demand for an extremely high slope value of 30% can be assumed for a short period operation; hence this will be supplied by the electric motor by its temporary high performance. The temporary high performance of the electric machines differs with respect to design parameters. UQM technologies report their electric machines used in vehicles can support high performance up to 90 seconds (Url-10).

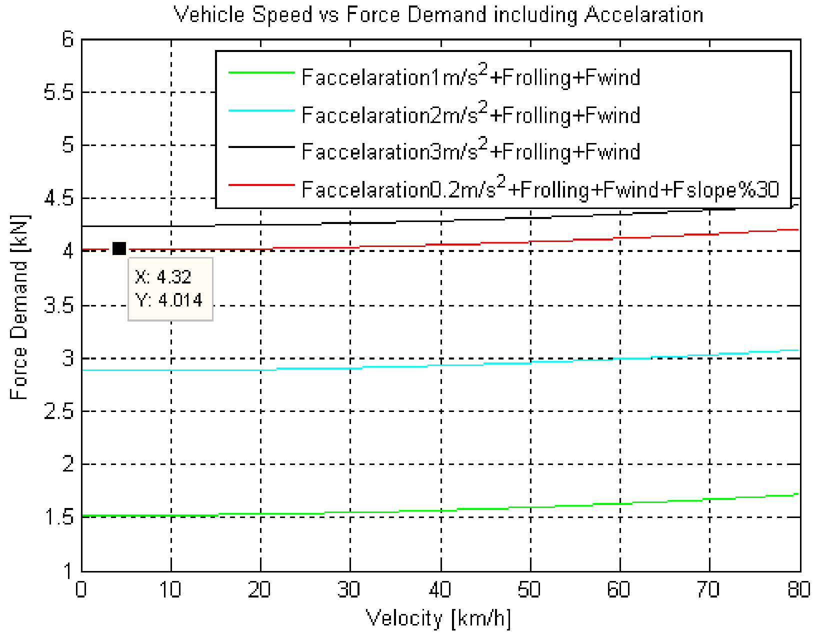


Figure 6.8 : Speed vs. Force Demand for Acceleration and Slope Levels.

The above figure gives information and also a comparison between the climbing and acceleration force requirements. One should also consider the acceleration demand while climbing a 30% slope when the vehicle is standing or running at a low velocity; the force demand is then becoming about 4 kN.

6.2 Potential of Eliminating the Gearbox

A gearbox consists of several gear pairs and a mechanism to change gears. Besides this there are bearing, sealing and other losses in a gearbox. All these things have effect on the efficiency of the transmission (Naunheimer and Lechner, 1999). The third gear efficiency map of the Saturn manual 5 speed transmission available in Advisor is given below to show the efficiency decrease for low loads. It includes other drive line losses, like final drive torque loss.

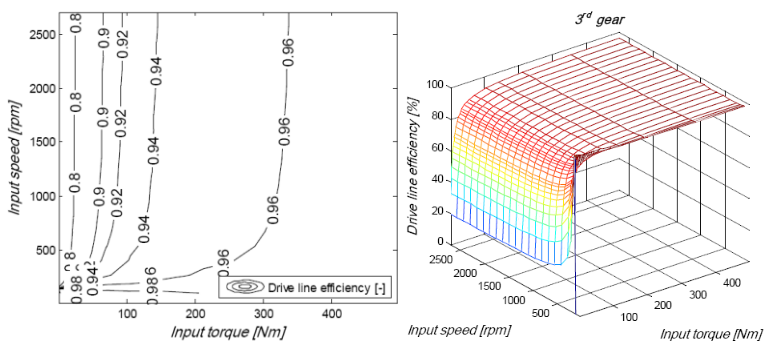


Figure 6.9 : 3rd Gear Drive Line Eff. of Saturn (Kuijpers and Smits, 2010)

In this part, the elimination potential of the gearbox will be discussed by utilizing the design constraints of the electric machine and demanded force & power for related driving conditions. Because of the pretty fitting electric machine characteristics mentioned in the previous parts, there is a possibility to eliminate the gearbox in the vehicle. Below, the figure illustrates different electric vehicle configurations. Since the REX electric vehicle has the same configuration potentials, these architectures might be assumed as REX electric vehicle potential configurations as well.

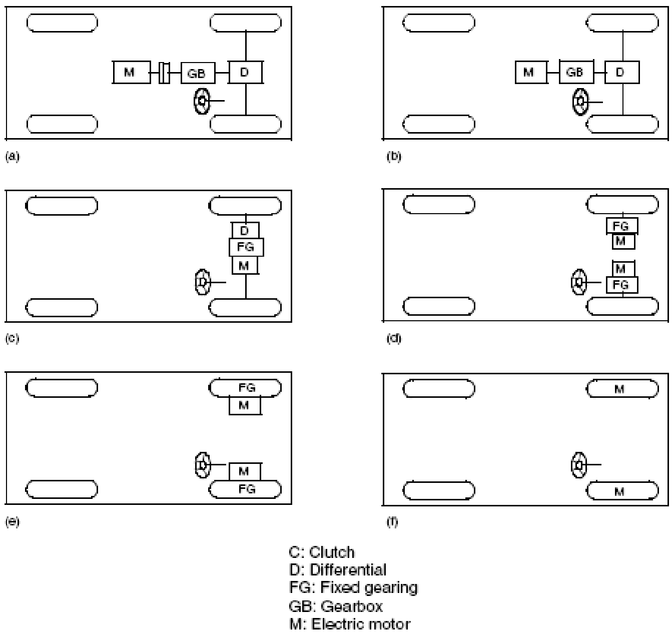


Figure 6.10 : EV Configurations (Ehsani et al, 2005).

In case the gearbox is not placed, the size, weight control and cost of the transmission vanish which makes the vehicle a simpler machine. To investigate the possibility, electric machines that are used in electric propulsion systems are researched. Also, one constraint for the selection of the machine is to be in use, since it is aimed to approach to a realistic simulation. Because, in real world, the operating motor/generator efficiency of the electric machine is not the maximum point, that is given almost in every datasheet. Hence, in simulations, electric machine is also modelled to investigate operating efficiency points.

Another constraint is top speed power output which is calculated as 31.34 kW for travelling at a speed of 140 km/h in “Top Speed” subchapter. A further constraint derives from maximum power output of the propulsion unit, which is studied in “Acceleration Performance” subchapter. While driving at 120 km/h, the power demand for 1 m/s^2 acceleration rate is 62.88 kW, and this rate at 140 km/h becomes 80 kW. The vehicle should also reach to 100 km/h under 12 seconds. This performance need to be verified after electric propulsion unit has been selected. Moreover, about 4 kN force demand is to be provided at the wheels to accomplish 30% hill climbing including an acceptable acceleration rate at this rare-expected condition. Lastly, the cycle analysis study realised in previous chapter has indicated that the maximum power demand during a very short time is 74.7 kW in US06, it fallows to 40 kW in ICC, considering differential efficiency, this would be 79.5 and 42.55 kW. Other important points can be summarised as high power density and high efficiency.

45 and 75 kW traction systems dominate the mass market 30–150 kW, a solution is possible using just two sizes of drive (Hodkinson and Fenton, 2001). Having researched the electric machines in use for electric vehicles, the model PowerPhase 75 produced by UQM Technologies is chosen. It gives detailed information about the product, has a compact structure, providing high peak and continuous torque, efficiency and power density. UQM also used in electric or hybrid vehicles such as Audi A1 etron, US Air Force electric trucks and is selected for Hybrid Bus Development Project by Michigan Mass Transportation Authority. UQM supplies fallowing electric machines:

Table 6.1 : List of Electric Machines supplied by UQM Technologies

Type	Power	Voltage	speed	Torque
	kw (hp)	VDC	rpm	Nm
HiTor Traction	50 (67)	250-430	6,500	440
PowerPhase 125	125 (167)	240-430	8,000	300
PowerPhase 145	145 (194)	240-430	8000	400
PowerPhase 150	150 (200)	240-430	5,000	650
PowerPhase 200	200 (268)	240-430	5,500	900
PowerPhase 75	75 (100)	250-430	8,000	240

The specifications of Powerphase 75 which will be used in the simulations are given below. Low weight and high maximum efficiency are drawn attention in the datasheet.

Dimensions		
Length	9.94 in	252 mm
Diameter	11.00 in	280 mm
Weight	90 lb	41 kg
Performance		
Peak power	100 hp	75 kW
Continuous power at 4,000 rpms	60 hp	45 kW
Peak torque	176 lbf•ft	240 N•m
Continuous torque	110 lbf•ft	150 N•m
Maximum speed	8000 RPM	
Maximum efficiency	94%	
Power density (based on 50 kW)	1.11 hp/lb	1.83 kW/kg

Figure 6.11 : Specifications of Selected Electric Machine (Url-10).

Motoring and generating performance and efficiency values at operating points including controller unit are provided by the supplier with the fallowing figures.

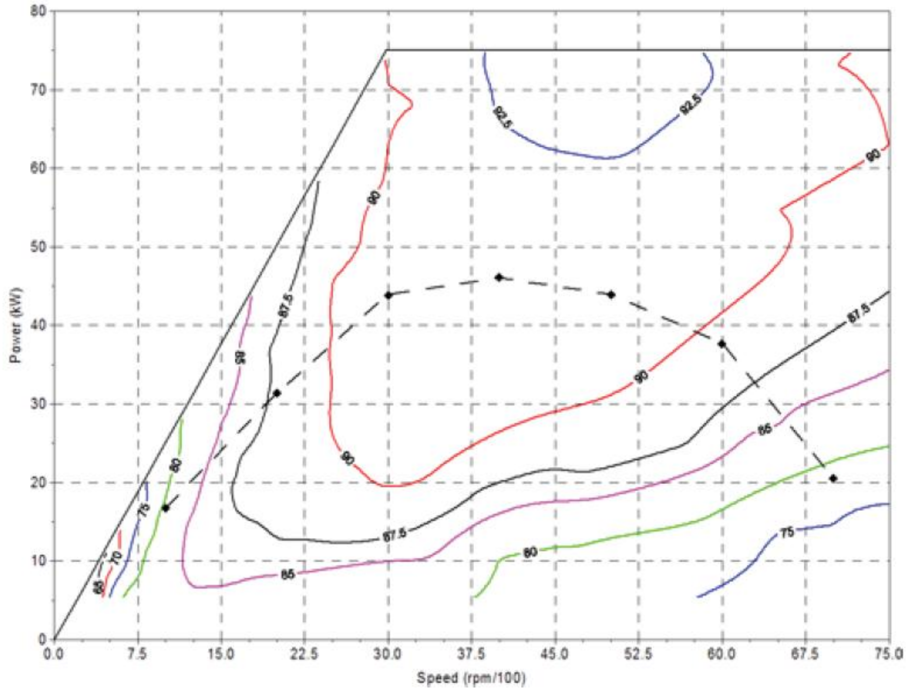


Figure 6.12 : Motoring Performance and Efficiency inc. Controller (Url-10).

The dashed line shows the continuous mode and the continous line the peak performance. In the datasheet, the peak performance duration is given up to 90 seconds.

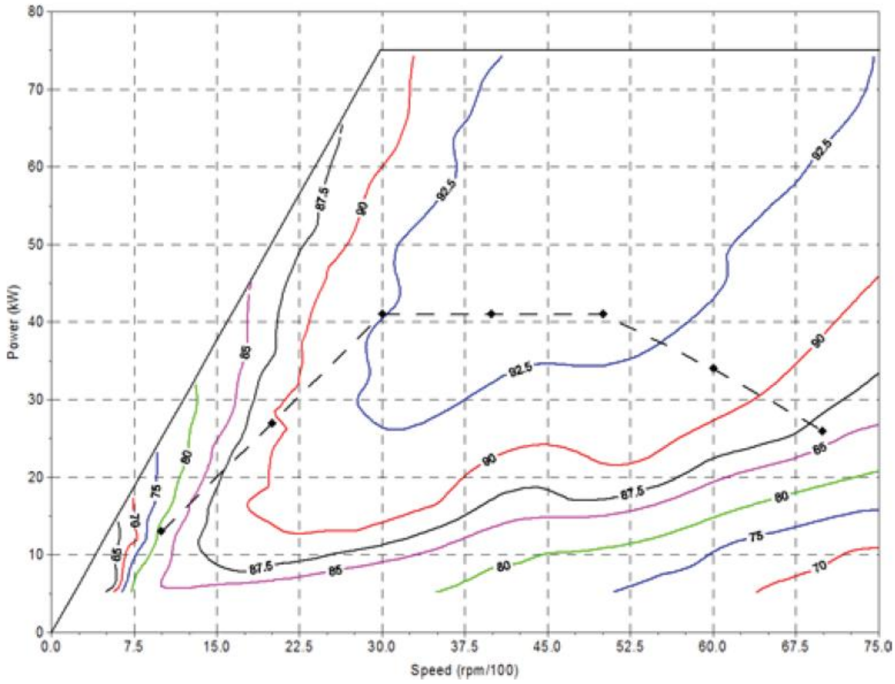


Figure 6.13 : Generating Power and Efficiency inc. Controller (Url-10).

The torque speed characteristics and efficiency map including controller on this characteristics is given below.

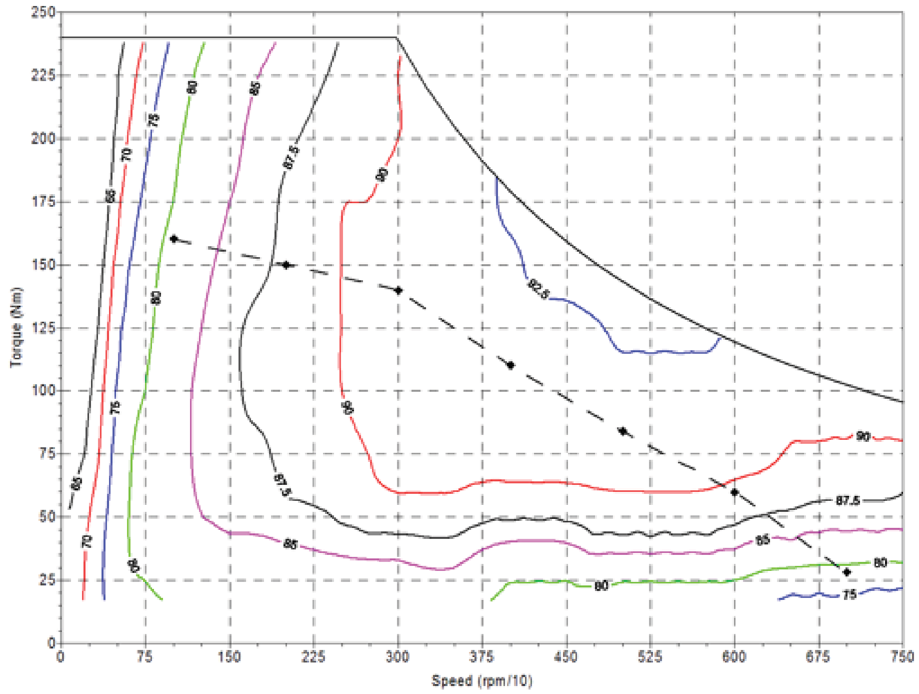


Figure 6.14 : Torque Performance and Efficiency inc. Controller (Url-10).

The tire parameters static and dynamic rolling radius are necessary for further calculations. The selected vehicle tire dimensions are 175/65 R 14, which gives effective radius of r =0.267 m and dynamic rolling radius R=0.283 m.

For the predefined top speed of 140 km/h (38.9 m/s), the required power has been calculated as 31.34 kW. However, letting a surplus power, the required power is rearranged to 35 kW. At 35 kW, the speed is 6200 rpm.

w = 2pi. n/60 =649.263 rad/s	**(6.1)**
w_max = V_max/R.ik = (38.9 m/s) / 0.283 m / ik	**(6.2)**
ik = w_max.R/V_max = 649.263 rad/s .0.283m / 38.9 m/s	**(6.3)**
ik = 4.72	**(6.4)**

The differential ratio ik = 4.72 provides a continuous speed of 140 km/h considering a surplus power of about 3.5 kW.

According to the evaluated differential ratio, the hill climbing performnace will be investigated. The maximum motor moment M_max is 240 Nm, assumed differential efficieny ik_eff is 0.94, effective rolling radius r_eff is 0.267m, hence the tractive force trasferred to to road can be calculated.

F_max = M_max/ r_eff .ik.ik_eff	**(6.5)**
F_max = 240/ 0.267 .4.72.0.94	**(6.6)**
F_max = 3.99 kN	**(6.7)**

With this calculations, a more than 30% hill performance could be achieved which was the aim at the beginning of this subchapter. The force is also enough to accelerate the vehicle on the 30% hill.

6.3 Verification Of Design Parameters

For the evaluated values, the demand and supply curves are drawn to verify the calculations. Additionally to the interfaces explained before, a driveline parameters selection interface provided to the user due which for different values of the parameters, the curves can be drawn in a quick way for an optimization goal.

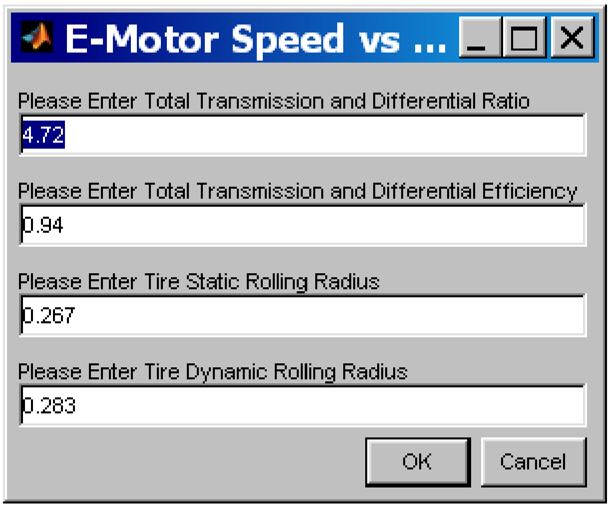


Figure 6.15 : Driveline Parameters Selection Window

Having defined the parameters, the demand-supply curves are evaluated as following.

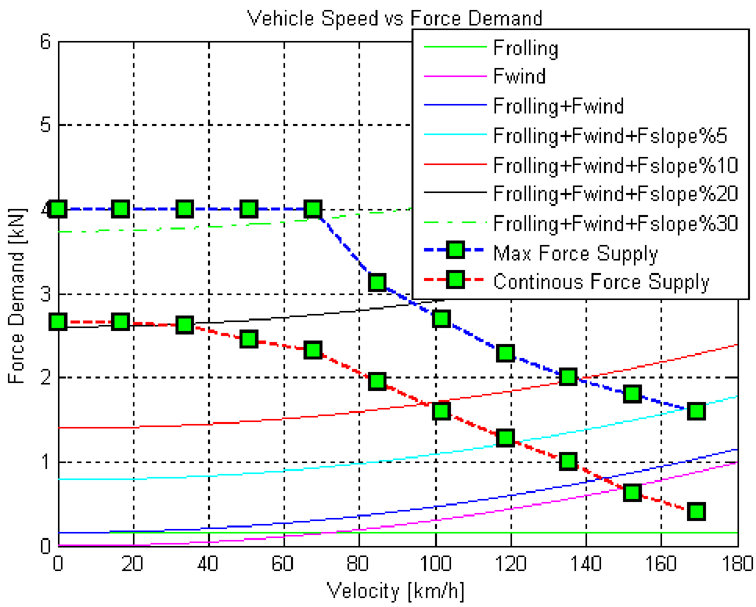


Figure 6.16 : Supply-Demand Curves including Various Incline Values

The above figure illustrates the supply and demand curves including different hill climbing performance demands while the below one shows the curves including different acceleration rates. In both graphs, continuous and temporary operation conditions of the selected electric machine are demonstrated.

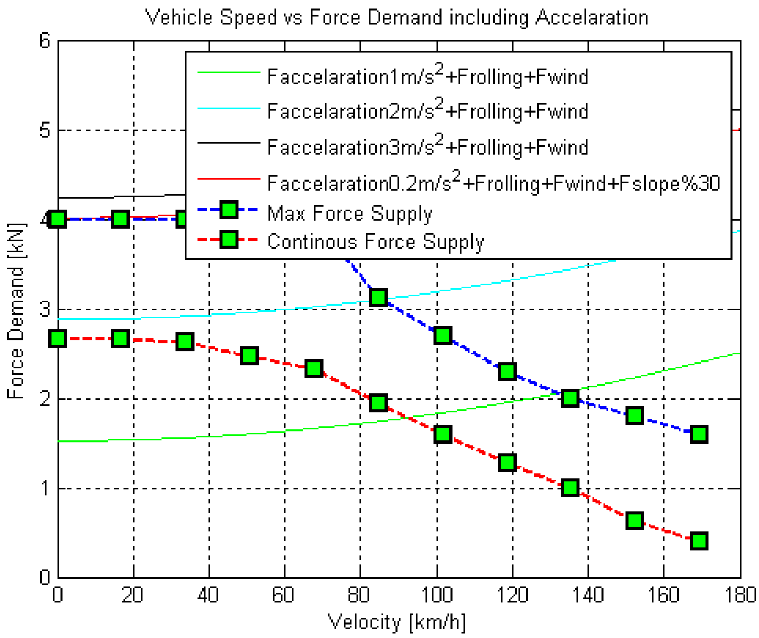


Figure 6.17 : Supply-Demand Curves including Various Acceleration Rates

From the figures, the maximum velocity and gradeability ar verified. The 0-100 km/h performance has also been a chosen as a design constraint and the necessary time to reach 100 km/h from standing position has been selected under 12 seconds in the previous subchapter. For the simulation, a driver mass of 70 kg is added to the vehicle unladen mass. The simulation is carried out at maximum torque as it mentioned in the acceleration performance subchapter.

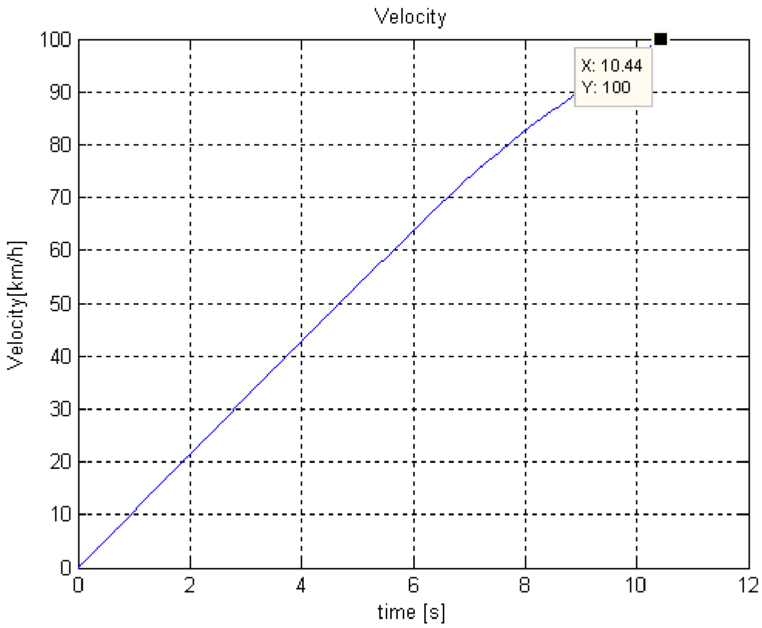


Figure 6.18 : Maximum Torque Velocity

The acceleration rate during the simulation is illustrated below.

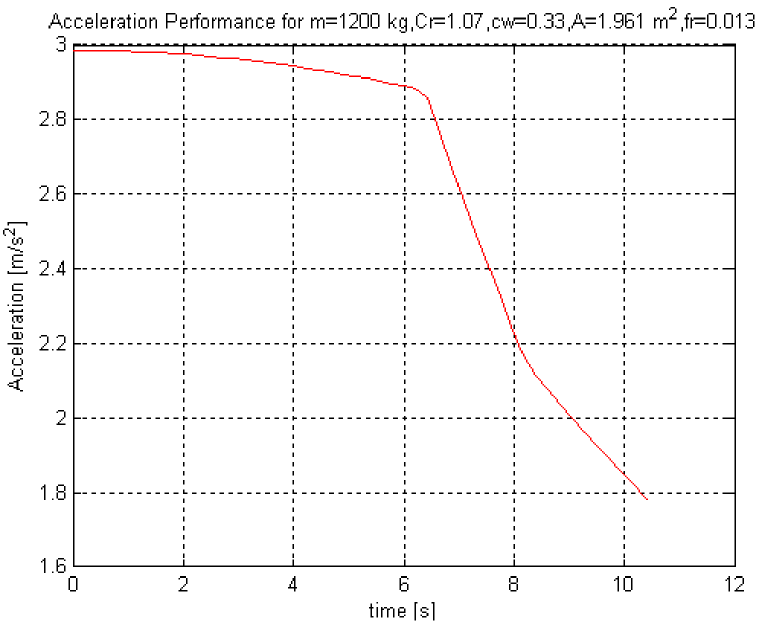


Figure 6.19 : Maximum Torque Acceleration

The force at wheels supplied by the electric machine is shown below.

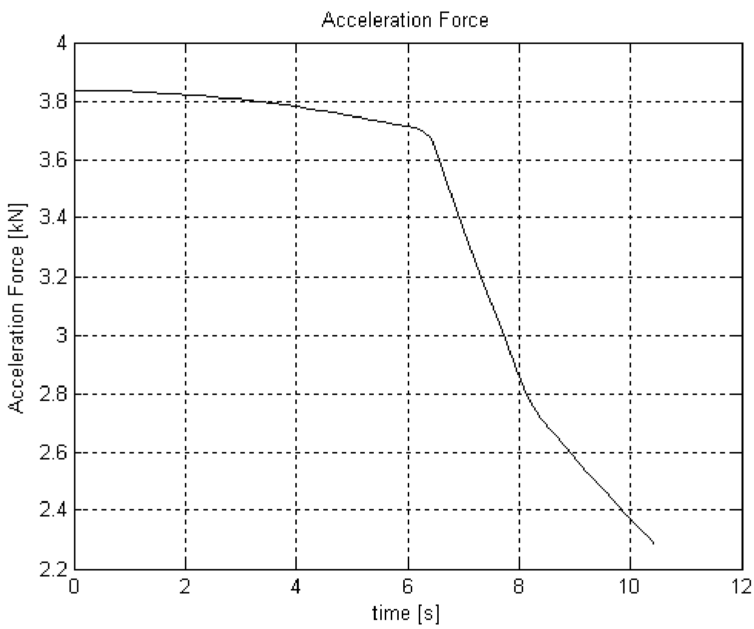


Figure 6.20 : Maximum Torque Acceleration Force

As a result, having chosen an appropriate electric machine and differential ratio, the vehicle is able to pass all the performance parameters defined at the beginning of the chapter successfully and even better than these constraints.

6.4 Range Extender Engine And Generator Considerations

The configuration of the REX Electric Vehicle can be seen below.

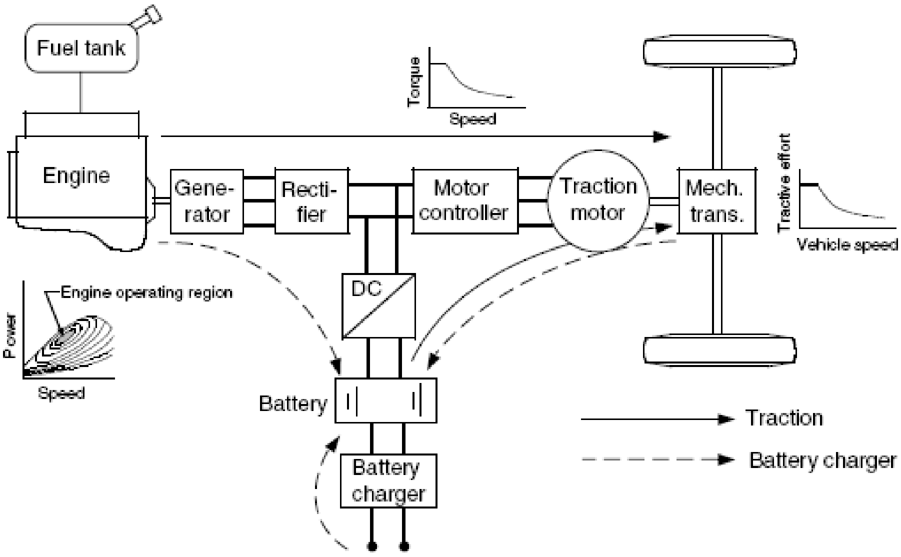


Figure 6.21 : Configuration of REX Electric Vehicle (Ehsani et al, 2008)

The power rating of the engine/generator is designed to be capable of supporting the vehicle at a regular highway speed (130 km/h) on a flat road (Ehsani et al,2005). To calculate required engine power, operating point efficiencies on the way from the engine to the wheels should be known, which consist of the efficiencies of engine-generator, rectifier, motor controller, traction motor and mechanical transmission.

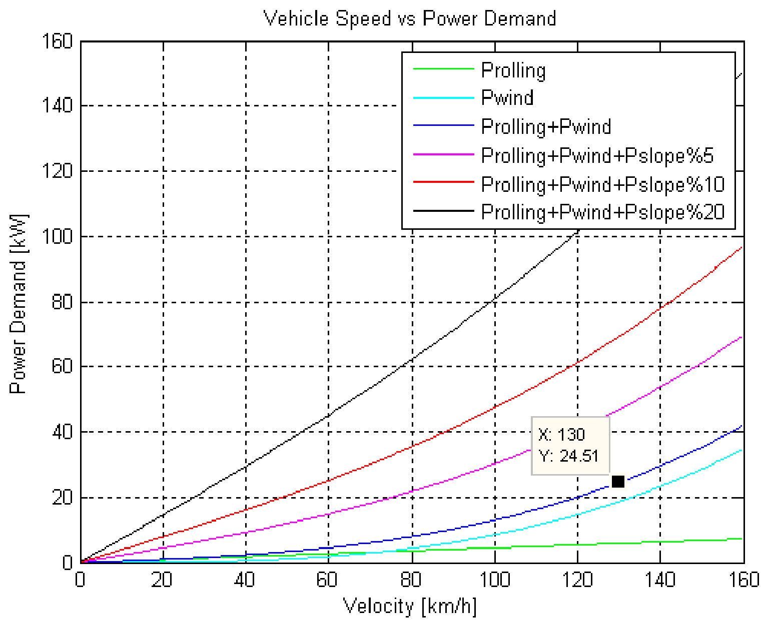
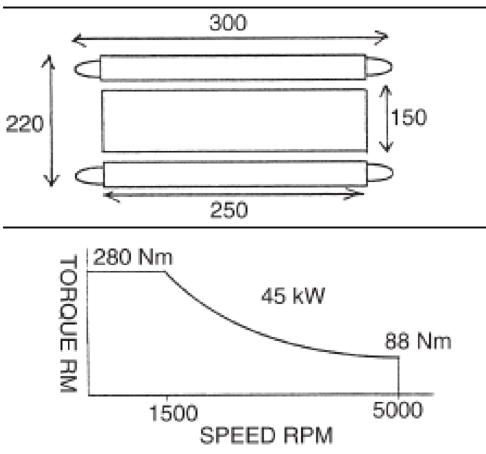


Figure 6.22 : Power Demand at Charge Sustaining Speed

Operating point or region efficiencies mentioned here are efficiencies at the defined continuous speed. Rectifier efficiency can be assumed as 95% (Url-17) and motor controller and motor efficiency map is given as one efficiency in the datasheet. For 130 km/h, 36.11 m/s, the motor speed is 602.28 rad/s or 5751.32 rpm. The necessary power is 24.51 kW as shown in the figure above, considering a 94% differential efficiency, this becomes 26.07 kW. For this power and speed region, the efficiency of the motor and controller is about 0.875. Hence, the power demand at the electric machine is 29.80 kW. At the rectifier, it is 31.37 kW with a 95% rectifier efficiency. Since the engine generator will operate almost at its high efficiency region, its efficiency will be higher than electric propulsion machine.

The machine of Coercive systems, 45 kW, 5000 rpm, has 96% efficiency at 1500 rpm 45 kW and 95% at 3500 rpm and 10 kW. In addition, an efficiency of % 95 for the engine generator will be used in the computations.



Coercive systems 45 kW 5000 rpm
BDC motor specification

Voltage current frequency	230 V 130 A 666 Hz
No. of poles	16
Weight	45 kg rating continuous
Efficiency at	
a. 1500 rpm 45 kW	96%
b. 3500 rpm 10 kW	95%
Cooling	Oil–2 litre/min
Cost (1000 up)	£1000 (batch prod.)
	£600 (mass prod.)

Figure 6.23 : REX Generator (Hodkinson and Fenton, 2001)

Hence, the power requirement for the REX becomes 33.02 kW including the generator efficiency and the overall efficiency from the REX to the wheels is calculated as 0.742 which consists of the differential, electric machine and controller unit, rectifier and engine generator having the values, 0.94, 0.875, 0.95, 0.95, respectively. To sum up, a constant speed of 130 km/h is with an 35 kW REX possible considering 2 kW accessory need mentioned previously, which means that on the highway the energy of the vehicle can be supplied by the engine, hence a significant life increase for the battery pack is possible which will be considered in fallowing chapter. Since the required energy on the highway will be at high load operating region, the efficiency of the engine is also significant higher than at city driving conditions.

The requirement from a conventional engine and a range extender engine are surely different. Because of the limited operation region of range extender engine system, engine simplifications are possible, as an comprehensive overload protection, over speed and complex transient operation conditions are not required (Atzwanger et al, 2010). For stroke versus two stroke, diesel versus gasoline or wankel engine concepts are to be taken account to choose the appropriate engine for the hybrid vehicle.

4-stroke engine has some significant advantages, the greatest is ease of manufacture, simplicity of after-treatment and the minimization of throttling loss considering full load operation region. It is also self-scavenging, which is a theoretical advantage over a 2-stroke externally scavenged engine pumping losses are similar to a 2-stroke engine at full load, because it is not functioning as an excess-air engine.

Meeting emissions limits for diesel engine, an expensive after-treatment system for both NOx and PM are required. Stoichiometric SI engine is also lighter then which may not actually realize as high efficiency.

HC emissions in Wankel engine is an disadvantage, however it allows for higher exhaust gas temperatures after engine start to faster light-off the catalyst and the generator drives the engine to start which brings a fast and smooth engine start up to target speed with focus on quick catalyst light-off (Atzwanger et al, 2010). Additionally, wankel engines provide perfect NVH and light weight.

An Inline four stroke engine is well known and has better fuel efficiency compared to wankel, low production cost due to common technology.

There are several companies which have produced range extender engines for electric vehicles. AVL's REX is a wankel engine producing 15 kW at 5000 rpm and 25 kW at 7000 rpm and weighting 64 kg. Chevrolet Volt uses an inline four stroke engine producing 75 kW and it has a weight of 90 kg. The REX of Lotus Proton Emas is 37 kW and 56 kg, 3 cylinders in line, 6 valves, 1.2 liters. Lotus Engineering offers also the supercharged variant of the REX having 50 kW power, 1.3 liter, 58 kg. Opel Ampera uses a 1.4 lt liter gasoline engine producing 62 kW.

In this work, a real engine is aimed to be used to have a realistic simulation result. According to the power considerations calculated above, and because the characteristics of the engine like engine map are required for simulation, and Lotus engine offer a pretty successful engine system, the REX of Lotus Engineering is chosen.

35% thermal efficiency is aimed for lotus REX although this value could be better. The Lotus claims that lightness, cost-effectiveness and efficiency should be thought altogether. Since the REX will always carried by the vehicle, it should be as light as possible. Because the EV will have an battery pack, the engine should be as cheap as possible to balance the total cost of the vehicle. Because of these two reasons, the efficiency should not be the first consideration (Turner et al, 2011).

General layout	1.2 litre 3-cylinder with 2 valves per cylinder, belt-driven single overhead camshaft
Construction	Monoblock with integrated exhaust manifold, separate two-piece chankcase
	All aluminium Primary couple balance shaft (deletable)
Bore and stroke	75.0 mm x 90.0 mm (1192.8 cc)
Compression ratio	10:1 (11:1 and higher protected for)
Maximum power	36.8 kW (51 bhp) at 3500 rpm (measured with balance shaft fitted – see text)
Maximum torque	102.6 Nm at 3000 rpm
Maximum BMEP	10.7 bar
Maximum engine speed	3500 rpm (with protection for 4000 rpm)
Crankshaft bearing diameters	Main bearings 38 mm Big end bearings 38 mm
Piston pin	18 mm diameter x 46.5 mm long
Fuel system	Port fuel injection, Lotus EMS
Fuels	95 RON ULG (minimum) / ethanol / methanol
Dry weight	60 kg with balance shaft, 56 kg without

Figure 6.24 : General Specifications of Lotus REX (Turner et al, 2011).

Lotus claim that fuel consumption of 241 g/kWh is considered to be extremely good, considering that this is a 2-valve-per-cylinder combustion system in a naturally-aspirated PFI engine.

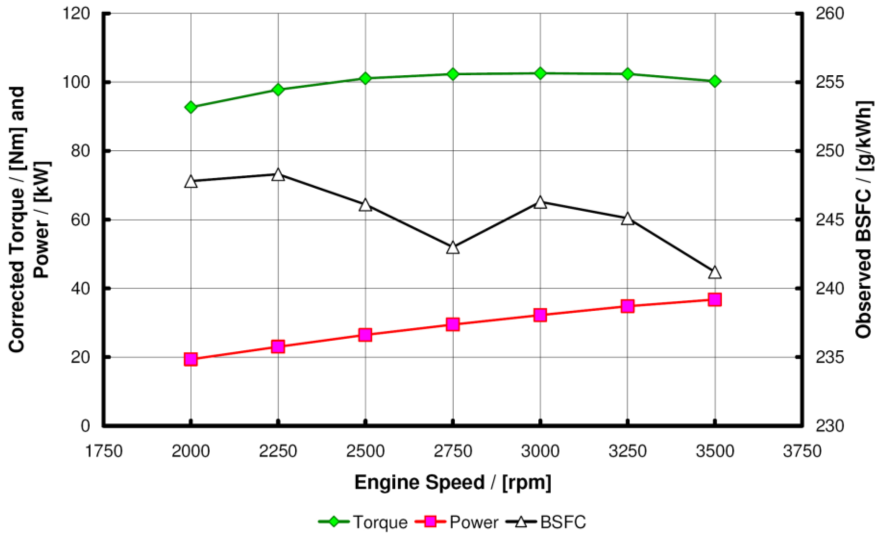


Figure 6.25 : Full Load Power, Torque and SFC (Turner et al, 2011).

The engine characteristics torque, power and SFC is shown in above figure while thermal efficiency characteristics can be seen in below figure.

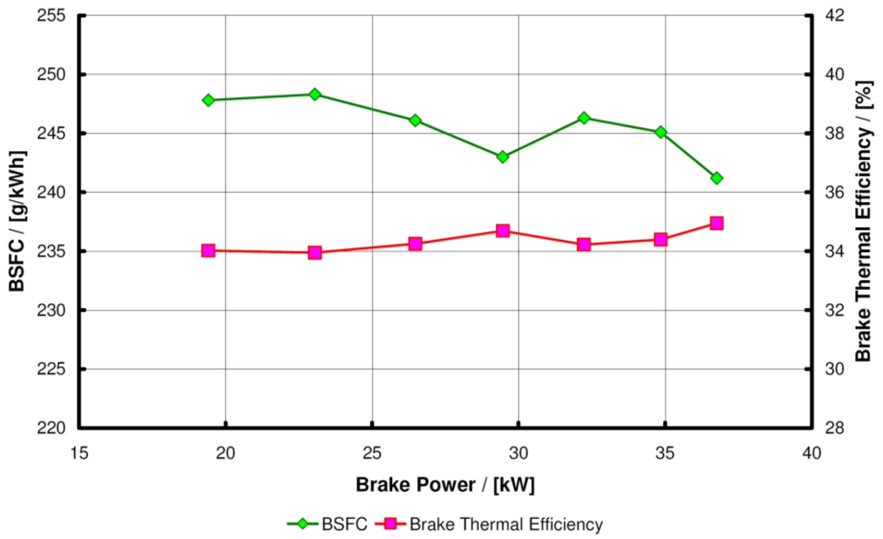


Figure 6.26 : Full Load BSFC And Thermal Efficiency (Turner et al, 2011).

Below, different types of symbol represent data points gathered from individual program are given:

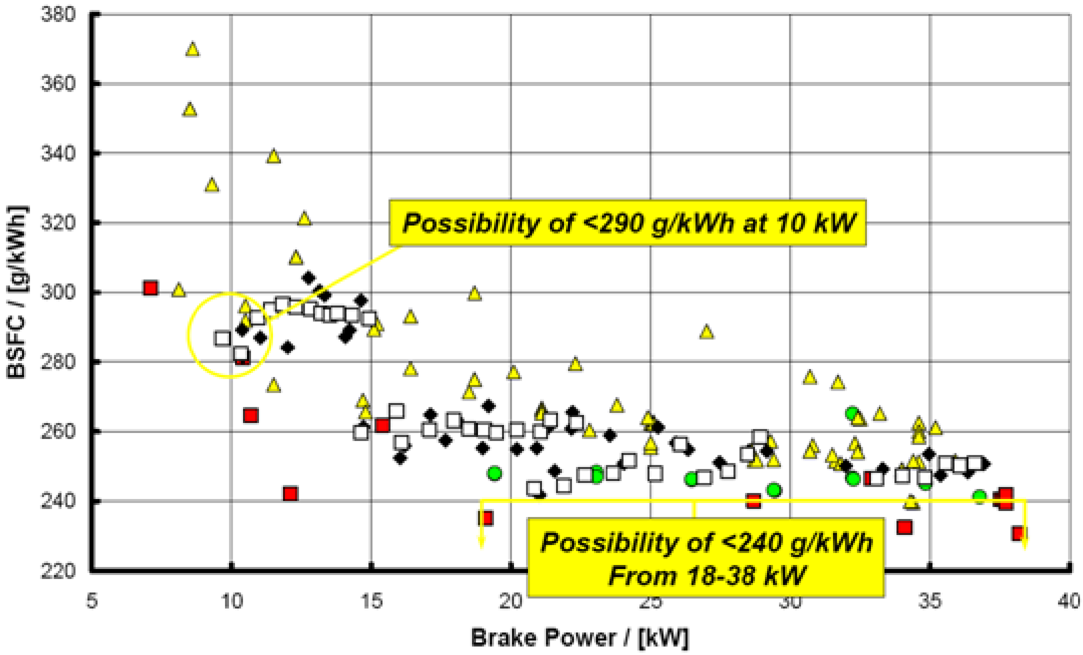


Figure 6.27 : Data From Several REX Builds (Turner et al, 2011).

6.5 Battery Sizing

Because of the low energy density of the batteries, the conventional series hybrid vehicles or full electric vehicles have heavy battery packs.

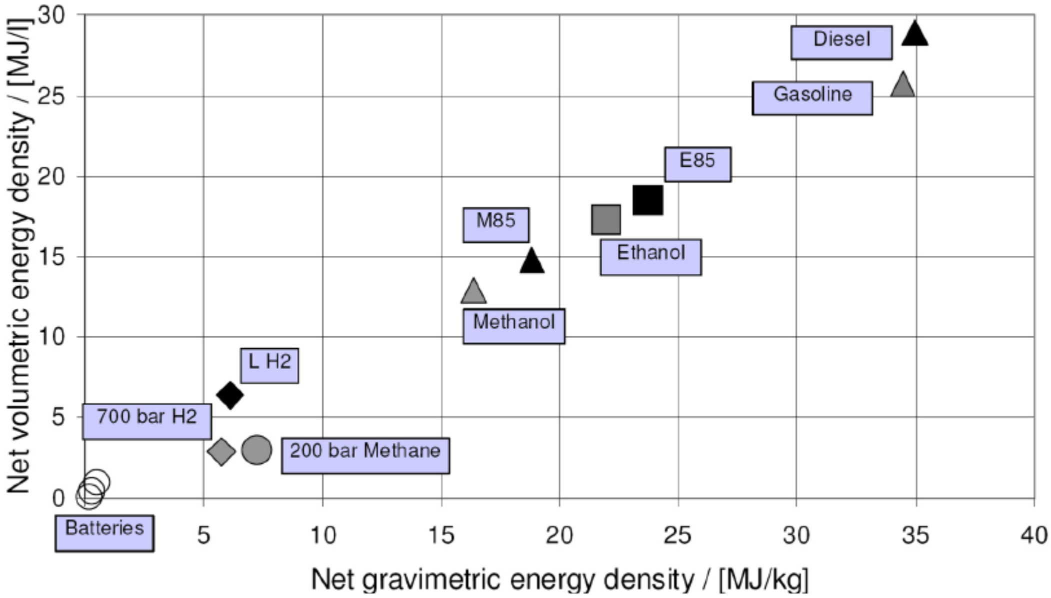


Figure 6.28 : Energy Densities of Fuels and Storages (Turner et al, 2011).

For battery sizing, power and energy capacity are to be considered. The sum of the output power of the engine/generator PPS should be greater than the power of the traction motor. The energy capacity of the PPS heavily depends on the drive cycle and overall control strategy, also allowed change in SOC (Ehsani et al, 2005).

6.5.1 Required Power Consideration

Although there is not transmission in the design, the electric machine short term performance allow the vehicle a sportive characteristic. The constant torque durates until 67.81 km/h, which takes about 6 seconds to reach from zero speed. For such an demand, the power supply is both battery and engine, as mentioned before.

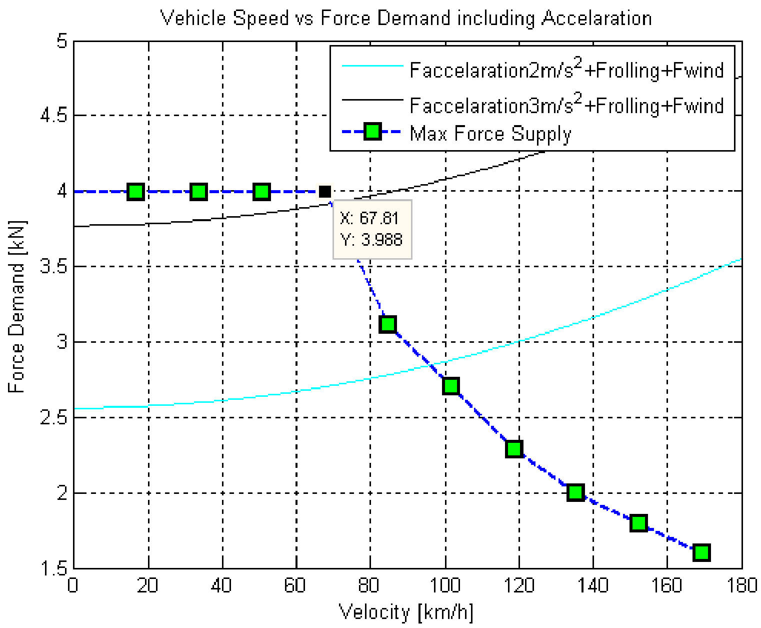


Figure 6.29 : Electric Machine Performance and Force Demands.

The engine to motor efficiency is 0.812 considering generator, rectifier, motor and control unit efficiencies, 0.95, 0.95, 0.90 respectively. Since the most power will be needed at the maximum power point, the efficiency of the motor and control unit at this point is considered. For lower power operation points, this efficiency is worse, however with the power requirement, the total power requirement including efficiency is becoming less. Therefore, a 35 kW engine provides 28.42 kW power to the motor, the rest should be supplied by the battery.

The efficiencies to be considered from the battery pack to the motor consist of battery efficiency, converter efficiency and motor & controller efficiency. James et al (2009) has evaluated the converter efficiency as 0.95 for hybrid and all electric vehicles. In literature, there are not much data about the battery efficiency and in most studies, it is not considered during computations. The battery efficiency is dependent on the battery type, temperature, discharge rate and SOC. Since NiMH and Li-Ion batteries are the most common battery types, these will be considered during the fallowing sections. An example data showing efficiencies of different batteries can be seen below.

Table 6.2 : Energy Reservoir Comparisons (Parra et al, 2009)

Type	Energy (Wh/kg)	Power (W/kg)	Lifetime (Cycles)	Efficiency (%)
PbAC	25--40	140--350	200--1500	70--75
NiCd	25--40	500	800--1500	70--75
NiMH	40--55	500--1400	500--2000	70--80
Li-Ion	70--130	600-3000	800--1500	85--90
Ultracapacitors	3--5	2000--10000	500k--1M	95--100

Another source for the specifications of batteries can be seen below.

Table 6.3 : Specifications of Different Battery Systems (Wagner, 2008)

Type	Unit	Pb/Gel	Ni/Cd	Ni/MH	ZnBr2	Li/Ion
En. Density	Wh/kg	30	40	60	60	150
Power Density	W/kg	60	200	175	60	200
Charging Time	h	10	0.5	1	4	1
Self-Discharging	% / d	<0.5	2 --10	2 --10	1	<1
Cycle Efficiency	%	70--90	65--85	65--85	50--70	60--80
Life	Full Cycles	600	1500	1500	1000	>1000
	Years	15	10	>5	>3	

However, the battery supplier Saft claims that their new Li-Ion batteries have the columbic efficiency close to 100%. The Coulombic efficiency or charge acceptance is a measure of how much usable energy is available during discharging compared with the energy used to charge the cell. Charge efficiency is also affected by temperature and SOC (Url-11). In simulations, charge and discharge efficiency of Li-Ion is assumed to be 0.97, of Ni-MH 0.925 efficiency which gives an overall efficiency of 0.94 and 0.85 for Li-Ion and Ni-MH, respectively. Hence the overall efficiency from battery to motor is the combination of the efficiencies of battery discharging, converter, motor & control unit, also 0.97 or 0.85, 0.95, 0.90 respectively. As a result for Li-Ion battery pack, the battery to motor efficiency is 0.829 and it 0.727 for NiMH battery system. Taking all into account, the battery power should be greater than 56.19 kW for Li-Ion and 64.07 kW for NiMH battery pack, which will be needed temporary.

Another constraint is that the battery power should cover the power demands in the cyles analysed before, because it is not an effective way to let often operate the engine from cold start considering emission. Ebner et al (2010) reports that the major emission release occurs in the first seconds after the engine cold start. The power request determines the catalyst light-off temperature time and since range extender engines run under high loads, the light off time can be reduced to a few seconds. Nevertheless, the high power requirement in cycles durates a few seconds and it is aimed that just the battery operates at this time span. The maximum power demands for Istanbul Cycle has been evaluated as 39.228 kW and 31.760 for NEDC. Taking the greater one and combining the full path efficiency give a 47.32 kW Li-Ion or 53.96 kW NiMH bottom boundary power. Both stay lower than the constraint calculated above for achieving maximum electric motor power.

6.5.2 Required Energy Consideration

The battery capacity plays a major role in the determination of range, fuel economy, and petroleum usage. Increasing battery capacity, more electric energy could be stored onboard, on the other hand, the additional weight effects the vehicle range negatively. The battery mass increases accordingly with the capacity increase, once specific energy of the battery is determined (Zhou et al, 2010). Electric range, allowed depth of discharge (DOD), electric machine efficiency during test cycles, and energy demand in the selected cycle determine the battery energy capacity.

To calculate required energy in cycles, the regenerative energy should be taken into account. Since, the regenerative powers are under maximum motor and also battery power, the remaining constraint is braking method. Ehsani et al (2004) explains that the optimal feel series braking system controls the braking forces on the front and rear wheels to minimize the stopping distance and optimize the driver's feel. In case deceleration rate is not greater than 0.2 g, only the regenerative braking on the front wheels is applied and if it is greater than 0.2 g, front and rear wheel braking will be applied considering ideal braking force distribution. The ratio of braking force is equal to the ratio of normal load. Front wheels braking consist of regenerative braking force and mechanically frictional braking force. If the electric machine is enough to absorb the brake power, only electrically regenerative braking will apply, otherwise, the electric motor will operate to produce its maximum braking torque, and the remaining braking force is met by the mechanical brake system. Chevrolet Volt explains that the regenerative braking in Volt can provide up to 0.2g of deceleration, which covers about 94 percent of braking events. Braking that involves more than 0.2g of deceleration is a combination of regenerative and friction braking (Url-21).

Below the acceleration and deceleration rates for different cycles are drawn:

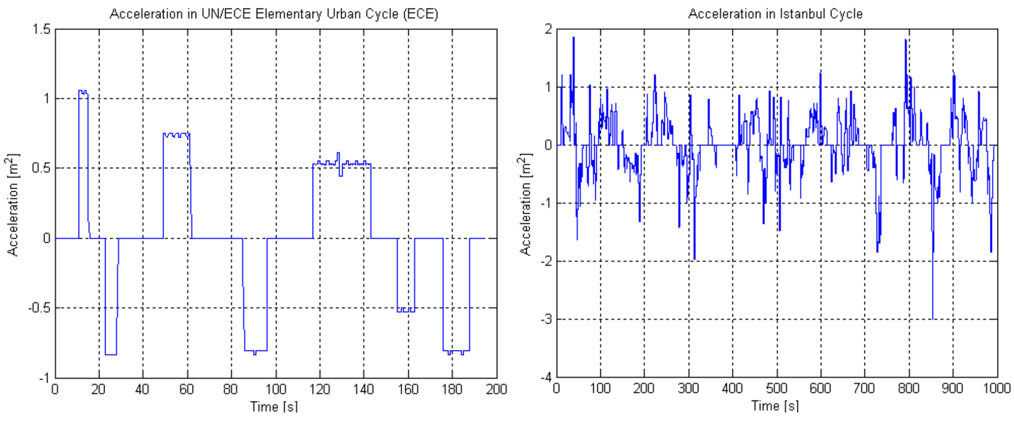


Figure 6.30 : Accelerations, ECE-15, left, and ICC, right

From the graphs, it is clear that only in NYCC and ICC the 0.2 g upper bound is exceeded, both continue very short time.

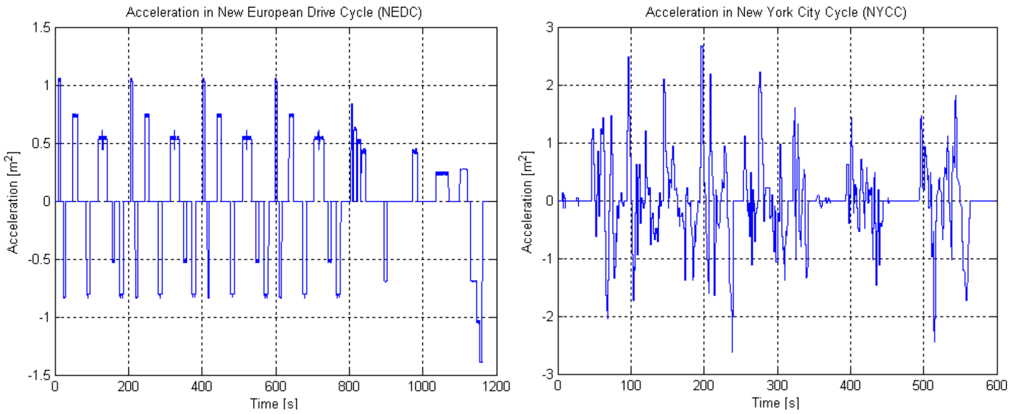


Figure 6.31 : Accelerations, NEDC, left, and NYCC, right

The instant and mean motoring and generating efficiencies for related cycles are drawn in the below figures.

Motor and generator & controller efficiency in ECE-15 Cycle are:

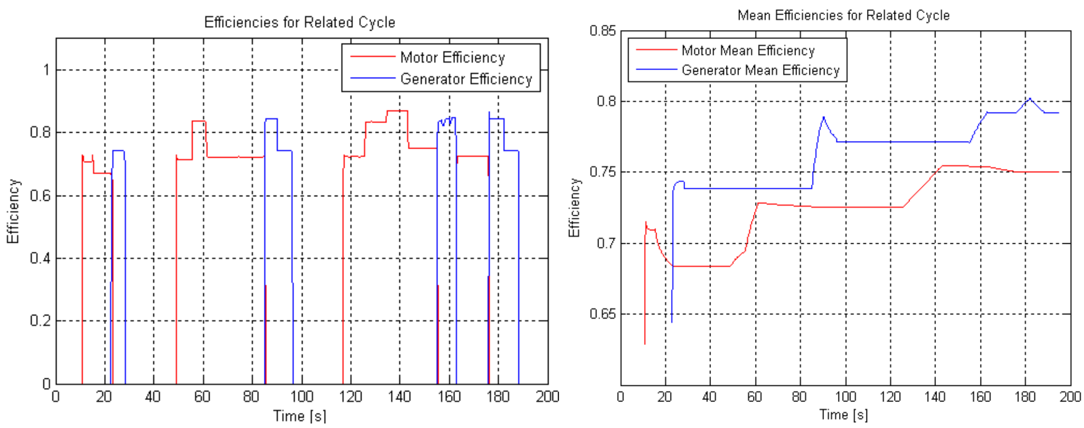


Figure 6.32 : Electric Machine Efficiency in ECE Cycle

Motor and generator & controller efficiency in NYCC Cycle are:

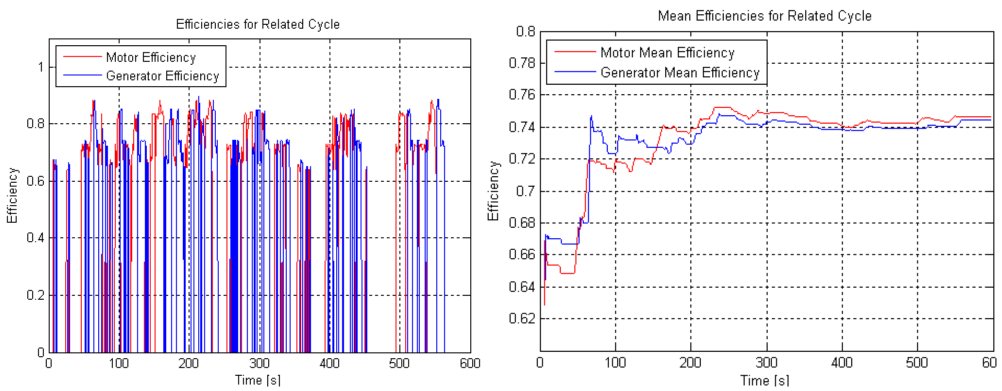


Figure 6.33 : Electric Machine Efficiency in NYCC Cycle

Motor and generator & controller efficiency in Istanbul Cycle are:

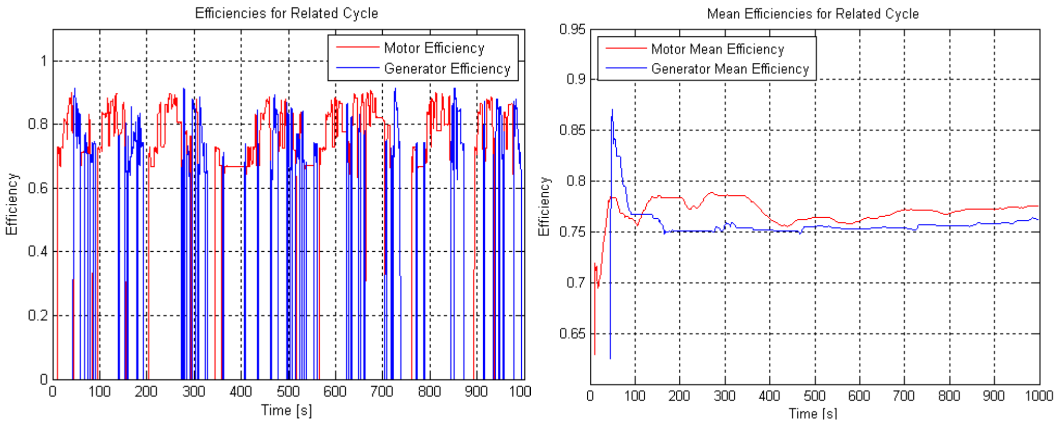


Figure 6.34 : Electric Machine Efficiency in Istanbul Cycle

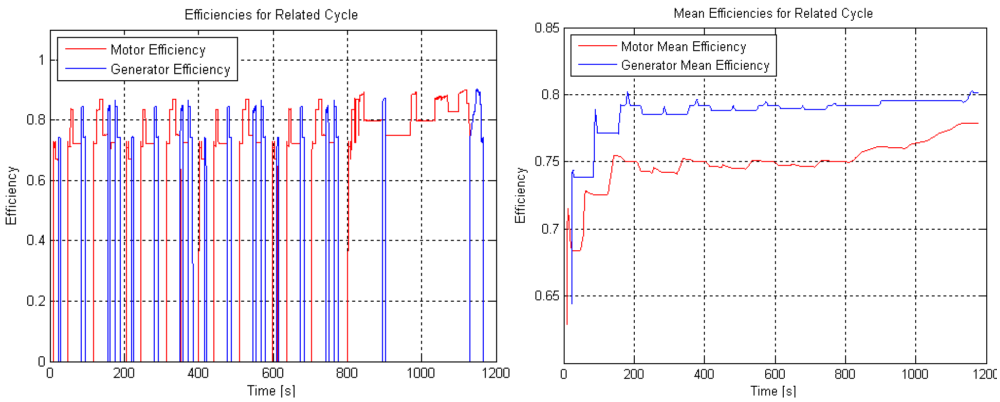


Figure 6.35 : Electric Machine Efficiency in NEDC Cycle

The motoring efficiencies changes from 0.74 to 0.80 in the given cycles. And according to the evaluated data, an efficiency table is constructed consisting of components and path efficiencies.

Table 6.4 : Components and Paths Efficiencies

Components	ECE	ICC	NEDC	NYCC
Rex_Generator_Eff	0.950	S	S	S
Rectifier_Eff	0.950	S	S	S
Converter_Eff	0.950	S	S	S
Battery_Charging_Eff	0.970	S	S	S
Battery_Discharging_Eff	0.970	S	S	S
Motoring_Eff	0.800	0.750	0.800	0.743
Generating_Eff	0.750	0.770	0.780	0.745
Differential_Eff	0.940	S	S	S
Battery_2_Wheel_Eff	0.693	0.650	0.693	0.644
Generator_2_Battery_Eff	0.650	0.667	0.676	0.645
REX_2_Wheel_Eff	0.679	0.636	0.679	0.630
REX_2_Battery_Eff	0.832	S	S	S

The letter “S” has the meaning of the “Same as the left cell. Now, the total and per km required and recupable energies in cycles can be evaluated.

The values in the only-city cycles ECE-15 and NYCC:

Table 6.5 : Required and Recupable Energies in ECE-15 and NYCC

Cycle	ECE-15 0.995km		NYCC 1.89km	
Unit	kWh	kWh/km	kWh	kWh/km
Req En at Wheels	0.096	0.096	0.265	0.140
Req En at Battery	0.139	0.139	0.382	0.202
Recup En at Wheels	0.042	0.042	0.166	0.088
Recup En at Battery	0.027	0.027	0.112	0.059
Net Req En at Wheels	0.054	0.054	0.099	0.052
Net Req En at Battery	0.111	0.112	0.270	0.143
Accessory En	0.030	0.030	0.057	0.030
inc Accessory En	0.141	0.142	0.327	0.173
Accessory/Kinetic	0.268		0.210	

NEDC and ICC includes urban and extra urban driving beheviours, the values:

Table 6.6 : Required and Recupable Energies in NEDC and ICC

Cycle	NEDC 11.0km		ICC 8.63km	
Unit	kWh	kWh/km	kWh	kWh/km
Req En at Wheels	1.234	0.112	0.937	0.109
Req En at Battery	1.781	0.162	1.442	0.167
Recup En at Wheels	0.319	0.029	0.357	0.041
Recup En at Battery	0.216	0.020	0.238	0.028
Net Req En at Wheels	0.915	0.083	0.580	0.067
Net Req En at Battery	1.565	0.142	1.204	0.140
Accessory En	0.289	0.026	0.227	0.026
inc Accessory En	1.854	0.169	1.431	0.166
Accessory/Kinetic	0.184		0.188	

To have a realistic energy demand, accessory energy needs have to be added to the results. Yang et al (2010) reports automotive air conditioning systems having about 1.26 kW maximum power. A luxury vehicle has maximum 2-3 kW accessory power, as mentioned before.

Accessory equipments in a vehicle are air conditioning, radio, cigarette lighter, central locking system, servo steering, lighting system, control adjustments, air blower, braking, windshield wiper, starter motor, horn, water pump, oil pump etc. Yearly average accessory energy consumption for 100 km can be assumed as 500 Wh on highway, 1500 Wh for intercity travelling and 3000 Wh for city driving vehicle (Wagner, 2008). An interesting result is that the accessory energy demands in city cycles ECE-15 and NYCC are significant comparing the kinetic energy demand, which emphasizes the importance of considering accessory energy demand that is overseen in most studies. The accessory energy in NEDC and ICC is calculated as third times in city added to the one intercity energy demand which is then divided by four.In this work, the battery energy will be sized according to the city cycles considering the vehicle chosen will mostly be used in city; Istanbul cycle and NEDC include also extra urban driving conditions, hence the NYCC and ECE-15 remain as candidate cycles, from which ECE-15 is selected, hence related parameters such as electric machine efficiency and energy demand per km will be used according to the calculated values in ECE-15 in further computations.

6.5.3 Battery Selection

If there were an optimization function f, that should optimize the battery of the vehicle, then it would optimize the parameters: cost, mass, specific energy, specific power, calendar life, cycle life, maintance, self discharge rate, operating temperature, capacity, recharge time, columbic efficiency and these might also be extended. To build such an optimization function correctly and that the result converges to the best point would take a long time surely. Because this work does not aim to the best solution, but an acceptable and as well as possible one, not all these parameters will be optimized. Instead, the most important considerations will be investigated.

Table 6.7 : Energy Reservoir Comparison (Parra et al, 2009)

Type	Energy (Wh/kg)	Power (W/kg)	Lifetime (Cycles)	Efficiency (%)
PbAC	25--40	140--350	200--1500	70--75
NiCd	25--40	500	800--1500	70--75
NiMH	40--55	500--1400	500--2000	70--80
Li-Ion	70--130	600-3000	800--1500	85--90
Ultracapacitors	3--5	2000--10000	500k--1M	95--100

To make some concepts clear, definitions in the MIT Electric Vehicle Team report will be utilized which are:

Specific Energy (Wh/kg): The nominal battery energy per unit mass, sometimes referred to as the gravimetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery weight required to achieve a given electric range.

Specific Power (W/kg): The maximum available power per unit mass. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery weight required to achieve a given performance target.

Cycle Life (number for a specific DOD): The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the rate and depth of cycles and by other conditions such as temperature and humidity. The higher the DOD, the lower the cycle life.

Battery Classifications: The main trade-off in battery development is between power and energy: batteries can be either high-power or high-energy, but not both. Often manufacturers will classify batteries using these categories (Url-18).

Explained before, an important parameter for battery selection is self discharging. NiMH batteries have about 3% /day self discharge rate, while it is almost zero for LiIon. The self discharge rates of different batteries is shown in the fallowing figure.

Although in first HEVs lead acid batteries were used, with technology advancements NiMH and Li-ion batteries are being used predominantly (Aditya and Ferdowsi, 2008). Below, hybrid vehicles using different types of batteries are given which verify the dominance of NiMH and LiIon batteries in the sector. Hence, in this work, NiMh and LiIon batteries will be investigated more intensively.

System	Specific Energy (Wh/kg)	Peak Power (W/kg)	Energy Efficiency (%)	Cycle Life	Self-Discharge (% per 48 h)
Acidic aqueous solution					
Lead/acid	35–50	150–400	>80	500–1000	0.6
Alkaline aqueous solution					
Nickel/cadmium	50–60	80–150	75	800	1
Nickel/iron	50–60	80–150	75	1500–2000	3
Nickel/zinc	55–75	170–260	65	300	1.6
Nickel/metal hydride	70–95	200–300	70	750–1200+	6
Aluminum/air	200–300	160	<50	?	?
Iron/air	80–120	90	60	500+	?
Zinc/air	100–220	30–80	60	600+	?
Flow					
Zinc/bromine	70–85	90–110	65–70	500–2000	?
Vanadium redox	20–30	110	75–85	—	—
Molten salt					
Sodium/sulfur	150–240	230	80	800+	0[a]
Sodium/nickel chloride	90–120	130–160	80	1200+	0[a]
Lithium/iron sulfide (FeS)	100–130	150–250	80	1000+	?
Organic/lithium					
Lithium-ion	80–130	200–300	>95	1000+	0.7

[a]No self-discharge, but some energy loss by cooling.

Figure 6.36 : Battery Status for Automotive Applications (Ehsani, 2005)

As mentioned in battery classification section, the batteries are manufactured as either high energy or high power batteries. In the fallowing figures, high power and high energy batteries are compared for NiMH and LiIon batteries.

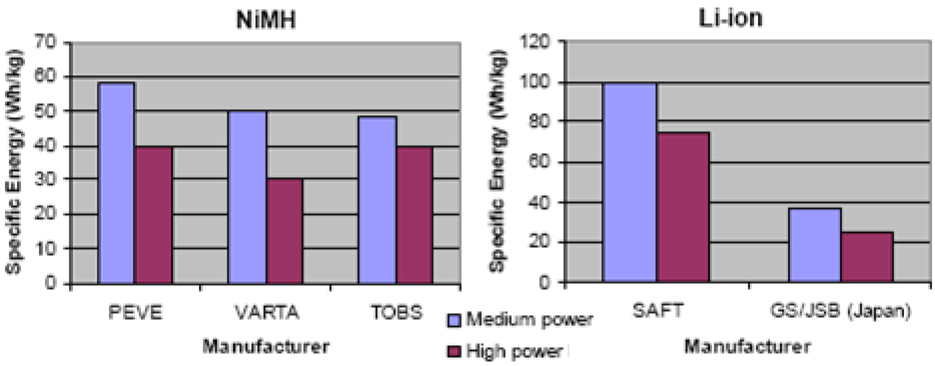


Figure 6.37 : Specific Energy Comparison (Aditya and Ferdowsi, 2008)

From the figure, it can be observed that LiIon battery provides higher specific energy and higher specific power. Although NiMH battery has lower energy and power density, Toyota uses it in Prius which is the most sold hybrid vehicle around the world and claims that the cost effectiveness of NiMH will be continued in the near feature (Url-19).

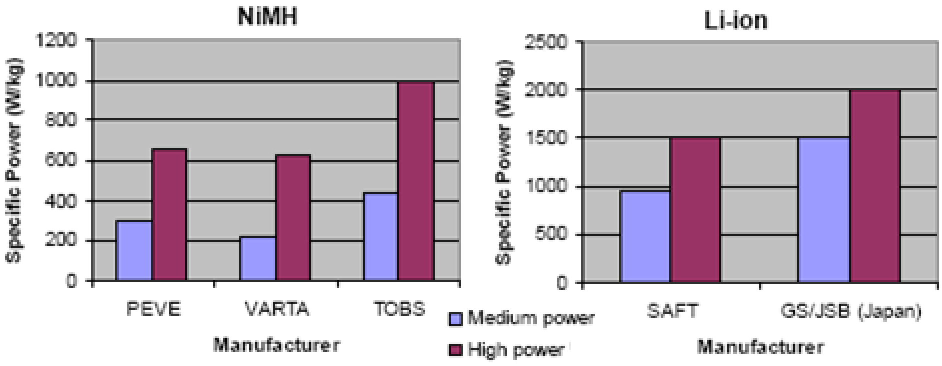


Figure 6.38 : Specific Power Comparison (Aditya and Ferdowsi, 2008)

The greatest disadvantage of LiIon is its high cost, which will be discussed in fallowing parts more deeply.Another issue is the maintenance requirement of the battery pack. As seen below, while LiIon does need any maintenance, NiMH should be maintained every three months.

Parameter	NiMH battery	Li-ion battery
Gravimetric energy density	60-120	110-160
Fast charge time	2-4h	2-4h
Resistance to overcharging	Low	Very low
Cell voltage	1.25V	3.6V
Maintenance Cycle	2 to 3 months	Not required

Figure 6.39 : NiMH and LiIon Comparison (Aditya and Ferdowsi, 2008)

Table 6.8 : Battery Specifications (Wagner, 2008)

Type	Unit	Pb/Gel	Ni/Cd	Ni/MH	ZnBr2	Li/Ion
En. Density	Wh/kg	30	40	60	60	150
Power Density	W/kg	60	200	175	60	200
Charging Time	h	10	0.5	1	4	1
Self-Discharging	% / d	<0.5	2 --10	2 --10	1	<1
Cycle Efficiency	%	70--90	65--85	65--85	50--70	60--80
Life	Full Cycles	600	1500	1500	1000	>1000
	Years	15	10	>5	>3	

It is clear from the above data that in different studies, authors have given different values for same parameters. This is because of the continuous development of battery technology and sources taken from different battery manufacturers or other sources. To have a more realistic approach to battery specifications, hybrid vehicles using NiMH and LiIon batteries and the specifications of the batteries used in related vehicles are given in fallowing.

	HEV							
	Nickel-metal-hydride battery(*)	Lithium-ion battery						
Manufacturer	Panasonic EV Energy	Automotive Energy Supply	Hitachi Vehicle Energy			Toshiba	Sanyo Electric	Blue Energy
Product name	Resin case square module	L3-3	2nd generation	3rd generation	4th generation	SCiB	--	EH6 (GS Yuasa poduct)
Primary direction	Toyota	Nissan, Mazda	Mitsubishi Fuso	GM	--	--	VW	Honda
Plans for shipment/mass production	Mass-production	Being shipped	Mass-production	Mass-production planned for 2010	Sample shipment planned for Fall 2009	Sample being shipped	Mass-production planned from the end of 2009	Plant to operate in Fall 2010
Car Models	Toyota Prius, etc.	Mazda Premacy Hydrogen RE Hybrid	Mitsubishi Fuso Canter Eco Hybrid	–	--	–	Plan to ship to Audi (2010)	–
Positive-electrode material	–	Manganese	Manganese	Manganese	Manganese	Manganese	Tertiary (nickel, cobalt, manganese)	Tertiary (nickel, cobalt, manganese)
Negative-electrode material	–	Carbon	Amorphous carbon	Amorphous carbon	Amorphous carbon	Lithium titanate	Carbon	Carbon
Capacity	6.5Ah	3.7Ah	5.5Ah	4.4Ah	4.8Ah	3.3Ah	5Ah (estimated)	6Ah
Voltage	7.2V (6-cell series)	3.6V	3.6V	3.6V	3.6V	2.5V	3.7V (estimated)	3.7V
Weight	1,040g	210g	300g	260g	240g	156g	206g	331g
Size (mm)	19.6 x 106 x 285	251 x 144.2 x 3.4	–	40 x 92	120 x 90 x 18	62 x 95 x 13	n.a.	112x21x82.6
Volume	592mL(**)	94mL	--	116mL(**)	194mL(**)	77mL(**)	92.5mL(**)	194mL(**)
Energy density (weight)	46Wh/kg	63Wh/kg	66Wh/kg(**)	60.9Wh/kg	72Wh/kg	52.9Wh/kg(**)	90Wh/kg	67.1Wh/kg
Energy density (volume)	79Wh/L(**)	142Wh/L	--	137.1Wh/L(**)	88.9Wh/L(**)	107.7Wh/L(**)	200Wh/L	114.3Wh/L(**)
Power density	1,300W/kg	2,250W/kg	2,600 W/kg	3,000W/kg	4,500W/kg	3,940W/kg	3,500 W/kg	3,600W/kg

Figure 6.40 : HEV Battery Specifications (Url-13)

Since Saft Battery Company has from the biggest LiIon battery manufacturer around the world, the batteries of Saft are also studied. With Johnson Controls, Saft, a global leader in the development and manufacture of advanced lithium-ion batteries for hybrid and electric vehicles, will supply the complete battery system for two electric vehicle platforms, which will be launched by the Beijing Electric Vehicle Company (BEVC), a subsidiary of Beijing Automotive Industry Company (BAIC). BEVC and BAIC have plans to manufacture 150,000 hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs) by 2015 (Url-14). Mercedes S400, Ford Transit Connect are other also other partners of the Saft battery company. The Saft batteries specifications will be given with other companies solution options in a list where an important comparison can be observed.

To select the battery to be used in this work, three constraints have been done, the first one is allowed Depth of Discharge (DOD), the second one is the battery pack should cover the power demand that is evaluated in previous parts; the last one is the only-electric-drive-range.

For the first constraint, Saft reports that their modular Li-ion battery technology offers cycling capability – 3,000 cycles at 80 % depth of discharge or 1 million cycles at 3 % depth of discharge (www.saftbatteries.com). Also, it can be assumed at 80% DOD 240 energy unit, and at 3% DOD 3000 energy unit. The relationship between the DOD and Lifetime Energy as a curve is given for the conventional LiIon battery below.

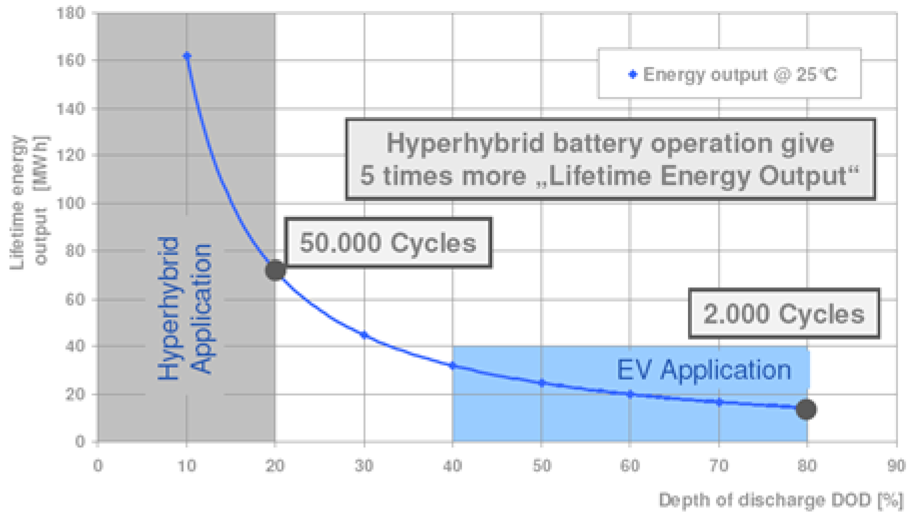


Figure 6.41 : Battery Lifetime Energy As a Function of DOD (Url-15)

NiMH batteries have also a similar lifetime energy function. The figure below shows cycle life function of various type batteries.

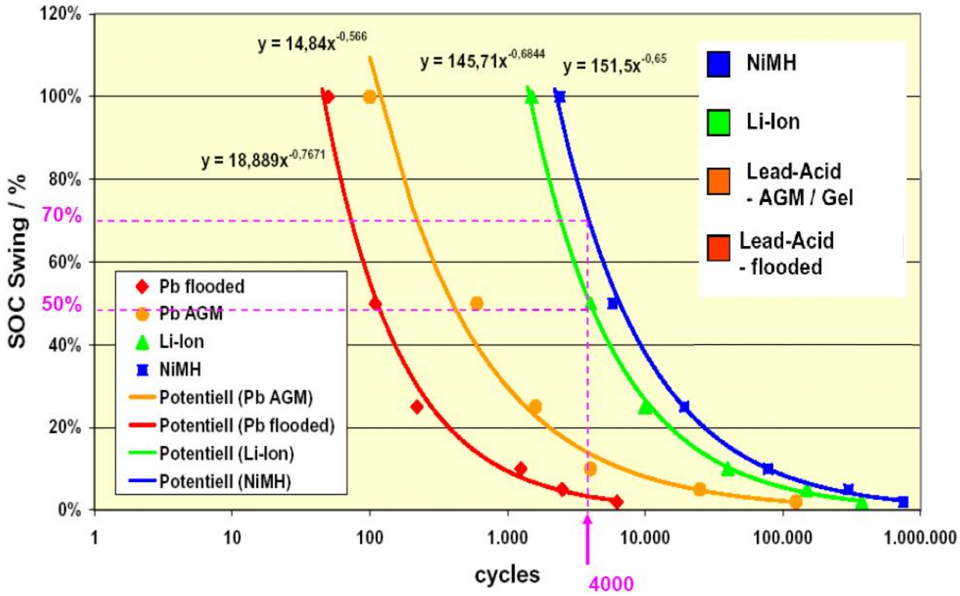


Figure 6.42 : Battery Lifetime Energy As a Function of DOD (Url-15/)

In practical instances, Toyota Prius (NiMH) utilizes 40% of the full energy, GM volt (LiIon) 65%, both giving 160.000 km 8 years warranty., The Prius' warranty has also been tested, however because the Volt is new, it is not tested. Considering calendar life and lifetime energy, 40% DOD, and 40-80% SOC swing are chosen in this work.

In the previous parts, the battery power requirement is computed as 56.19 for LiIon and 64.07 kW for NiMH battery, which are the second constraint.

The last constraint is only electric range. The REX electric vehicle do need only electric range less than full electric vehicles; hence the battery weight in REX electric vehicles is much less. Opel informs that according to a research, about 80% of Germans drives under 50 km (Url-9). The REX electric vehicles Lotus Proton Emas has a 50 km, Opel Ampera a 40 km only electric range.

Hitachi, the battery supplier for GM and Mitsubishi, however, plans in newly developed products an 20km cruise in EV mode on Plug-in Hybrid Car. Considering the battery can be charged via REX in case of requirements and the REX can also supply power to the electric machine, and aiming a cost effective solution, and the battery can be charged via line charger after arriving to the office, and hence a 60 km daily only electric drive is possible, the only electric range in the study is selected as 30km.

According to the constraint, two detailed data chart has been constructed, one for the power constraint, the other for the energy constraint. The appropriate-for-HEV batteries and their specifications are given below:

Where q_p represents specific power, q_e specific energy, C capacity, m mass, V potential.

Table 6.9 : Battery Specifications for Candidate Batteries

	Firm	SAFT Li-Ion				Hitachi Li-Ion			Panasonic
	Unit	VL41	VL27	VL25	VL45	Gen 3	Gen 4	Next	NiMH
q_p	W/kg	794	987	2000	900	3000	4500	2400	1300
q_e	Wh/kg	136	124	100	149	61	72	120	44
C	Ah	41	27	28	45	22	24	25	7.8
m	Kg	1.07	0.77	0.94	1.07	1.3	1.2	0.75	1.04
V	V	3.6	3.6	3.3	3.6	3.6	3.6	3.6	1.2

Next step is applying the constraints to the battery types given above.

Table 6.10 : Power Constraint Result for Candidate Battery Types

	Firm	SAFT LiIon				Hitac. LiIon	Lotus Proton	Panaso. Prius
	unit	VL41	VL27	VL25	VL45	Gen 3	LiIon	NiMH
q_p	W/kg	794	987	2000	900	3000	800	1300
q_e	Wh/kg	136	124	100	149	61	150	44
C	Ah	41	27	28	45	22	31	7.8
m	kg	1.07	0.77	0.94	1.07	1.3	0.75	1.04
V	V	3.6	3.6	3.3	3.6	3.6	3.6	1.2
P_max	kW	56.19	56.19	56.19	56.19	56.19	56.19	64.07
DOD		0.4	0.4	0.4	0.4	0.4	0.4	0.4
W	kWh/km	0.11	0.11	0.11	0.11	0.11	0.11	0.11
m_pack	kg	70.77	56.93	28.10	62.43	18.73	70.24	49.28
P_pack	kW	56.19	56.19	56.19	56.19	56.19	56.19	64.07
n		66.14	73.94	29.89	58.35	14.41	93.65	47.39
V_pack	V	238.10	266.17	98.63	210.06	51.87	337.14	56.87
C_pack	Ah	41.00	27.00	28.00	45.00	22.00	31.00	7.80
W_pack	kWh	9.62	7.06	2.81	9.30	1.14	10.54	2.17
DOD	0.40	3.85	2.82	1.12	3.72	0.46	4.21	0.87
Range	km	24.65	18.08	7.19	23.82	2.93	26.98	5.55

Here, n is the cell number. The power and DOD conditions are in the middle rows. The energy per km row is used to calculate the range for evaluated battery power. Also, first the battery mass is evaluated using specific power, consequently the battery energy and range are calculated by using the pack mass.

Table 6.11 : Energy Constraint Result for Candidate Battery Types

	Firm	SAFT LiIon				Hitac. LiIon	Lotus Proton	Panaso. Prius
	unit	VL41	VL27	VL25	VL45	Gen 3	LiIon	NiMH
q_p	W/kg	794	987	2000	900	3000	800	1300
q_e	Wh/kg	136	124	100	149	61	150	44
C	Ah	41	27	28	45	22	31	7.8
m	kg	1.07	0.77	0.94	1.07	1.3	0.75	1.04
V	V	3.6	3.6	3.3	3.6	3.6	3.6	1.2
W	kWh/km	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Range	km	30	30	30	30	30	30	30
W_20	km	3.3	3.3	3.3	3.3	3.3	3.3	3.3
DOD		0.4	0.4	0.4	0.4	0.4	0.4	0.4
W_pack		8.25	8.25	8.25	8.25	8.25	8.25	8.25
m_pack	kg	60.66	66.53	82.50	55.37	135.25	55.00	187.50
P_pack	kW	48.17	65.67	165.00	49.83	405.74	44.00	243.75
n_cell		56.69	86.41	87.77	51.75	104.04	73.33	180.29
V_pack	V	204.10	311.06	289.63	186.29	374.53	264.00	216.35
C_pack	Ah	41.00	27.00	28.00	45.00	22.00	31.00	7.80

Since Hitachi Generation 3 LiIon battery has a low specific energy, and hence the mass of battery is going relative high, it is eliminated. One important point to consider is the range would decrease with increasing mass and the power demand would increase. The NiMH battery pack can be though as alternative because of its low cost, on the other hand to supply enough energy, the mass is almost the third of the LiIon batteries and its self-discharge rate is about 3% per day10. It has also to be maintained every three months. One advantage is its low cost. However, LiIon battery costs are estimated to be comparable in near future. Today, LiIon batteries are about 4-5 times more expensive then NiMH batteries.

Battery	Specific energy Wh.kg^{-1}	Energy density Wh.L^{-1}	Specific power W.kg^{-1}	Current cost
Lead acid	30	75	250	0.5
NiCad	50	80	150	1.5
NiMH	65	150	200	2.0
Zebra	100	150	150	2.0
Li-ion[5]	90	150	300	10
Zinc-air	230	270	105	?

Figure 6.43 : Comparison of Batteries (Larminie and Lowry, 2003)

The actual price of LiIon battery is 1000 €/kWh and in middle term 100-300 €/kWh is prognosed while NiMH cost is about 220 €/kWh. Below, the prognosen of Deutsche Bank can be seen. The DB Auto team has lowered its advanced lithium ion battery cost projection by about 30% for 2012. Current prices have fallen from $650/kWh+ in 2009 to about $450/kWh now (Url-16).

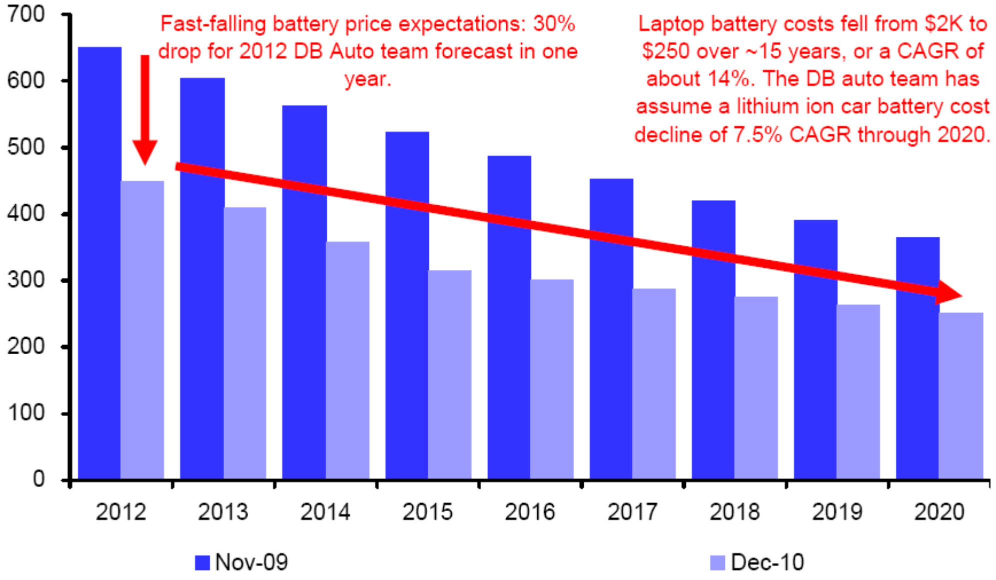


Figure 6.44 : DB Auto Team Li-Ion Battery Forecast ($/kWh)

Considering the rapid cost decrease of LiIon batteries and other disadvantages of NiMH batteries mentioned before, NiMH battery is also eliminated.

Among the LiIon batteries, Saft VLM25 has relative high mass in comparison with other remaining types to have an 30 km range, which is the reason of its elimination.

There is not such a significant difference between the remaining alternatives. To match the power goals, SAFT VLM41 and Lotus Proton's used LiIon battery packs should be about 70 kg., having then 9.62 kWh and 10.54 kWh energy, respectively. The remaining battery features are listed to meet the minimum needs.

Table 6.12 : Rearranged List to Satisfy The Power and Energy Constraints

	Firm	SAFT LiIon			Lotus Proton
	unit	VL41	VL27	VL45	LiIon
q_p	W/kg	794	987	900	800
q_e	Wh/kg	136	124	149	150
C	Ah	41	27	45	31
m	kg	1.07	0.77	1.07	0.75
V	V	3.6	3.6	3.6	3.6
m_pack	kg	70.77	66.53	62.43	70.24
P_pack	kW	56.19	65.67	56.19	56.19
n		66.14	86.41	58.35	93.65
V_pack	V	238.10	311.06	210.06	337.14
C_pack	Ah	41.00	27.00	45.00	31.00
W_pack	kWh	9.62	8.25	9.30	10.54
DOD	0.40	3.85	3.30	3.72	4.21
Range	km	35.00	30.00	33.83	38.31

Now, a condensate list is available. The best matching of the desired conditions is SAft VLM 27 battery. According to the Deutsche Bank data, the 8.25 kWh battery pack would cost 3,712.5 US $ or 5,568.75 TL considering 1 $ is 1.5 TL and in 2020 this would be 2,062.5 $ or 3,093.75 TL. Gaines and Cuenca (2000) reports that high-power cells are cheaper on a mass basis than the high-energy cells, because of their reduced cathode active material use. Taking into account that it is also the lightest solution, that makes this battery to be selected. A choose of another battery from the list above would also not change the result so much. To emphasize, the use of NiMH battery would weight 187.5 kg which is almost third time heavier than this selected battery. Below, the only electric range for different cycles is calculated in case of using or not using accessory equipments such as air conditioning considering 40% and 65% DOD.

Table 6.13 : Only-Electric Ranges for Different Cycles

Range	ECE-15	NYCC	NEDC	ICC
Range in km 40% DOD	30.00	23.08	23.19	23.65
Range in km inc. Accessory	23.57	19.08	19.58	19.91
Range in km 65% DOD	48.75	37.50	37.69	38.43
Range in km inc. Accessory	38.30	31.00	31.82	32.35

Since vehicle lighting equipment consume very low power, for instance, long headlight consumes 60 W, parking lamp 5 W or reverse gear lamp is 16 W. As mentioned before, the most power-consuming unit is air-conditioner and in case it is not used, the vehicle has a range of about 30 km. Moreover, if selecting the DOD 50%, the range would be about 37.5 km.

6.6 Weight Comparison of REX Electric Vehicle with Conventional Vehicle

The hybrid vehicles in literature is assumed to heavier than conventional vehicles because of the battery and second propulsion system. One of the important parameters was weight consideration during this study. Electric machine, its controller, battery system etc. are chosen as light as possible. A table of the components that differ in a comparable conventional vehicle and the designed REX electric machine is built. A conventional engine with a similar power weights about 122 kg. Since there is no gearbox in the designed vehicle, automatic transmission is considered in the compared conventional vehicle to give a similar comfort to the driver. The weight of the automatic transmission is chosen as a one used in a C segment car, also a family car. The total weight of the transmission includes the controller unit as well. For the designed REX vehicle, the extra component specifications are given during the thesis. The power electronics units rectifier, converter weights are estimated as 15 kg. Other components weights are taken from datasheets of the manufacturers.

Table 6.14 : Weight (kg) Comparison of the REXEV with a Conventional

Component	Conv.	REX	Supplier
Engine (75 kW)	122		Hyundai Getz (Alfa 1.4)
Automatic Transmission	81		FIAT (Family Car)
Fuel Tank (4kg) with fuel (full=45 lt)	37.3		
Battery (50Ah)	13.3		Mutlu Aku
Starter Motor & Alternator	5		
Rex (37 kW)		56	Lotus
Rex Generator (45 kW)		25	Coercive systems
Battery		66.53	SAFT
Electric Machine (75kW)		41	UQM
Inverter/Controller		15.4	UQM
Rectifier & Converter		15	Estimated
Line Charger		4.8	Quiq
Fuel Tank (3 kg) with fuel (full=15 lt)		14	
Sum	258.6	237.7	
Difference	-20.87		

The compared components in conventional vehicle weight 258.6 kg while this value is 234.18 kg in REX vehicle, which shows a REX electric vehicle do not weight more than a conventional vehicle, even 21 kg lighter, while it offers similar or even better performance. Since the designed vehicle weights similar to the conventional vehicle, from which the battery energy and power constraints are calculated, the REX electric vehicle would have, more range than 30 km and would require less than 56 kW, which were predetermined for the comparable conventional vehicle.

7. SIMULATION AND RESULTS

In this section, the model built previously will be simulated. All the related parameters as battery mass, electric machine torque–speed–efficiency characteristics etc. are updated by using user interface program and look-up tables. Because the overall mass of the vehicle is about 21 kg less than the previously selected comparable vehicle, operating characteristics of electric machine, both motoring and generating, remain similar to the previous one. The battery system is newly added according to the selection constraints, hence its characteristics need to be studied.

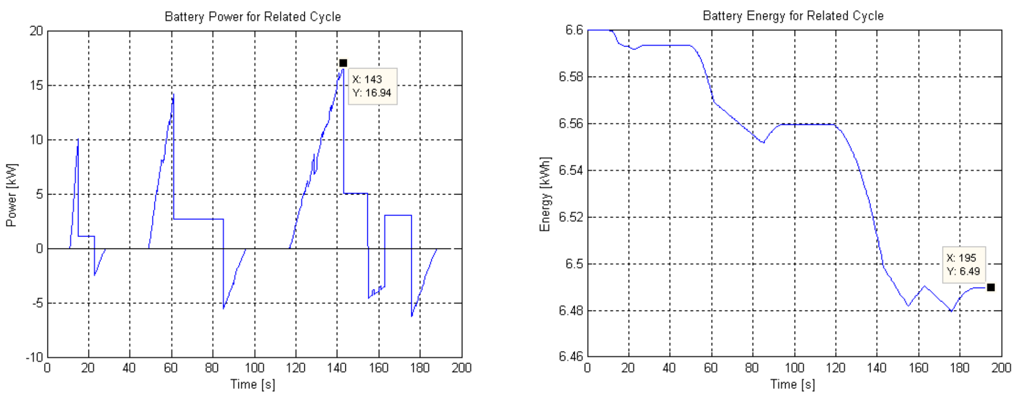


Figure 7.1 : Battery Power and Energy in ECE-15 Cycle.

The maximum battery power for vehicle traction in ECE-15 Cycle reaches about 17 kW. In the recoupable power analyses, it has been assumed that there is no constraint at the motor/generator and battery part to limit the regenerative power. Here, the verification of this approach can be observed. Maximum recoupable power at battery is about 5 kW which would be allowed both by battery system and electric machine. Since the battery allowed SOC swing is between 40% and 80%, the voltage of a cell between this range do not change significantly, hence the battery current can be computed by using battery power and pack potential. And, the SOC change can be seen in the above figure, on the right. Since the ECE-15 Cycle distance is about 1 km, the SOC swing is little.

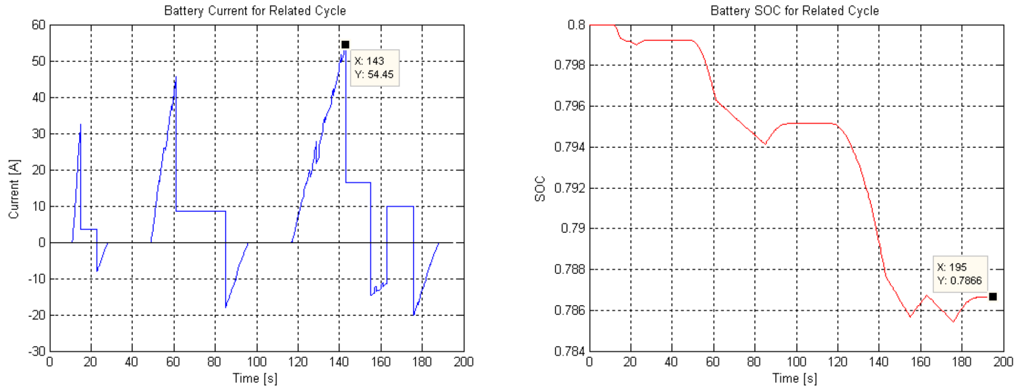


Figure 7.2 : Battery Current and SOC Swing in ECE-15 Cycle.

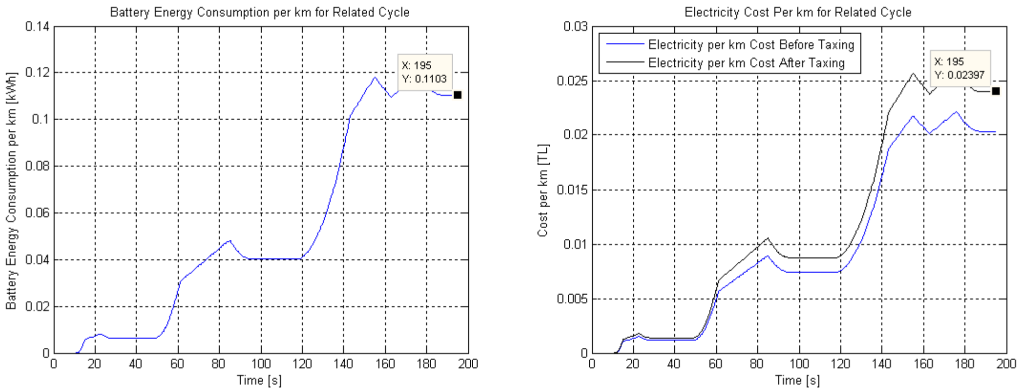


Figure 7.3 : Battery Energy Consumption And Cost, both per km for ECE15.

The battery energy consumption per km is 0.1103 kWh/km. In case of using 50% DOD, the only electric range would be about 37.4 km, and for 65% DOD it becomes 44.72 km.

Lastly, the cost is computed using battery energy change. The line charger efficiency is also added to the system, because it is assumed that at the beginning, the battery was recharged by using home electricity. In case of REX charging the battery, this would be not included in the computations. For the electricity per km cost, taxing should be also considered. In Turkey, the value added tax (VAT) for home electricity is 18%. The electricity cost per km is circa 0.02 TL before taxing and 0.024 TL after taxing, also 2 TL/100 km and 2.4 TL/100 km before and after taxing, respectively. The graphs show the costs both before and after taxing which has been done intentionally, since the oil prices include taxing as well.

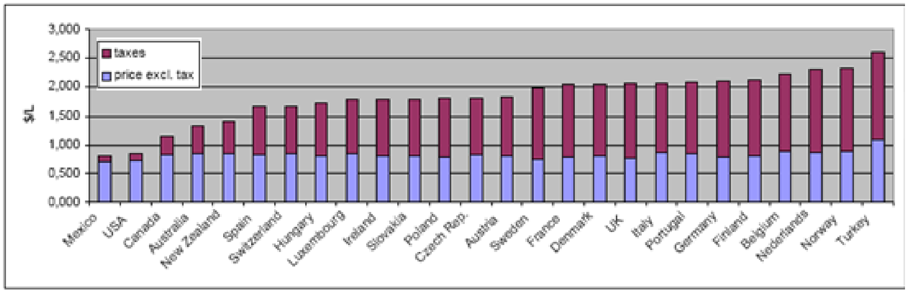


Figure 7.4 : Unleadad 95 Gas Prices in 2008 (Davoust, 2008).

The fuel taxes in various countries is given in above figure. In Turkey, the fuel tax is about 59% of the fuel price. The list of taxes in the world is added below.

Unleaded 95	Price before Taxes	Taxes	Total Price	Taxes / Total Price		Taxes / Price before taxes	
Mexico	0.706	0.106	0.812	Mexico	13%	Mexico	15%
United States	0.718	0.133	0.851	United States	16%	United States	18%
Canada	0.830	0.315	1.145	Canada	28%	Canada	38%
Australia	0.851	0.465	1.316	Australia	35%	Australia	55%
New Zealand	0.849	0.555	1.404	New Zealand	40%	New Zealand	65%
Spain	0.823	0.826	1.649	Switzerland	49%	Switzerland	95%
Switzerland	0.849	0.805	1.654	Spain	50%	Spain	100%
Hungary	0.808	0.900	1.708	Luxembourg	52%	Luxembourg	110%
Luxembourg	0.846	0.928	1.774	Hungary	53%	Hungary	111%
Ireland	0.807	0.979	1.786	Czech Republic	54%	Czech Republic	119%
Slovakia	0.800	0.989	1.789	Austria	55%	Ireland	121%
Poland	0.777	1.014	1.791	Ireland	55%	Slovakia	124%
Czech Republic	0.824	0.982	1.806	Slovakia	55%	Austria	124%
Austria	0.814	1.011	1.825	Poland	57%	Poland	130%
Sweden	0.745	1.241	1.986	Italy	58%	Italy	137%
France	0.795	1.249	2.044	Turkey	59%	Turkey	144%
Denmark	0.816	1.235	2.051	Belgium	60%	Portugal	148%
United Kingdom	0.765	1.302	2.067	Denmark	60%	Belgium	148%
Italy	0.874	1.196	2.07	Portugal	60%	Denmark	151%
Portugal	0.842	1.243	2.085	France	61%	France	157%
Germany	0.786	1.328	2.114	Norway	61%	Norway	159%
Finland	0.806	1.331	2.137	Finland	62%	Netherlands	162%
Belgium	0.894	1.324	2.218	Netherlands	62%	Finland	165%
Netherlands	0.878	1.421	2.299	Germany	63%	Sweden	167%
Norway	0.894	1.423	2.317	United Kingdom	63%	Germany	169%
Turkey	1.066	1.533	2.599	Sweden	63%	United Kingdom	170%

Figure 7.5 : Fuel Prices and Taxes in Different Countries (Davoust, 2008).

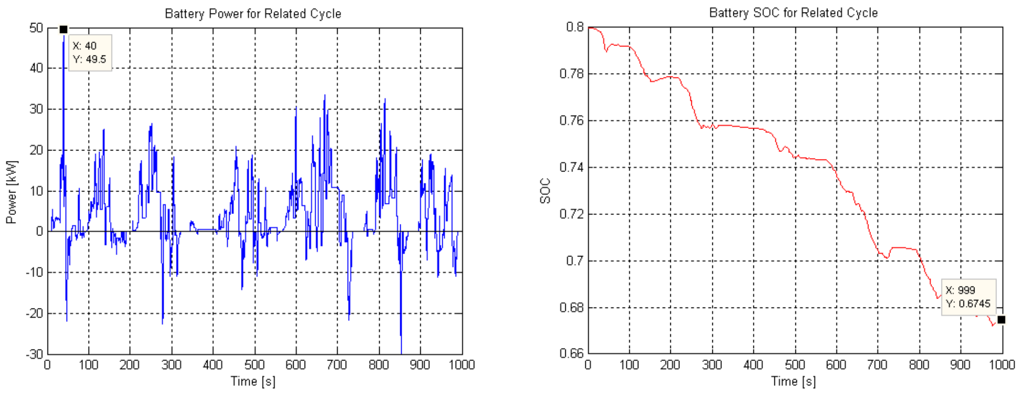


Figure 7.6 : Battery Power and SOC Swing in ICC Cycle.

The Istanbul City Cycle is also run and related results can be seen in above und below figures. Since ICC has a distance about 9 km, the SOC swing is more visible than ECE-15 cycle.

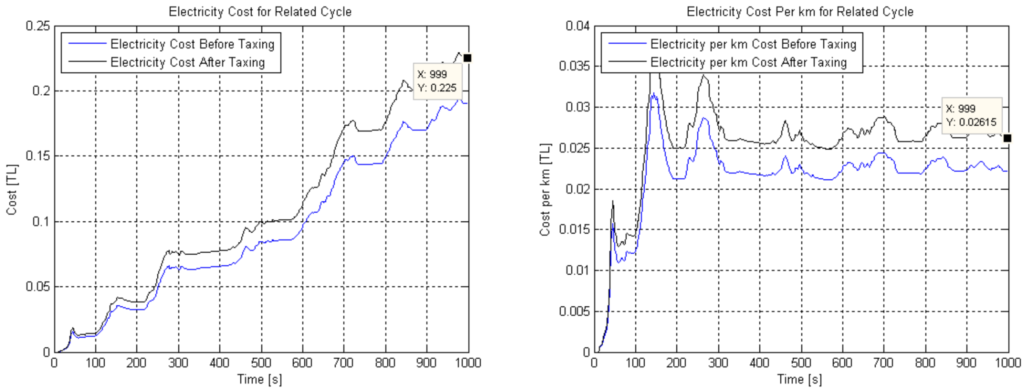


Figure 7.7 : Battery Electricity Cycle Cost And per km Cost in ICC.

The result shows that a person that drives in ICC would need 0.02615 TL including VAT for driving one km, before taxing it would be circa 0.022 TL/km, which means that considering a daily home to work 10 km travel would cost just 0.26 TL with a realistic approach, which show a significant cost difference between the conventional vehicle and REX electric vehicle designed in this thesis. The accessory energy to kinetic energy ratio has been calculated as 0.188 in the previous chapters, hence this cost would be around 0.309 TL including accessory energy. The battery energy consumption per km in ICC is 0.1204 kWh/km and considering the accessory energy requirements, 23.07 km range is available. This range would be approximately 27.41 km in case of neglecting accessory energy.Although last part of NEDC has high velocity points, the results are investigated for NEDC as well. Battery power is enough for this cycle considering the selected battery has a power of 66 kW.

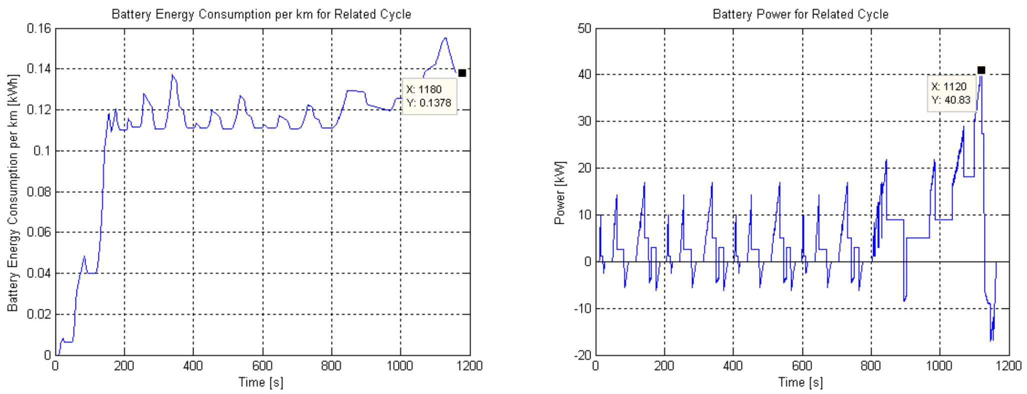


Figure 7.8 : Battery Energy Consumption per km and Power in NEDC.

NEDC has 11 km range and SOC decreases from 0.8 to 0.62 in this cycle. The electricity cost is almost 3 TL/100 km.

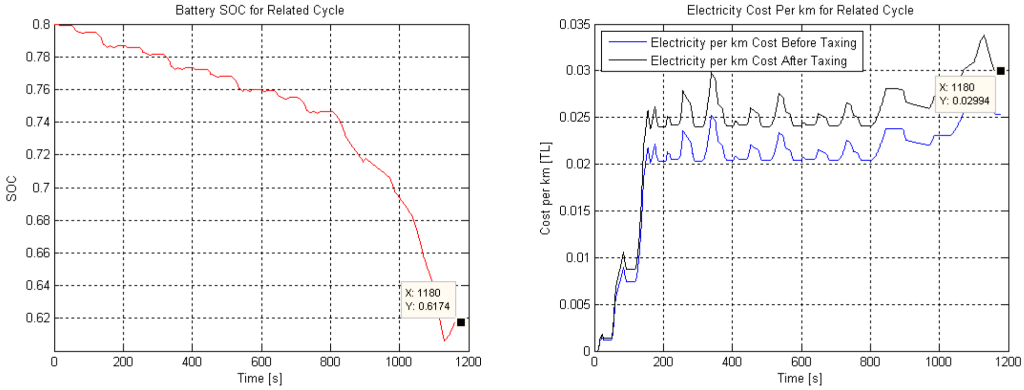


Figure 7.9 : Battery SOC Swing and Electricity Cost per km in NEDC.

The result for the test cycle FTP-75 is given below. This cycle has a total distance of 18 km.

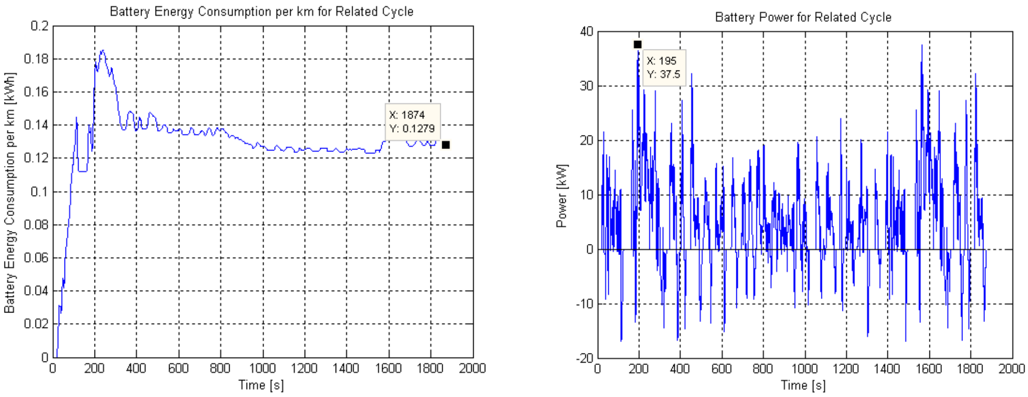


Figure 7.10 : Battery Energy Consumption per km and Power in FTP-75.

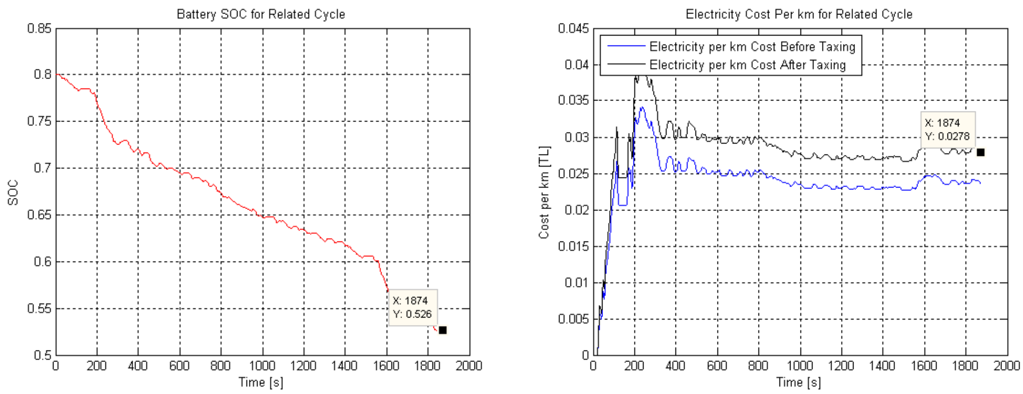


Figure 7.11 : Battery SOC Swing and Electricity Cost per km in FTP-75.

The SOC swing is almost 0.275 and the per km electricity cost is about 0.028 TL.

In the fallowing part, the highway performance of the vehicle will be investigated. First, a constant speed of 120 km/h and a distance of 100 km will be examined.

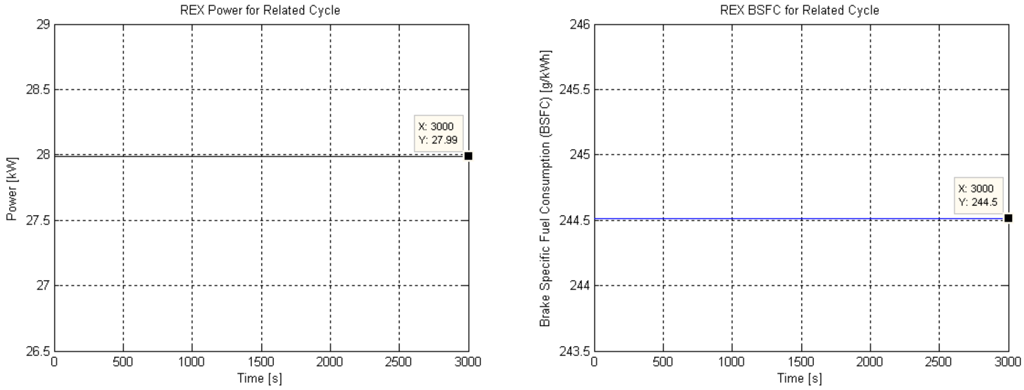


Figure 7.12 : REX Power and BSFC on the Highway for 120 km/h Speed.

Since the velocity is constant, the curves are linear. The required power is about 28 kW and the BSFC is 244.5 g/kWh.

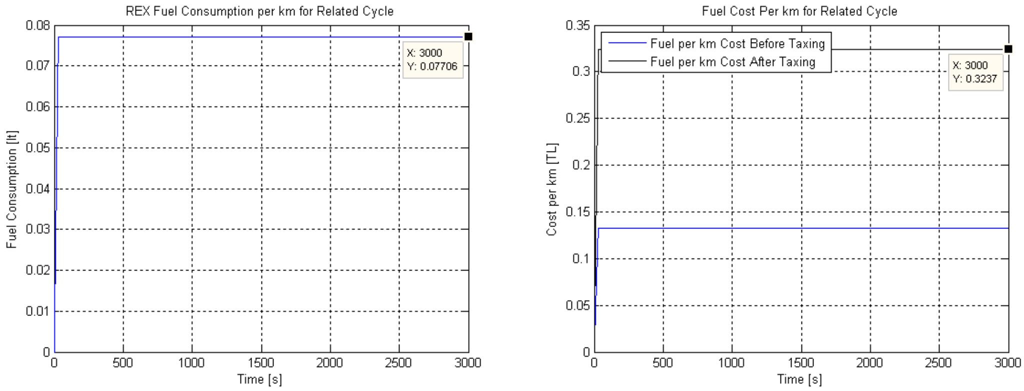


Figure 7.13 : REX Fuel Consumption and Cost per km

The fuel consumption on the highway is 7.7 lt/100 km when the vehicle has a constant velocity of 120 km/h. The fuel cost of the vehicle is also given before and after taxing. Before taxing the fuel price for 1 km is 0.14TL and after taxing it is about 0.33 TL. To compare in-city and highway driving; the in-city driving with battery energy has been calculated as 0.024 TL including VAT for driving one km, 0.02 TL/km before taxing in previous part showing ECE15 cycle results.

In literature, there is not many highway test cycles. The Highway Fuel Economy Test (HWYFET) Cycle is one of the highway cycles. However, it can be concluded from the average velocity (77.7 km/h) that it does not represent the real highway driving conditions. TRL WSL Motorway 113 Cycle is one of the Warren Spring Laboratory (WSL) cycles, which has been developed by TRL over the Stevenage and Hithcin routes, used by the former Warren Spring Laboratory for road tests (Barlow et al, 2009).

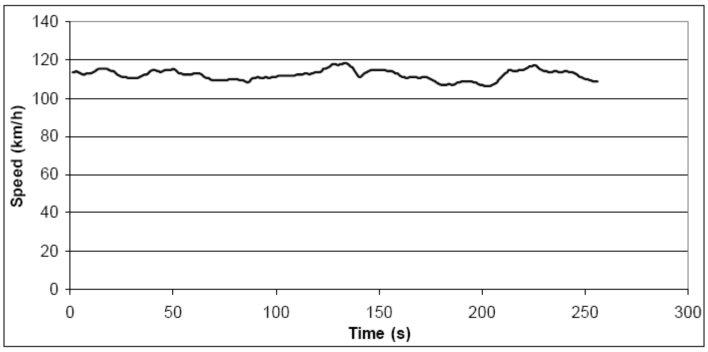


Figure 7.14 : TRL WSL Motorway 113 Cycle.

This cycle has an average velocity of 112.1 km/h and there is almost no acceleration. In the simulation for Motorway 113 Cycle, a constant speed of 112.1 is considered and accelerations are neglected because they are low and Time – Velocity table could not been found neither on the web nor in the related reference books.

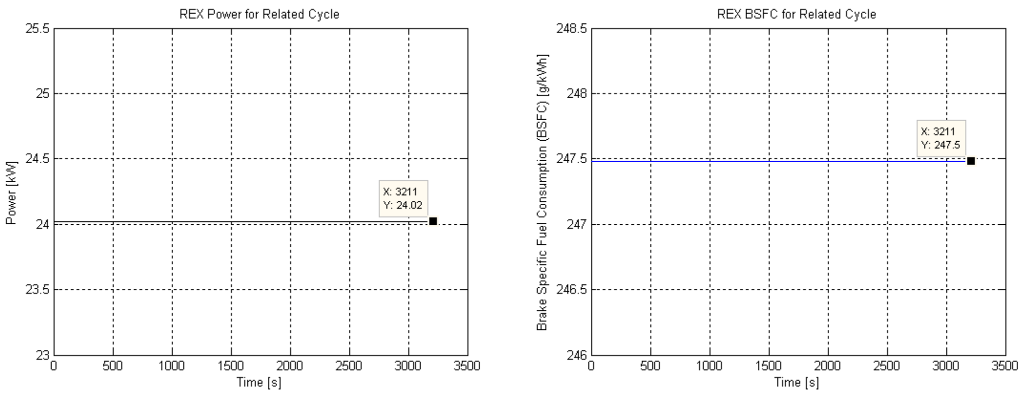


Figure 7.15 : REX Power and BSFC on TRL WSL Motorway 113 Cycle.

The REX power in this cycle is calculated as about 24 kW and the BSFC is 247.5 g/kWh.

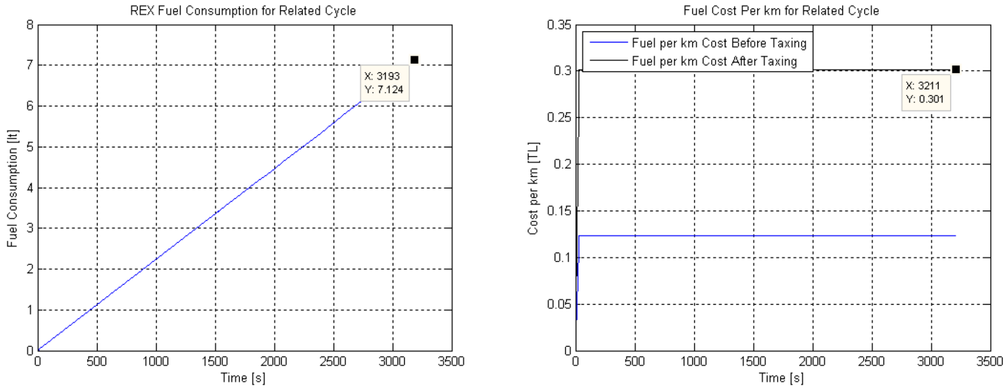


Figure 7.16 : REX Fuel Consumption and Cost per km.

The fuel consumption is circa 7lt/100km and fuel cost per km is about 0.3 km/TL after taxing.

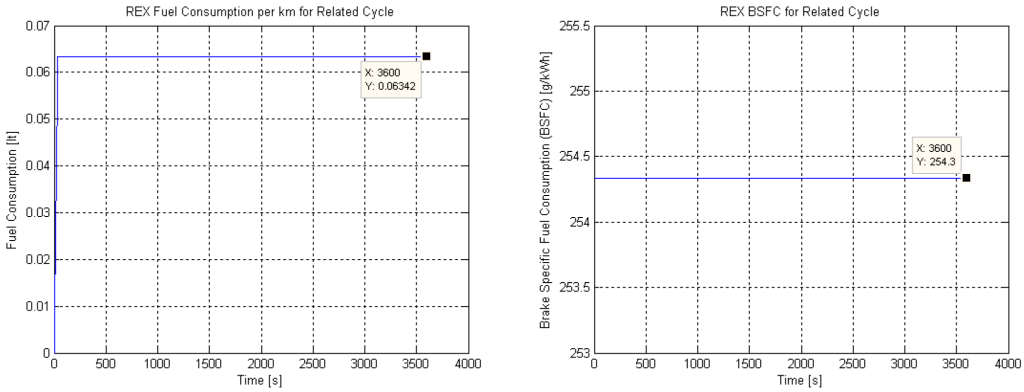


Figure 7.17 : REX Fuel Consumption and Cost per km.

For a constant velocity of 100 km/h, the fuel consumption is evaluated as 6.3 lt/100 km, BSFC is 254 g/kWh and REX power is 18.45 kW.

8. CASE STUDY FOR A LIGHTWEIGHT DUTY VEHICLE

This section covers a range extended electric vehicle (REXEV) case study for an in-city load transporting van, for this aim Ford Van is selected. The series hybrid vehicles are especially advantageous for city-driving conditions, as in city-driving, the ICE of the conventional vehicle spends a long time for idling and low load operation conditions, while electric motors does not consume current and also power during standing and it does not consume more electricity per energy unit for low loads. Since the REXEV belongs to the series hybrid vehicle family, it is also well suited for in-city vans.

8.1 REXE-Van Design Considerations

The design considerations for a vehicle have been discussed in previous sections; therefore, there will be design calculations rather than explanations in this part. In Turkey, the speed limit for vans is 50 km/h in urban areas and 95 km/h on the highway, which means a maximum velocity of the van can be designed as about 95 km/h, on the other hand, a surplus of about 15-20 km/h should be considered for worst-case-scenarios, hence 110 km/h will be the top-speed design criteria in this study. This is 10 km/h more than the 100 km/h top speed of light duty electric vehicle Renault eKango.

Another design objective is hill climbing performance, as the original vehicle the REXEV-Van should perform about 30% gradeability with full load. For both design criteria, firstly the vehicle mass should be estimated.

Neglecting the battery weight, the REXEV would be 184 kg lighter. The battery pack, however, would affect the total weight significantly, since this vehicle will have a relative more range in comparison to the family car designed in previous parts. The range of the vehicle will be calculated according to the average weight of the vehicle, and it will be verified having added the battery weight.

Table 8.1 : Weight (kg) Comparison of the Original Vehicle with REXEV

Component	Conv.	REX	Supplier
Engine (96 kW)	198		Ford
Transmission	51		Ford
Fuel Tank (7kg) with fuel (full=80 lt)	73.4		
Battery (80Ah)	22		Mutlu Aku
Starter Motor & Alternator	15		
Rex (37 kW)		56	Lotus
Rex_generator (45 kW)		25	Coercive
Battery		------	SAFT
Electric Machine (125kW)		41	UQM
Inverter/Controller		15.9	UQM
Rectifier & Converter		15	Estimated
Line Charger		4.8	Quiq
Fuel Tank (3kg) with fuel (full=20 lt)		17.8	
Sum	359.4	175.5	
Difference	-183.9		

The unloaded mass is 1639 kg, the fully loaded weight is 2800 kg, and hence an average mass is 2219 kg. The vehicle parameters in the simulations are the rolling coefficient 0.013, drag coefficient 0.394, front area 3.6m^2, rolling mass coefficient 1.09, differential efficiency 0.94, wheelbase 2.933m, distance of the mass centre to the front axle 1.173m, height of the mass centre 0.765m.

8.1.1 Top Speed

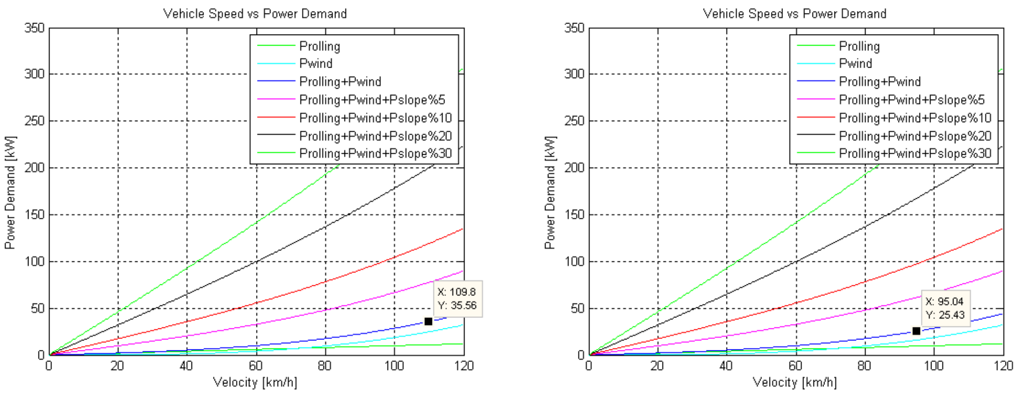


Figure 8.1 : Vehicle Speed vs. Power Demand for Fully Loaded Van.

The power demand at wheels for 110 km/h speed on the highway is 35.5 kW, 28.6 kW for 100 km/h, 25.4 kW for 95 km/h.

8.1.2 Hill Climbing Performance

For hill climbing performance, 30% gradeability with full load 2800 kg is investigated. The force for these parameters is calculated as 8.254 kN.

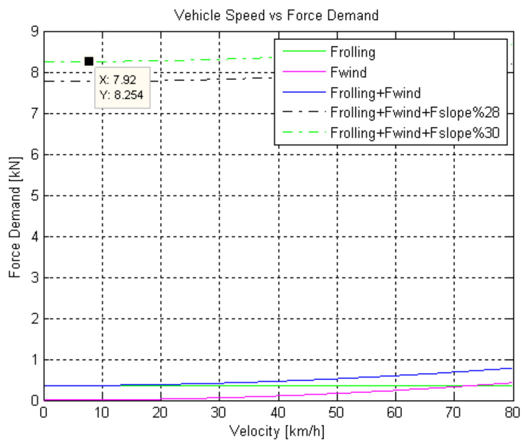


Figure 8.2 : Speed vs. Force Demand for Fully Loaded Van.

Considering the vehicle has 96 kW engine, an electric machine at about this power will be selected. The Uqm 45kW continuous and 125 kW peak power electric machine or 75 continuous and 145 kW peak are candidates.

8.1.3 Verification Of Design Parameters

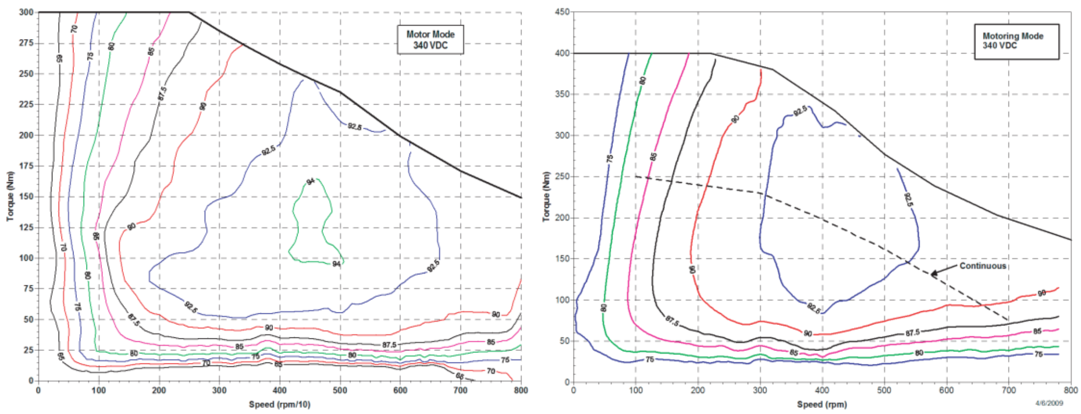


Figure 8.3 : Electric Machine Characteristics, left 75 kW and right125 kW.

For the machine having 75 kW power, the differential ratio 8.728 fulfils the top speed criteria. With this differential ratio, 30% gradeability including differential efficiency of 0.94 is available.

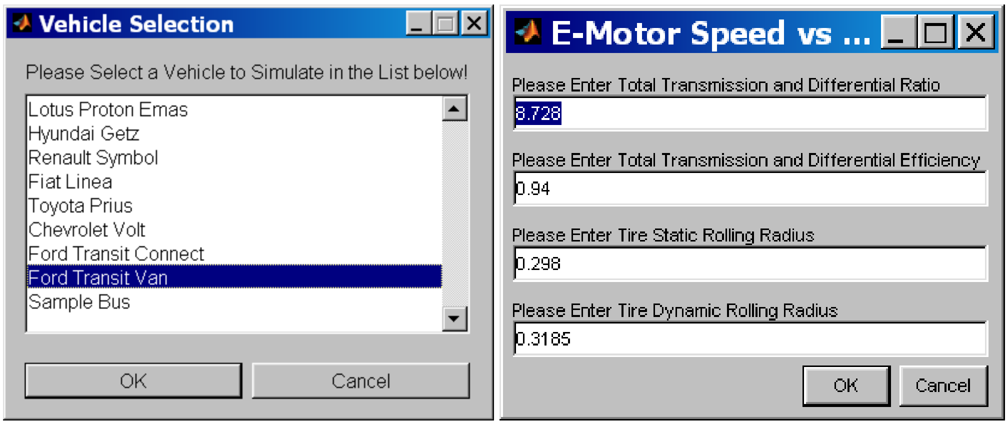


Figure 8.4 : Interface for Vehicle Performance Verifications.

For the selected parameter values, the supply-demand curves can be observed below.

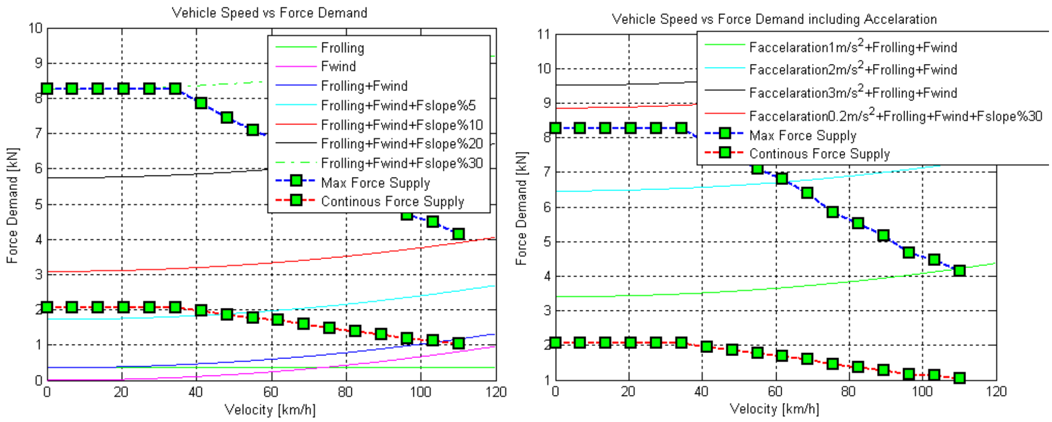


Figure 8.5 : Supply-Demand Curves including Predefined Criteria.

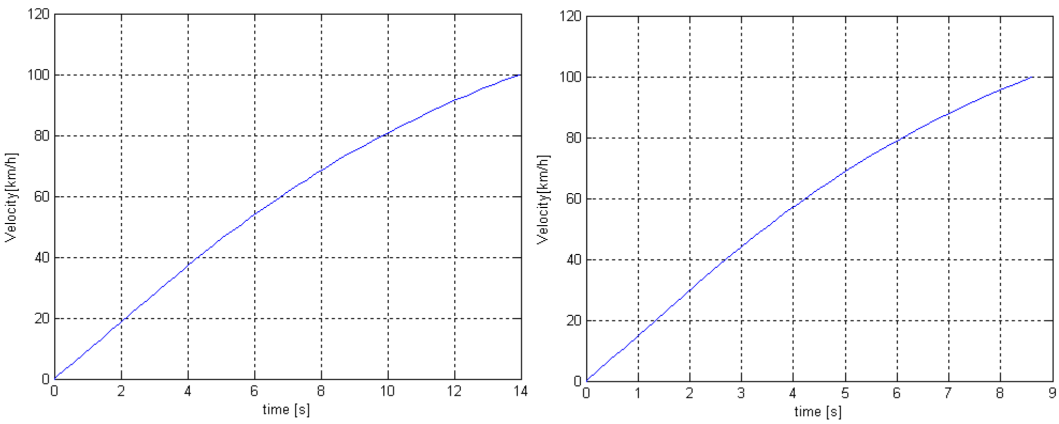


Figure 8.6 : 0-100 km/h Acceleration, Loaded and Unloaded inc. Driver.

The fully loaded vehicle having the mass of 2800 kg accelerates from 0 to 100 km/h in 14 s, this time takes 8.5 s for the unloaded vehicle including a driver having the mass of 1770 kg. The conventional vehicle accelerates from 0 to 100 km/h in 19.1 s (Erbeyler, 2007).

8.1.4 Range Extender Engine And Generator Considerations

In previous chapters, the power demand speed on the highway has been calculated as 35.5 kW for 110 km/h, 28.6 kW for 100 km/h and 25.4 kW for 95 km/h for fully loaded vehicle. Considering the operating conditions at high speed and high torque areas, the REX generator, rectifier, motoring and differential efficiency can be assumed as 0.95, 0.95, 0.90, and 0.94. With these, the REX to wheel efficiency is about 0.76-0.77. Hence, the power demand for 110 km/h is 46 kW, 37 kW for 100 km/h and 33 kW for 95 km/h. The Lotus REX and selected generator from Coercive Systems used in previous part allow the vehicle having a 100 km/h continuous speed which is 5 km/h greater than the regulations. Hence, this REX fulfils the REX criteria of the vehicle. The vehicle has been designed to travel with a 110 km/h speed in previous part, hence with a surplus power from the battery this is still possible.

8.1.5 Battery Sizing

The engine to motor efficiency is 0.812 considering generator, rectifier, motor and control unit efficiencies, 0.95, 0.95, 0.90 respectively. Since the most power will be needed at the maximum power point, the efficiencies of the motor and control unit at these points are considered. A 38 kW engine provides 30.86 kW power to the motor, the rest should be supplied by the battery. The overall efficiency from battery to motor is the combination of the efficiencies of battery discharging, converter, motor & control unit, also 0.97, 0.95, 0.90 respectively. Since the motor is capable of 125 kW, and 30.86 kW will be supplied by the engine, the rest 91.14 kW should be provided by the battery. Taking efficiencies on the path from the battery to the motor into account, the battery pack should provide 113.52 kW power.

For the energy considerations, the electric machine mean efficiency for a half loaded vehicle will be considered, since the vehicle is a commercial vehicle (Kocagül, 2009).

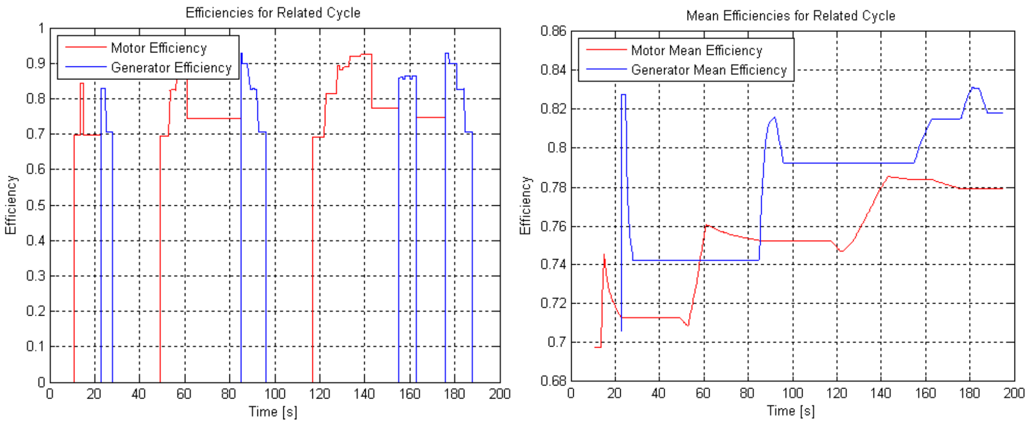


Figure 8.7 : EM Instant and Mean Efficiencies in ECE Cycle.

The electric maschine has a 0.78 and 0.82 mean motoring and generating efficiency including controller, respectively.

Table 8.2 : Components and Paths Efficiencies

Components	ECE	ICC	NEDC	NYCC
Rex_Generator_Eff	0.950	S	S	S
Rectifier_Eff	0.950	S	S	S
Converter_Eff	0.950	S	S	S
Battery_Charging_Eff	0.970	S	S	S
Battery_Discharging_Eff	0.970	S	S	S
Motoring_Eff	0.780	0.795	0.810	0.774
Generating_Eff	0.820	0.793	0.830	0.768
Differential_Eff	0.940	S	S	S
Battery_2_Wheel_Eff	0.676	0.689	0.702	0.670
Generator_2_Battery_Eff	0.710	0.686	0.719	0.665
REX_2_Wheel_Eff	0.662	0.675	0.687	0.657
REX_2_Battery_Eff	0.832	S	S	S

In following, required and recupable energies in cycles are investigated. While computing the regenerative energies, optimal feeling series braking method is considered as it has been done in Chapter 6.

Table 8.3 : Required and Recupable Energies in ECE-15 and NYCC

Cycle	ECE-15 0.995km		NYCC 1.89km	
Unit	kWh	kWh/km	kWh	kWh/km
Req En at Wheels	0.177	0.178	0.484	0.256
Req En at Battery	0.262	0.263	0.690	0.365
Recup En at Wheels	0.075	0.076	0.302	0.160
Recup En at Battery	0.053	0.054	0.217	0.115
Net Req En at Wheels	0.101	0.102	0.182	0.096
Net Req En at Battery	0.208	0.209	0.473	0.250
Accessory En	0.030	0.030	0.057	0.030
inc Accessory En	0.238	0.239	0.530	0.280
Accessory/Kinetic	0.143		0.120	

In this work, the battery energy will be sized according to the city cycles considering the vehicle chosen will mostly be used in city; Istanbul cycle and NEDC include also extra urban driving conditions, hence the NYCC and ECE-15 remain as candidate cycles, from which ECE-15 is selected, hence related parameters such as electric machine efficiency and energy demand per km will be used according to the calculated values in ECE-15 in further computations.

Table 8.4 : Required and Recupable Energies in NEDC and ICC

Cycle	NEDC 11.0km		ICC 8.63km	
Unit	kWh	kWh/km	kWh	kWh/km
Req En at Wheels	2.375	0.216	1.754	0.203
Req En at Battery	3.385	0.308	2.546	0.295
Recup En at Wheels	0.562	0.051	0.637	0.074
Recup En at Battery	0.404	0.037	0.437	0.051
Net Req En at Wheels	1.813	0.165	1.117	0.129
Net Req En at Battery	2.981	0.271	2.109	0.244
Accessory En	0.289	0.026	0.227	0.026
inc Accessory En	3.270	0.297	2.335	0.271
Accessory/Kinetic	0.097		0.107	

For the energy considerations, the daily travelling distance of a van should be considered. The light duty vehicles Renault e-Kango has a range of 130 km and eDucato 160 km.

The candidate battery types used in previous chapter is given below again.

Table 8.5 : Battery Specifications for Candidate Batteries

	Firm	SAFT Li-Ion				Hitachi Li-Ion			Panasonic
	Unit	VL41	VL27	VL25	VL45	Gen 3	Gen 4	Next	NiMH
q_p	W/kg	794	987	2000	900	3000	4500	2400	1300
q_e	Wh/kg	136	124	100	149	61	72	120	44
C	Ah	41	27	28	45	22	24	25	7.8
m	Kg	1.07	0.77	0.94	1.07	1.3	1.2	0.75	1.04
V	V	3.6	3.6	3.3	3.6	3.6	3.6	3.6	1.2

The next step is investigating the power and energy constraints.

Table 8.6 : Power Constraint Result for Candidate Battery Types

	Firm	SAFT LiIon			Hitac. LiIon	Lotus Proton	Panaso. Prius
	unit	VL41	VL27	VL45	Gen 3	LiIon	NiMH
q_p	W/kg	794	987	900	3000	800	1300
q_e	Wh/kg	136	124	149	61	150	44
C	Ah	41	27	45	22	31	7.8
m	kg	1.07	0.77	1.07	1.3	0.75	1.04
V	V	3.6	3.6	3.6	3.6	3.6	1.2
P_max	kW	113.52	113.52	113.52	113.52	113.52	113.52
DOD		0.4	0.4	0.4	0.4	0.4	0.4
W	kWh/km	0.209	0.209	0.209	0.209	0.209	0.209
m_pack	kg	142.97	115.02	126.13	37.84	141.90	87.32
P_pack	kW	113.52	113.52	113.52	113.52	113.52	113.52
n		133.62	149.37	117.88	29.11	189.20	83.96
C_pack	Ah	41.00	27.00	45.00	22.00	31.00	7.80
W_pack	kWh	19.44	14.26	18.79	2.31	21.29	3.84
DOD	0.40	7.78	5.70	7.52	0.92	8.51	1.54
Range	km	37.17	27.27	35.93	4.41	40.69	7.35

A van travel about 200-250 km per day. The battery supplier Saft claims that their Li-Ion batteries have fast charge capability 1C that means that the charge current will charge the entire battery in 1 hour. Hence, the battery DOD is selected as 40%, that means 0.4 hour or 24 min. is required to charge the battery. This is possible during the midday pause, so 100 km before the midday and 100 km after the midday give a sum of 200 km range per day.

Table 8.7 : Energy Constraint Result for Batteries 100 km Range

	Firm	SAFT LiIon			Hitac. LiIon	Lotus Proton	Panaso. Prius
	unit	VL41	VL27	VL45	Gen 3	LiIon	NiMH
q_p	W/kg	794	987	900	3000	800	1300
q_e	Wh/kg	136	124	149	61	150	44
C	Ah	41	27	45	22	31	7.8
m	kg	1.07	0.77	1.07	1.3	0.75	1.04
V	V	3.6	3.6	3.6	3.6	3.6	1.2
W	kWh/km	0.209	0.209	0.209	0.209	0.209	0.209
Range	km	100	100	100	100	100	100
W_100	km	20.9	20.9	20.9	20.9	20.9	20.9
DOD		0.4	0.4	0.4	0.4	0.4	0.4
W_pack		52.25	52.25	52.25	52.25	52.25	52.25
m_pack	kg	384.19	421.37	350.67	856.56	348.33	1187.50
P_pack	kW	305.05	415.89	315.60	2569.67	278.67	1543.75
n_cell		359.06	547.24	327.73	658.89	464.44	1141.83
C_pack	Ah	41.00	27.00	45.00	22.00	31.00	7.80

Because of its very high mass, NiMH battery with its low energy density is not appropriate for the to be designed vehicle. The best result give VL45 and the battery used in Lotus Proton. VL45 is selected for the REXE-Van. It can be observed that in case fulfilling energy constraint, power constraint is also fulfilled.

The result shows for 1 km, 3.507 kg or 0.523 kWh battery is required. From the power constraint of VL45, the pack must be heavier than 126.13 kg having 18.77 kWh energy and 35.93 km range.

The results show that for a range of 100 km, the best battery has a weight of 350 kg and it is 52.25 kWh. Although the operating cost is low, the battery cost would be very high. A solution would be battery exchange stations. In that case, with an advance payment, the battery would be rented, which would make a smaller and lighter pack possible.

At the beginning of this section, it is found that REXE-Van would be 184 kg lighter in case of neglecting the battery weight. Adding the battery weight for 100 km, the REXE-Van becomes 166 kg heavier.

9. SIMULATION AND RESULTS OF REXE-VAN

After updating the simulation parameters according to the design parameters, the model is simulated. The average vehicle mass is 2386 kg, also 166 kg heavier than the conventional vehicle because of the high battery weight.

9.1 In-City And Highway Performance of the REXE-Van

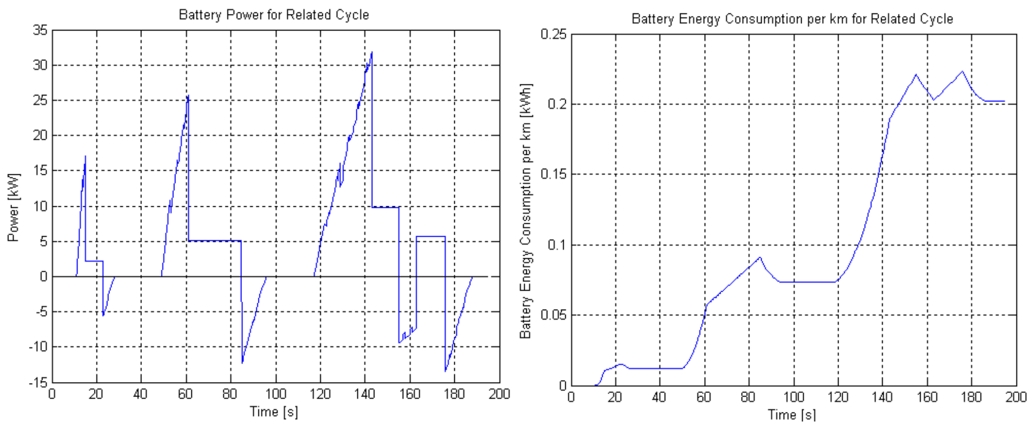


Figure 9.1 : Battery Power and Energy Consumption per km in ECE-15.

The battery power reaches above 30 kW and energy consumption above 0.2 kWh per km.

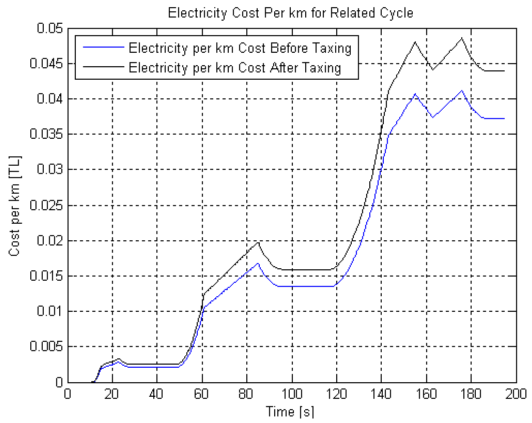


Figure 9.2 : Battery Electricity Cost per km for ECE-15.

The battery electricity cost is 0.044 TL/km that means 100 km travelling costs just 4.4 TL including VAT. It is very low price comparing with the conventional fuels considering 95 octane gasoline and diesel cost about 4.1-4.2 TL/lt and 3.6-3.65 TL/lt, respectively.

For investigating the REX fuel economy of the vehicle, the maximum allowed speed of the regulation on the highway 95 km/h is simulated. The vehicle is assumed to have a constant speed.

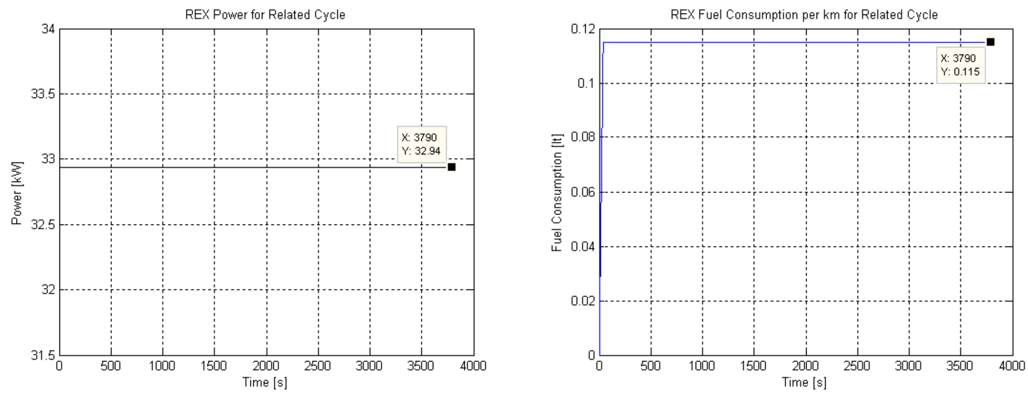


Figure 9.3 : REX Power and Fuel Consumption per km for V=95 km/h.

The REX power at that speed is about 33 kW and it consumes 0.115 lt/km or 11.5 lt/100km gasoline, the BSFC is 245.5 g/kWh and fuel cost is about 0.48 TL/km considering gasoline cost 4.2 TL/lt.

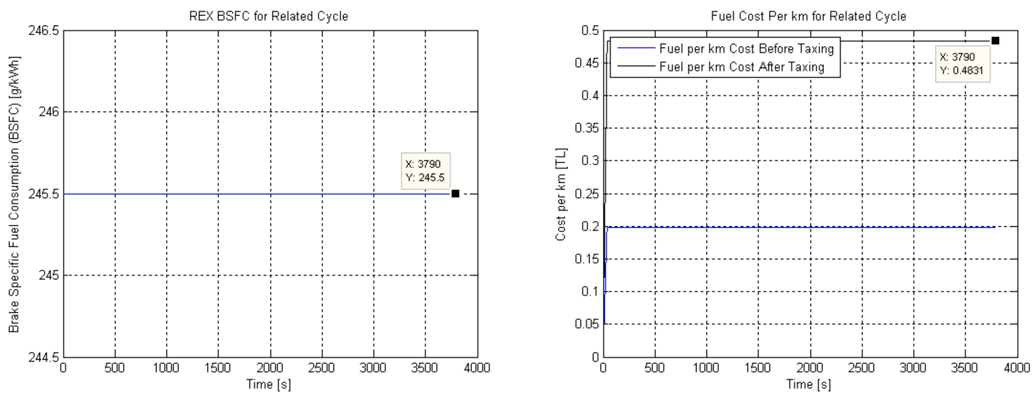


Figure 9.4 : REX BSFC and Fuel Cost per km for V=95 km/h.

9.2 Comparison of the REXE-Van With The Conventional Van

To compare the result with the conventional vehicle, the fuel consumption map of the vehicle and other required parameters are added to the model.

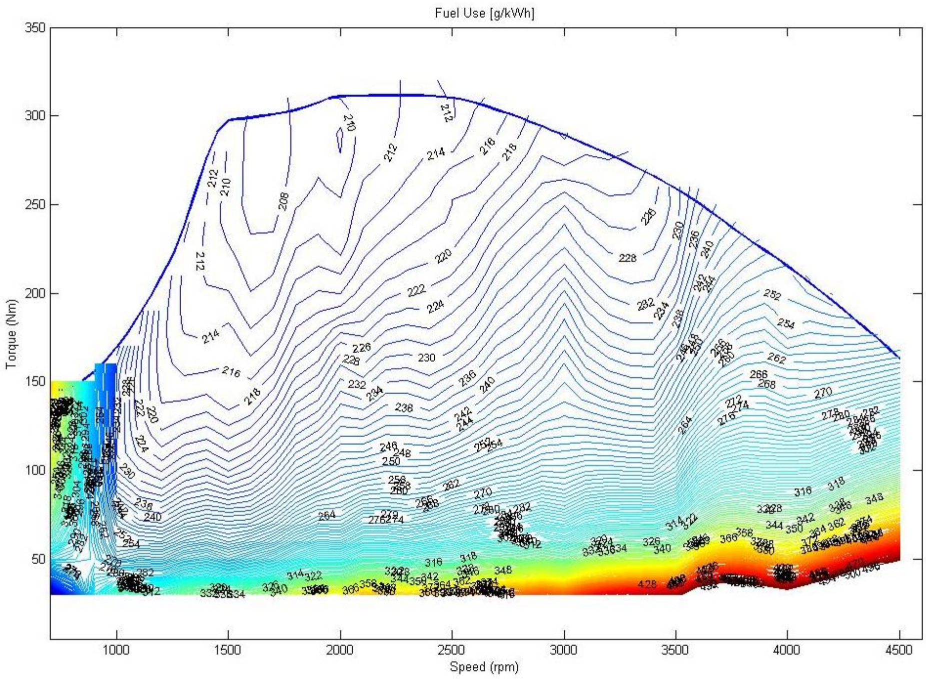


Figure 9.5 : BSFC of The Engine Used in The Conventional Vehicle

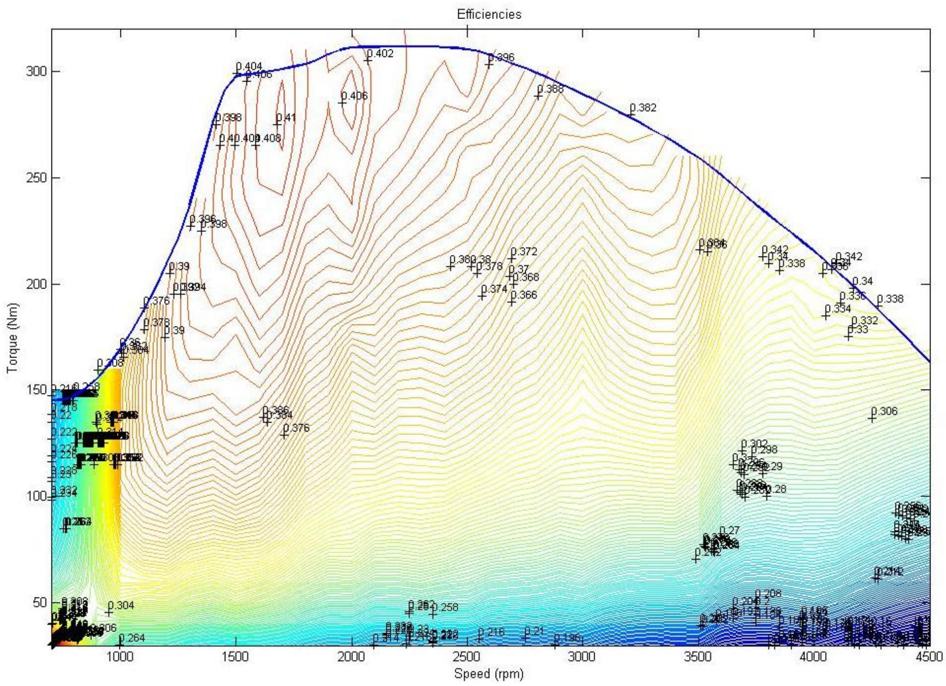


Figure 9.6 : Efficiency Points of The Engine in The Conventional Vehicle

To verify the model, the results of the conventional vehicle is compared with the Phd. Thesis of Ali Boyali (2008) and vehicle catalogue. In the thesis, a 3000 kg is run in ECE-15 cycle and the fuel consumption per 100 km is found 11 lt. In the catalogue, the fuel consumption for combined cycle is 8.1 lt, the mass in the catalogue is the reference mass.

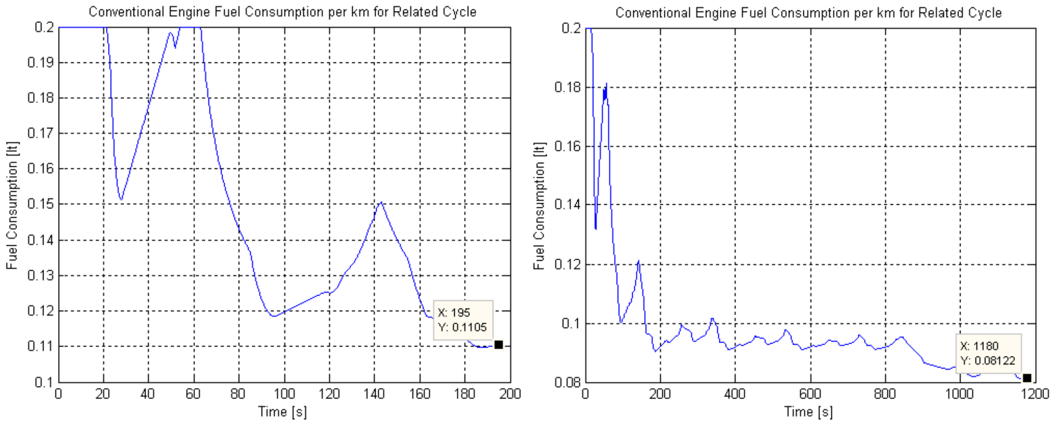


Figure 9.7 : Fuel Consumptions per km in ECE-15 and NEDC

The simulation result fits well with the data in the thesis and vehicle catalogue. In ECE-15 cycle fuel consumption per km is 0.1105 lt and it is 0.08122 lt in NEDC for 3000 kg and 1800 kg vehicle masses, respectively.

Having verified the model, the vehicle having the average weight 2219 kg is simulated.

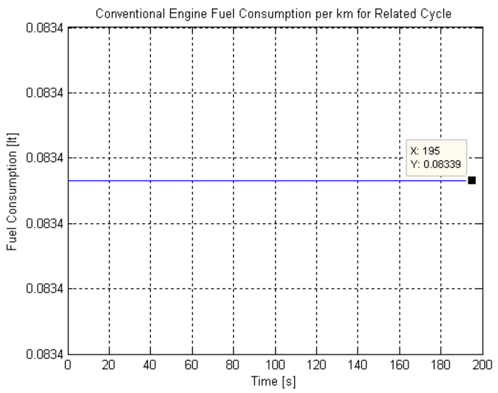


Figure 9.8 : Conv. Vehicle Fuel Consumption per km for V=95 km/h.

The transmission efficiency at V=95 km/h is assumed to be 0.93. The mean weight of the conventional vehile has been colculated as 2219 kg, 580 kg transportation mass is available for this average mass. If the conventional vehicle is simulated for this transportation mass, the fuel consumption is 0.08339 lt/km or 8.339 lt/100 km which gives 0.3 TL/km or 30 TL/100 km fuel cost. Comparing the gasoline REX having 0.48 TL/km, it can be commented that in case of travelling oft on the highway, the REX should be a diesel engine for better fuel economy.

To compare the in-city performance of the vehicle, the model is simulated for ECE15 cycle.

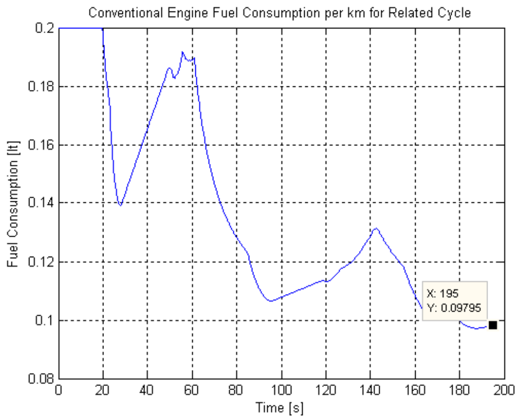


Figure 9.9 : Fuel Consumption per km in ECE-15 for m= 2219 kg

The conventional vehicle having the mass the same mass, 2219 kg, has the fuel consumption 0.098 lt/km or 9.795 lt/100km diesel fuel. Considering the diesel cost 3.6 TL/lt, the fuel cost is about 0.353 TL/km or 35.26 TL/100km. The electric Van has the electricty cost of 0.044 TL/km or 4.4 TL/100km. That shows 30.36 TL less cost can be afforded by using electric van. For a daily travel of 200 km, the electric vehicle is 61 TL more cost-effective than the conventional vehicle. Considering a 26 work-days in a mounth, that makes 1,578.72 TL a mounth and 18,944.64 TL a year. The Li-Ion battery cost decleared by Deutsche Bank stated in the battery selection chapter in this study is 450 $/kWh. For the REXE-Van designed, the battery cost is 23,512.5 $ or 35,268.8 TL with assumption of 1US $ is 1.5 TL. The battery cost amortise in 1.86 years or 22.3 mounths. The porgnosen of Deutshe Bank shows that the LiIon battery cost will decrease to 250 US $/kWh in 220. Hence the battery cost for the REXE-Van would be 13,062.2 $ or 19,593.3 TL in 2020.

The result shows for today and for the future shows the significant potential of the electric vehicles, especially for in-city driving. The REXEV give the unlimited range opportunity and hence it is superior to the only electric vehicles.

10. CONCLUSION AND RECOMMENDATIONS

In previous chapters, two vehicle models, forward and backward flow, are explained and built. The user interface program developed during the thesis study is presented. Various test cycles and power & energy analysis of these driving cycles are evaluated. Vehicle design parameters such as maximum speed, maximum gradeability, 0-100 km/h performance, continuous speed power requirements etc. are defined and considering these parameters, a wide research of the power train and drive train has been accomplished. The vehicle is designed within the boundaries of the predetermined conditions. The designed vehicle is also verified to fulfil these requirements. The state of art energy storage systems are investigated deeply utilizing various scientific papers and different data sheets of the in-use systems to be able to cross the sources. Detailed comparisons of the battery systems are evaluated and the most appropriate one is chosen after systematic calculations in different comparison tables.

Later on, the, all the related parameters are updated by using user interface program and look-up tables and the model is simulated. The simulations are run and results are analysed for the cycles ECE-15, ICC, MYHWY, HWYFET , from which the first one represents a full city cycle, the second one the in city and slightly highway, the third one a constant speed highway and the last one the fuel economy test for highway Having evaluated different types of test results help to analyse vehicle performance for both in-city and highway conditions. Results have shown that the REXEV has a promising future considering the down going prices of batteries. The vehicle is also designed lighter than a comparable vehicle, although it offers better performance, which disproof the assumption of being hybrid vehicles heavier than conventional vehicles.

The designed vehicle would also not cost much, since the only electric range is considered as being allowing for 30 km driving, considering a 40% DOD. However, the ICE would supply the vehicle above these ranges, which gives a distance freedom that is from the most important problems of today's only electric vehicles. In the fallowing part, a conventional lightweight duty vehicle is converted to an REXE-Van which is afterwards modelled and simulated. To compare the results with the conventional vehicle, the conventional vehicle is also modelled, simulated and verified.

A further work would be appropriate for battery management and optimization. Considering most of the time the battery energy would be enough to propel the vehicle and since the REX operates in the stochiometric region, emissions would also result quite less than the conventional vehicle, in case the REX recharges the battery during driving. A study on emissions would also be favourable to prove this approach. Another interesting research area would be done in the production cost of the REXEV. The battery prices in the thesis are discussed according to various sources however cost of the control unit, electric machine, regenerative systems are to be researched considering today's technology developments. Lastly, the hill up-down climbing energy economy comparison in conventional and REXEV would be useful considering the in-city road conditions for cities like İstanbul.

REFERENCES

Aditya J., Ferdowski M., 2008. Comparison of NiMH and LiIon Batteries in Automotive Applications, *IEEE Vehicle Power and Propulsion Conference (VPPC)*.

Atzwanger M. And Hubman, C, 2011, Two-Cylinder Gasoline Engine Concept for Highly Integrated Range Extender and Hybrid Powertrain Applications, *SAE Technical Paper Series*, 2011-32-0130.

Barlow, T., Latham, S., McCrae, I. And Boulter, R., 2009, A Reference Book Of Driving Cycles For Use In The Measurement Of Road Vehicle Emissions, TRL Limited.

Boyalı, A., 2008. Hibrit Elektrikli Araçların Modellenmesi ve Kontrolü, *PhD Thesis,* İTÜ Fen Bilimleri Enstitüsü, İstanbul

Davoust, R., 2008. Gasoline and Diesel Prices and Taxes in Industrialized Countries, European Governance and the Geopolitics of Energy.

Ebner A., Winkler F. and Abart M., 2011, Study of Possible Range Extender Concepts with Respect to Future Emission Limits, *SAE Technical Paper Series*, 2011-32-0129.

Ehsani M., Yimin G. and Emadi A., 2005, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles. CRC Press, Washington D.C., USA.

Erbeyler, A., 2007. Hibrit Elektrikli Hafif Ticari Araçta Dizel Motoru Azotoksit Emisyonlarının Optimizasyonu, *MSc Thesis,* İTÜ Fen Bilimleri Enstitüsü, İstanbul

Gaines and Cuenca., 2000. Costs of Lithium-Ion Batteries for Vehicles, United States Department of Energy, Illinois, USA.

Gillespie T., 1992, Fundamentals of Vehicle Dynamics, *Society of Automotive Engineers (SAE)*.

Hodkinson R. and Fenton J., 2001, Lightweight Electric/Hybrid Vehicle Design. Butterworth Heineman, Oxford, England.

Kocagül, M., 2009, Hibrid Taşıtlarda Seyir Çevrimine Göre Yakıt Tüketimi Ve Emisyonların Optimizasyonu, *MSc Thesis,* İTÜ Fen Bilimleri Enstitüsü, İstanbul

Kuijpers, B. and Smits, M., 2011, Optimization Study of a Plug-in Hybrid Electric MPV, *PhD Thesis,* Eindhoven University of Technology.

Larminie J. and Lowry J., 2003, Electric Vehicle Technology Explained. John Wiles & Sons, West Sussex, England.

Naunheimer, H. and Lechner, G. 1999, Automotive Transmissions. Berlin Heidelberg, Springer.

Parra H., Magnusen F. and Bosga S., 2009, Challenges for Electric Machines and Power Electronics in Automotive Applications, *Ecologic Vehicles Renewable Energies EVER.*

Short M., Pont M., and Huang, Q., 2004. Simulation of Vehicle Longitudinal Dynamics , Embedded Systems Laboratory Univeristy of Leicester Technical Report, Leicester, England.

Turner J., Blake D. and Jason M., 2011, The Lotus Range Extender Engine, *SAE Technical Paper Series,* 2011-01-2208.

United Nations Emission Regulations, 2008, Regulation No. 83.

Url-1 <*http://*green.autoblog.com >, accessed at 07.02.2011.

Url-2 < http:// www.swri.org>, accessed at 12.02.2011.

Url-3 < http://www.lotuscars.com>, accessed at 18.02.2011.

Url-4 <*http://* bugatti.com>, accessed at 27.02.2011.

Url-5 < http:// http://www.renault.com.tr>, accessed at 04.03.2011.

Url-6 < http://www.hyundai.com.tr>, accessed at 04.03.2011.

Url-7 < *http://www.toyotaegypt.com*>, accessed at 04.03.2011.

Url-8 < http://www.fiat.com.tr>, accessed at 04.03.2011.

Url-9 < http://www.opel-ampera.com>, accessed at 11.03.2011.

Url-10 < www.uqm.com/pdfs/PowerPhase%2075.pdf>,accessed at 16.03.2011.

Url-11 < http://www.mpoweruk.com/soc.htm>, accessed at 27.03.2011.

Url-12 < http://www.hybridcarblog.com>, accessed at 07.04.2011

Url-13 <www.e2af.com/review>,accessed at 11.03.2011.

Url-14 <http://www.saftbatteries.com>, accessed at 16.03.2011.

Url-15 < http://www.obrist.at>, accessed at 27.03.2011.

Url-16 < www.bioage.typepad.com/files/1223fm-05.pdf>, accessed at 07.04.2011

Url-17 < www.eltec.com>, accessed at 18.04.2011

Url-18 <http://web.mit.edu/evt >, accessed at 24.04.2011

Url-19 < http://www.hybridcarblog.com>, accessed at 01.05.2011

Url-20 < http://www.metricmind.com/data/cycles.pdf>, accessed at 01.05.2011

Url-21 <http://gm-volt.com/>, accessed at 01.05.2011

Url-22 < http://hyundaiengine.com>, accessed at 18.02.2011.

Wagner U., 2008, Elektrische Strassenfahrzeuge, Vorlusung Skripte, Munich, Germany.

Yang, P., Liu F. And Liu J., 2011. Design of Power-Assisted Motor for Vehicle Air-Conditioning Systems, *Proceedings of the IEEE*, ICEM 2011.

CURRICULUM VITAE

Ersin Hasan Doğrugüven was born in Istanbul, 1985. He graduated from the Highschool Istanbul Erkek Lisesi in 2004 and Electrical and Electronics Engineering Faculty of the Istanbul Technical University in 2009. He studied his third college year at the Technical University of Munich. In 2009, he began to study Automotive Engineering at the Istanbul Technical University and Industrial Engineering at the Boğaziçi University. He has worked on the project "Sliding Mode Control for ABS Systems in Electric Vehicles" supported by the Scientific and Research Council of Turkey (TUBITAK) three months because of which he did not continue his Industrial Engineering study. After three months, he began to work as research engineer at the Center of Research for Advanced Technologies of Informatics and Information Security (BILGEM) of TUBITAK. He speaks German and English very well and Spanish at basic level.