



CHALMERS
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Techno-Economic Design of EV Powertrain Based on Customer Perspective

Master's thesis in Electric Engineering

Dishanth Sollapura Vishwanath
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MASTER'S THESIS 2020

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Gothenburg, Sweden 2020

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Abstract

In this thesis work, literature studies were done related to the customer preferences based on their driving patterns to identify and define potential electric vehicle buyers. From this study the customers were adopted and performance matrix for those customers is defined. Based on the adoption of customers, four different drivelines (city driving customer, mixed driving customer, long range driving customer, shared mobility customer) with 3 different battery pack options were designed after performance requirements with data on existing battery electric vehicles as a frame of reference. The acceleration performance, energy consumption, traction battery sizing, electric machine sizing was determined and analyzed for the standard WLTC drive cycle. Acceleration requirement turned out to be dominant over other factors such as top speed while powertrain sizing regarding torque and power. The entire modeling and simulation was done via a 1D CFD commercial software GT-SUITE.

Further, important step was to compute consumer centric total cost of ownership (TCO) for twelve powertrains with two different charging preferences (cost focused customer, premium customer) which includes virtual costs over five years of ownership. TCO analysis consider electricity cost, maintenance cost and depreciation cost. Investigation of battery full cycle life helped in finding the depreciation of the battery. To compute virtual cost such as cost of waiting time and cost for have to stop for fast charging a unique model of driving range distribution and energy distribution is used which is based on NHTS database. TCO is presented in terms of per year and per km which helps in comparing between the customers. Our findings suggest that virtual cost attributes such as cost of having to stop and cost for charging is not a big for electric vehicle buyers.

Keywords: Battery Electric Vehicle, Lithium ion Battery, Electric Motor, Battery thermal management, Total cost of ownership, Energy distribution curve, Driving range distribution, Cost of waiting time for charging, Electricity cost, Customer.

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Abbreviations

BEV	Battery Electric Vehicle.
BTM	Battery Thermal Management.
CFD	Computational fluid dynamics.
EM	Electric Motor.
FWD	Front Wheel Drive.
NHTS	National household Travel Survey.
PMSM	Permanent Magnet Synchronous Machine.
SOC	State of charge.
TC	Thermal Conduction.
TCO	Total Cost of Ownership.
WLTC	Worldwide Harmonized Light Vehicles Test Cycles.

1

Introduction

1.1 Background

Battery Electric Vehicle (BEV) research and interests are growing exponentially in recent years, from both engineering and customers perspective. BEV's are seen as one way of reducing fossil fuel use and greenhouse gas emissions, but the cost of batteries, performance and corresponding charging infrastructure is always challenging for their market. Frequent awareness in the customers regarding operational cost savings and urban pollution reduction capabilities of BEV's has thus been nurtured into the society [5]. Limitations in the current technology such as energy storage capacity in the low-cost battery and lack of infrastructure facilities for fast charging stations are preventing mass-market deployment of BEV's [7]. Development of BEVs includes several economic factors like functional cost, development cost and total cost ownership (TCO). These factors depend on the driving cycle, motor capacity and further, manufacturing cost of the battery. The vehicle cost or total cost of ownership is depend on the size of the battery, the number of cells accommodated in the battery pack and the durability of the battery. BEV's utilizes expensive electric motor and battery pack in order to meet the performance requirement of the vehicle, hence the cost of the electric powertrain is more expensive than the conventional powertrain.

1.2 Problem definition

The thesis projects have following goals:

1. Literature work on the customers to derive performance requirements of each powertrain.
2. Sizing of electric motor and traction battery based on the customer requirement.
3. Build simulation models of Battery electric vehicle and analyze the simulation results in different case studies.
4. Determine new methodology for calculating TCO.
5. Analyzing cost for having to stop and cost of waiting time for fast-charging.

1.3 Objective

The aim is to determine the TCO for different BEV powertrains based on customer requirements through studies of complete propulsion systems. Different components and control strategy will be built in GT-Suite to find optimal size of the battery and electric motor. Attributes to be considered as cost, performance, driving range, vehicle mass and top speed. Different customers scenarios and concepts will be studied. The results from the simulations part and TCO model is being used to analyse which solution is most attractive for the different customers.

1.4 Assumptions and limitations

A complete propulsion system will be modelled in GT Suite and not tested with the real time vehicle. This thesis will cover only simulations of battery and inductions motor while using a simple vehicle model running for a standardized driving cycle (WLTC). Other components are considered as black box using efficiencies. Loses in the electrical components cannot be investigated completely during the simulation.

2

Customer's Review

2.1 Literature study.

The key factor to any of the automobile industry are customer experience, weather during the sales process or aftersales market. This is because customer invest huge amount of money to purchase a vehicle, often equal to months of income and it should be valued. Customer desire a vehicle to be safe, comfortable and affordable which helps to full-fill their daily needs [2]. To attract customer's for the use of BEV incentives are been designed and implemented in many of the European countries which includes purchase subsidies, ownership benefits (reduction of tax), road toll exceptions (for example in Norway), and local incentives (free parking and charging facilities) [3]. The other biggest advantage is low cost per kilometer of BEV's when compared to conventional vehicles [4]. Figure 2.1 [6] shows how customers consider the adaption BEV's and the importance of TCO in the future, which will be further discussed in the section 4.

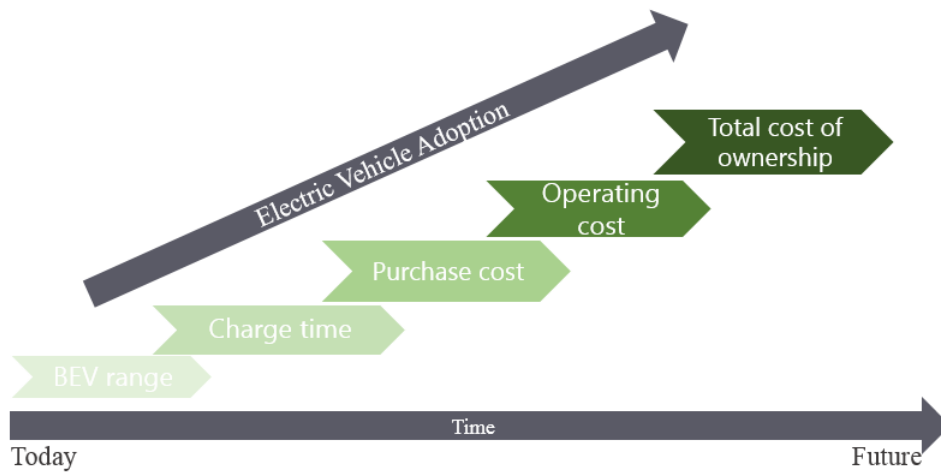


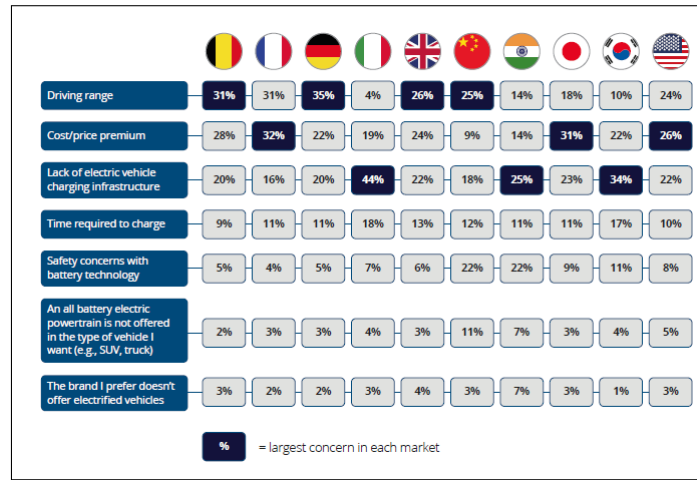
Figure 2.1: Important attributes for electric vehicle adaption.

In general, attributes such as short driving range, lengthy charging time and high purchasing cost are the main barriers for the BEV customers. If customers can overcome these attributes, the total cost of ownership (TCO) and lifetime cost of the vehicle will be fundamentals in the marketing of BEV's and economics will be then be a key factor for the adoption of BEV technology [8]. This literature work is carried out to define the performance requirement of BEV based on the customer review and some of the important outcomes which are used in this thesis are been

presented below.

- **Major concerns of customers regarding BEV's.**

From the Figure 2.2, driving range (32%) and cost of the vehicle (30%) are the two main attributes which are concern for customer's. These attributes all are interconnected since a larger battery leads to longer range, but increase in vehicle price as well charging patterns and charging infrastructure [10]. According to the survey made by DTTL global manufacturing industry group 85% of survey responds range, charging time and cost to charge are extremely important for purchasing of and sharing mobility usage of BEV's [6]. So, these attributes are considered to model BEV powertrain in this thesis work.

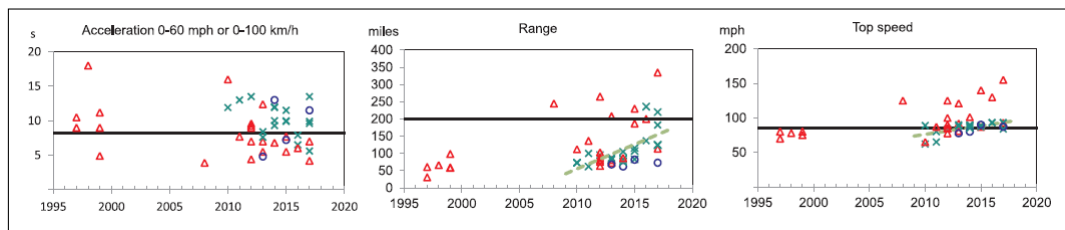


*Source: Deolitte Automotive consumer survey 2018

Figure 2.2: Customer concern regarding BEV's.

- **Variations in BEV attributes.**

Figure 2.3 depicts attributes which were obtained by assessing 48 models available to the customers from the 1997 to 2017. This figure shows three price percentile of car market based on US car market. Blue circle shows lowest third, green x mid third and red triangle most expensive third price percentiles. The diversity of these attributes can adapt into different models in this thesis work.



*Source: B. Nykvist et al. [10]

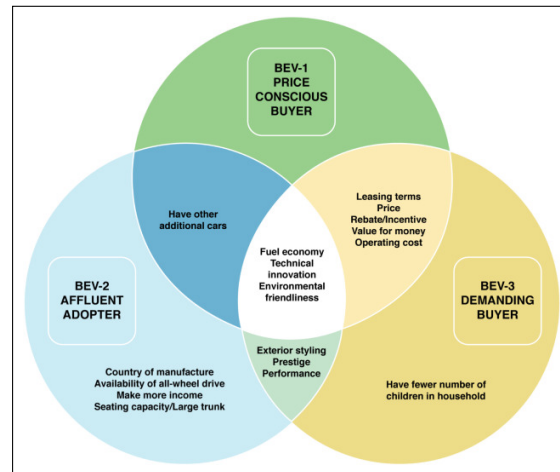
Figure 2.3: Development of BEV attributes from 1995 to 2017.

- **Driving range distribution**

Daily driving distance study is the important considerations to determine the battery size and also essential to gain knowledge of how far driver usually travel [9]. Majority of the data regarding daily driving distance is studied from National Household Travel Survey (NHTS) survey from U.S.Department of Transportation. The main outcomes which can be used form this data or graphs are average daily commuting distance, average daily driving over a whole population and also the distance between the charging.

- **Identifying potential customer's**

Modelling of BEV powertrains requires better understanding of potential customer's. To identify the potential customers, data mining approach was developed to understand the 88,404 nationally representative survey of new car buyers in U.S.market [11]. Figure 2.4 shows Venn diagram describing different types of BEV buyers. BEV-1 cares mainly about operating costs, BEV-2 has higher average income and cares mainly about performance and styling. BEV-3 are more demanding buyers of BEV consumers segments and has lower income than the average and values for performance, style but they are cost focused.



**Source: R.Dua et.al [11]*

Figure 2.4: Different potential customers.

2.2 Adaption of customers

In this section, different electric vehicle buying customers are considered and defined based on the driving patterns and charging preference's as shown in Table 2.1.

Table 2.1: Adaption of customers model

Customers based on driving patterns and charging preference's			
Cost focused customer City driving	Cost focused customer Mixed driving	Cost focused customer Long range driving	Cost focused customer Shared mobility
Premium customer City driving	Premium customer Mixed driving	Premium customer Long range driving	Premium customer Shared mobility

Based on the value for time and cost, two different charging preferences are considered and they are,

- **Cost focused customer:** These are the customers who has less importance for value of time. They fall in the category who has below average income.
- **Premium customer:** These are the customer who gives more importance for value of time. They fall in the category of higher average income.

Based on the driving patterns,

- **City driving customer:** The customers who typically drive in the city limits most of the days in a year and they hardly commute long distances.
- **Mixed driving customer:** These customers drive both in the city limits and commute long distance most of the days in the year.
- **Long range driving customer:** These are the customer who typically commute longer distance in a day when compared to city and mixed driving customer.
- **Shared mobility:** It is the new type of urban sustainable mobility, which is similar to mixed driving customer but they commute much more distance in a day when compared to mixed driving customer.

The values and assumptions for the above mentioned customer are detailed in the Table 4.1

2.3 Frame work for performance requirements based on customers data.

The required performance data for different customer's is extracted from the literature studies and shown in the Table 2.2. By using performance requirement matrix BEV powertrains are modelled and sized.

Table 2.2: Performance requirement data based on different customers

Factors	City driving customer	Mixed driving Customer	Long range Driving customer	Shared Mobility Customer
Top speed (km/h)	130	150	180	150
Accelerate 0-100 km/h	12	10	8	10
Range (km)	200	320	500	800
Acceleration (Take -off (m/s^2))	3.5	4.5	5.5	4.5

These are the basic factors used to for the sizing of Electric motor (EM) and battery to analyze how much energy consumed by BEV.

3

Technological Review

3.1 Battery Electric Vehicle Modeling and Simulation.

In this section, four different driveline design with each 3 different battery pack options are explained. So, twelve powertrains with different battery and electric machine sizes are built. And in this chapter a generalized powertrain modelling and sizing of components is discussed. It includes similar Vehicle Model, Control units, Battery Thermal Management (BTM) and Battery controller for each powertrain, so that there would be no variation while calculating TCO.

3.1.1 BEV powertrain layout

The BEV powertrain for different customers is modeled and sized in GT-Suite. Basic outline of the powertrain in with vehicle model is shown in Figure 3.1. It includes high voltage and low voltage systems with different controller which will be discussed in further sections.

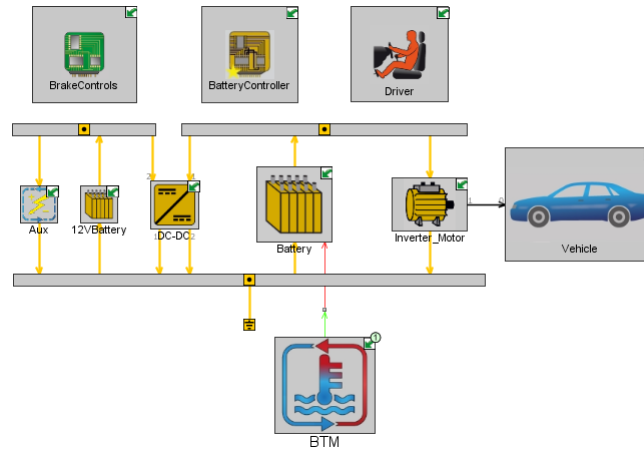


Figure 3.1: Battery Electric Powertrain model in GT-Suite

3.1.2 Vehicle Model

The model has Front Wheel Drive (FWD) drive train, driveshaft connecting to the differential and the two axles. The differential is simple locking differential model where the speeds of both half axles connected to it rotate at the same speed. The

moment of inertia of input and output shafts are assumed to have low value (0.05) and total gear ratio is defined in the differential model which is calculated by using Equation 3.5. The power demand from the wheel depends on the driving cycle and transferred to the front axles and to the differential connected to the electric machine. The electric machine torque is sized for required take-off acceleration.

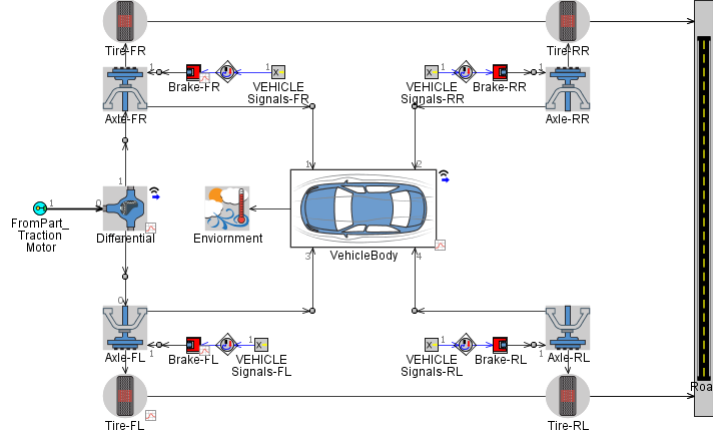


Figure 3.2: The vehicle and tire model in GT-Suite

The vehicle model tries to explain the dynamic studies, where powertrain load and energy consumption will be analyzed. Here the dynamics is studied only in one direction i.e. longitudinal forward direction by assuming stability of the vehicle is not disturbed under different circumstances.[12].

According to Newtons second law of mechanics

$$m \frac{d}{dt} v(t) = F_{traction}(t) - F_{resistance}(t) \quad (3.1)$$

Where $m(kg)$ is the equivalent mass of the vehicle, $\frac{d}{dt} v(t)$ is time rate of change of vehicle speed i.e. acceleration (m/s^2), $F_{traction}(t)(Nm)$ is the traction force acting to increase the vehicle speed and $F_{resistance}(t)$ is the sum of forces acting opposite the vehicle speed and they are aerodynamic drag F_a , rolling resistance F_r and gradient force F_g . According to Equation 3.1 vehicle will accelerate when the traction force is higher than the sum of resistance forces and decelerate when it is vice-versa. If net traction force and net resistance force are equal than the vehicle will run at constant speed.

3.1.2.1 Aerodynamic drag

The aerodynamic drag (F_a) is the force acting opposite to the moving vehicle body which is inevitable. The F_a is directly dependent on the square of the vehicle speed (V) as given in the Equation 3.2. Co-efficient of drag C_d is the dimension less quantity that used to quantify the drag or resistance of the vehicle and the values for C_d are shown in Table 3.1

$$F_a = \frac{1}{2} * \rho_{air} * C_d * A_f * (V)^2 \quad (3.2)$$

Where, $\rho_{air}(kg/m^3)$ is the density of air, $A_f(m^2)$ is the frontal cross section of the vehicle it varies depending on the vehicle size.

3.1.2.2 Rolling resistance

Rolling Resistance is the friction force acting opposite to the tire rolling direction. Rolling resistance co-efficient C_r is the dimensionless quantity which is depends on the tire and road material as well as the tire operating conditions. [13]. Values of C_r are shown in Table 3.1

$$F_r = C_r * m * g * \cos\theta \quad (3.3)$$

Where, $g(m/s^2)$ is the gravity constant, θ is the incline angle and it is neglected in this studies.

3.1.2.3 Traction Force

Traction force F_{trac} is provided by the powertrain to the wheels to overcome the resistance force and to maintain the vehicle speed, the equation is given below

$$F_{trac} = F_{acc} + F_r + F_g + F_a \quad (3.4)$$

Where F_{acc} force required to accelerate the vehicle, here the wheel force may be both negative and positive forces. While vehicle is moving along the longitudinal direction it accelerates than it is positive forces on the wheel and during braking it experiences negative force as it generates part of recuperation or regenerative energy from the electric motor back to the wheels. And this deviation in the vehicle's speed can be controlled by adopting the differential.

By using the traction force obtained by using Equation 3.4, the total gear ratio (i_{gtot}) between deferential and the wheel can be calculated and it is based on relationship between vehicle top speed (V_{top}) and maximum electric machine speed which is given by Equation 3.5

$$i_{gtot} = \frac{\omega_{em}}{V} * r_{wheel} \quad (3.5)$$

Where, $\omega_{em}(rpm)$ speed of the electric machine and $r_{wheel}(m)$ is the radius of the wheel.

Further by using F_{trac} and i_{gtot} torque of the EM can be obtained which is used for the sizing of the EM, and the equation is given by,

$$T_{em} = \frac{F_{trac} * r_{wheel}}{i_{gtot}} \quad (3.6)$$

The power for the propulsion of the vehicle can be computed by using following equation

$$P_{wheel} = F_{trac} * V_{speed} \quad (3.7)$$

Energy demand is the energy consumed at the wheels over the driving cycle, this can be computed by time integral of the power as,[16]

$$E_{wheel} = \int P_{wheel} t dt \quad (3.8)$$

3. Technological Review

Total energy consumption depends on the duration of the driving cycle. When the power demand is high at the wheels then energy consumption will be high and vice versa during braking. (Less energy consumption).

Table 3.1: Vehicle data for four different customers

Factors	City driving customer			Mixed driving customer			Long range driving customer			Shared mobility customer		
Mass (kg)	1200	1250	1300	1500	1550	1600	1800	1850	1900	1600	1650	1700
Frontal area (m^2)	2			2.3			2.8			2.6		
Wheel radius (m)	0.31			0.34			0.37			0.34		
C_d	0.25			0.28			0.35			0.35		
C_r	0.006			0.006			0.006			0.006		

3.1.3 Driver Model

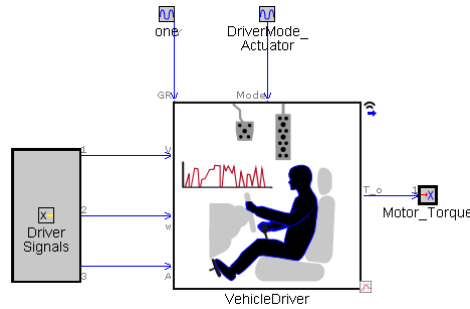


Figure 3.3: Driver template in GT-Suite.

Figure 3.3 shows the driver template in GT-Suite. It is PID controller which targets vehicle speed and calculates required torque from the driving cycle. In this project WLTC class III driving is given as input for all the models which has pre-defined vehicle speed with respect to time. By controlling accelerator and brake pedal with motor speed the speed is targeted.

3.2 Powertrain components sizing, modeling and control units

In this chapter, each of the customer (12) cars will be assigned with base-line powertrain setup, which includes modeling and sizing of the electric machine and the Traction battery. This thesis work requires a system-level propulsion system modeling so different component templates are used in GT-Suite to simplify the modeling. The powertrain component sizing for City driving customers, Mixed driving customers, Shared mobility customers and Long range driving customers is computed by using equations mentioned in section 3.1 and the generalized method followed in the calculation is given in the Figure 3.4. For simplification other components in the powertrain are considered as the black box.

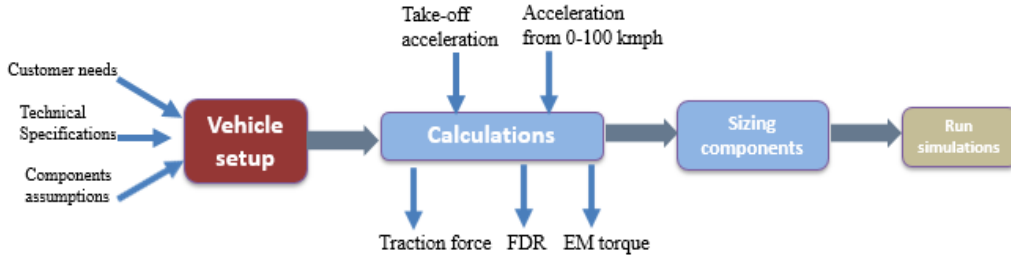


Figure 3.4: Generalized method for EV powertrain sizing

3.2.1 Battery model

The characteristics of the reference cell used in this thesis work as follows: Cathode material - NMC and LMO; Anode material - Graphite; Electrolyte material $LiPF_6$; Separator material - Ceramic coated; and the experimental data used in the modelling is from the Chalmers laboratory [14]. The battery model includes circuit parameters which is shown in Table 3.2 and number of cell connected in series and parallel are given as input in the battery template. In this thesis project, the specification and the properties of the individual cell remains same for all the different models but the arrangement of parallel cells have been changed based on the power requirement of the individual customer. The battery model provides information regarding charging and discharging, transient behavior of battery as function of temperature. The battery is modelled by using simple equivalent circuit as shown in the Figure 3.5. Where V_{oc} is the Open Circuit Voltage of the battery, R_0 is the internal resistance of the battery present in electrodes, separators and electrolyte. The RC link represents the charge taking place on negative and positive electrode and also Lithium-ion diffusion process inside and outside of the active electrode particles, I_{Cout} is the instantaneous current through open circuit [15].

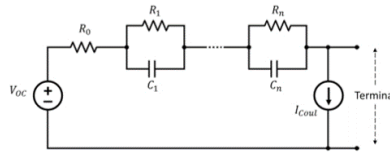


Figure 3.5: Simple Equivalent circuit of battery model used in GT-Suite

Table 3.2: Battery model circuit parameters for 12 powertrains used in GT-Suite

Parameters	Values
OCV at 100% SOC V_{oc}	320 (V)
Cell Current Capacity (I_{cell})	56 (Ah)
Cell Voltage at 100% SOC	3.49
Nominal cell Voltage at 50% SOC (V_{nom})	3.31
Cell Voltage at 0% SOC	2.59

Figure 3.6 shows cell voltage curve used in the battery template. The figure represents voltage levels at 5% and 95% SOC. The average voltage within the SOC window is 3.25 V and the average cell charge capacity is assumed as 56 Ah.

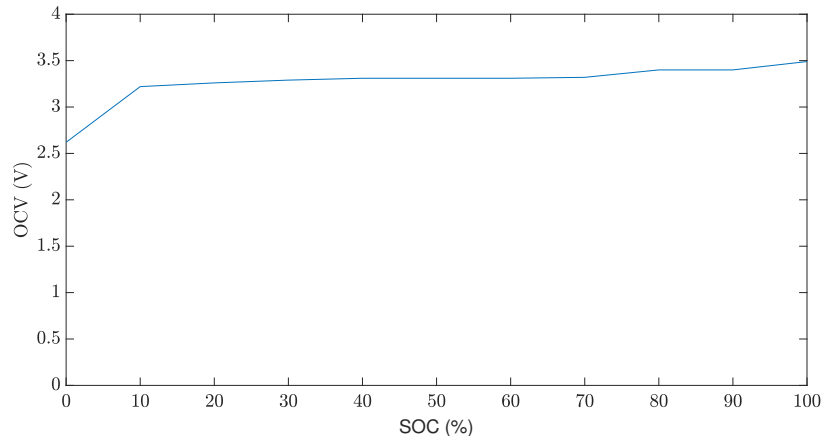


Figure 3.6: Battery cell OCV as function of SOC %

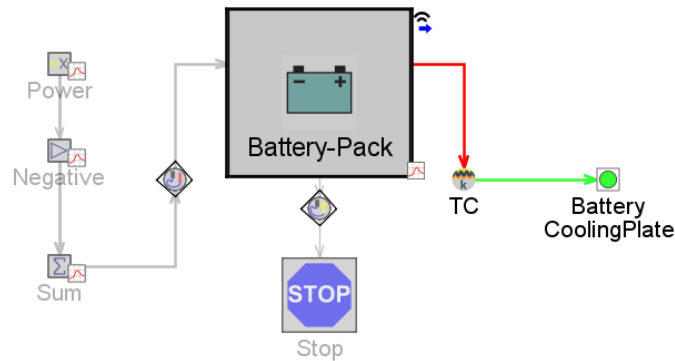


Figure 3.7: Battery model in GT-Suite

In GT-Suite many templates can be utilized directly which helps to simplify the model building. The battery model for all 12 powertrains and implemented template is shown in the Figure 3.7. This template includes defining parameters such as number of cells in series, number of cells in parallel, cell capacity, circuit parameters and cell thermal model. As shown in the Figure 3.7 it receives power signals signals from different components such as traction motor, High temperature cooling circuit and Low temperature cooling circuit. The red and yellow lines are the signals sent to the battery cooling plate through conduction heat transfer from a connection called Thermal Conduction (TC) which is based on the temperature condition of the battery, which will be discussed in the section 3.3. The important factors considered during sizing of battery for different powertrains are similar battery cells, number of cells in series is kept same so that the voltage level in all the powertrains remains the same and the main difference is configuration of number of cells in parallel is varied. The number of cells in series and parallel is given in Table 3.3 for different customer profiles.

State of charge (SOC) is the percentage of full charge capacity of the battery which changes with battery current over the time . SOC represents the percentage of the remaining energy in the battery available for the usage and is given by,

$$SOC(t) = SOC_{init} - \frac{\int_t^{t_0} I(\tau) d\tau}{Q_{tot}} \quad (3.9)$$

where, SOC_{init} is the initial SOC and Q_{tot} is the total charge capacity of the battery (Ah).The battery's usable SOC capacity is 95%. The Energy storage capacity of the battery ($E_{battery}$) is given by equation

$$E_{battery} = V_{nom} * I_{cell} * N_s * N_p \quad (3.10)$$

Where, N_s is number of cells in parallel configuration and N_p is the number cell in series configuration.

Table 3.3: Battery data for 4 different customer powertrains

Customers/ Factors	City driving customer			Mixed driving customer			Shared mobility driving customer			Long range customer		
Energy capacity [kWh]	18	36	54	36	54	72	36	54	72	54	72	90
Series cells	96			96			96			96		
Parallel cells	1	2	3	2	3	4	2	3	4	3	4	5

3.2.1.1 Battery controller model.

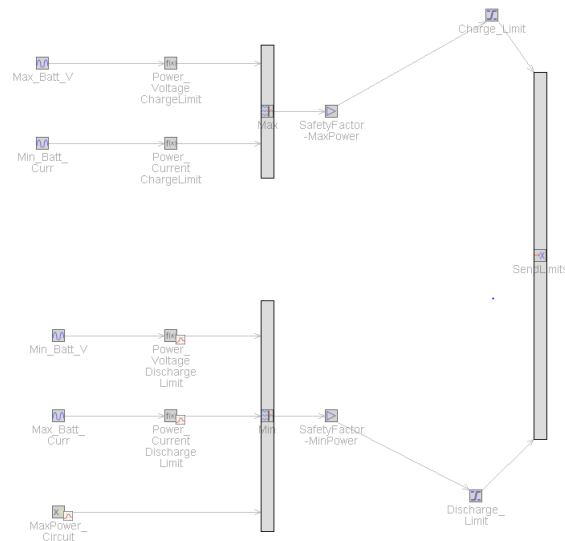


Figure 3.8: Battery controller model in GT-Suite

Nevertheless, these Li-ion batteries need some controlling device called a battery controller which is modeled in GT-Suite and this controller controls the protective mechanism between the overcharged and undercharged status of the cells that can reduce the life expectancy and the efficiency of the battery. So, the key factor or key terminology to keep battery life longer is to investigate the performance of the Li-ion battery by balancing the cell voltage and current level while charging and discharging the battery and this can be done using this battery controller which is shown in Figure 3.8. And also it limits and calculates the maximum discharge power by maximum voltage and minimum current and maximum charge power by minimum voltage, maximum current.

3.2.2 Electric machine

An electric machine is one of the important components in the battery electric vehicle which is been used to control the vehicle movement in terms of traction applications. Many kinds of electric machines have been used for the last few years depending on industrial usage, but the most used machine in recent years for battery electric vehicles is the Permanent Magnet Synchronous Machine (PMSM) since it has very high efficiency, good in terms of social and economic aspects. Electric machines used in the electric vehicle should have capable of producing require initial torque which is needed for the driver model at large speed range. In this traction application, the machine should be operating for the whole operating range to maximize the efficiency of the entire machine.

Since this thesis concentrates on the total cost of the ownership, the electric machine for traction application is currently more challenging in terms of power, efficiency

weight, cost of the motor which is the most important factor in current industries. Electric machines used in the EV's is to convert electrical energy to mechanical energy to give movement or propulsion for the vehicle model and used to regenerate the energy when the driver applies for the brake. However, the motor is not only used for propulsion or regenerate the energy it also been very important in current industries to look forward in terms of performance aspects like high initial acceleration, high initial torque, frequent starts, and stops. All electric motors which are used in the EV's have some constraints or limitation depending on few parameters like materials used to build stator and rotor, power output from the motor and the cooling system which we will be provided to maintain the optimum temperature.

Map-based motor/generator template is being used to model electric machine in GT-Suite based on the requirement of the vehicle and which is shown in the Figure 3.9 and to maintain good efficiency or take out maximum power from the motor there should be proper thermal behavior and cooling system which has been included in the motor design. For example, city driving car requires maximum initial torque to drive the vehicle at required acceleration $3.5m/s^2$ is 175 Nm and this can be controlled using the traction motor controller, where this main objective is to control and fulfill the required torque which is needed to drive the vehicle. And for the rest of the models, the specification and characteristic features of the motor remain the same but the motor has been downsized using torque multiplier based on the performance requirement of the vehicle. The demanded torque for the sizing of electric machine is determined by the acceleration requirement for all 12 customers. The torque required is calculated by using Equations 3.4, 3.5, 3.6. The calculated values are shown in the Table 3.4 and the results of respective torques are shown in the Figure 3.10, 3.11, 3.12, 3.13 respectively.

Table 3.4: Electric motor sizing parameters

Customers/ Factors	City driving customer			Mixed driving customer			Long range driving customer			Shared mobility customer		
Battery Variant (<i>kWh</i>)	18	36	54	36	54	72	36	54	72	54	72	90
Traction force (<i>N</i>)	4270	4485	4626	6838	7066	7294	10060	10284	10562	7294	7522	7750
Gear ratio	7.91			7.52			6.8			7.52		
Torque (<i>Nm</i>)	167	174	181	309	319	330	542	558	573	330	340	350

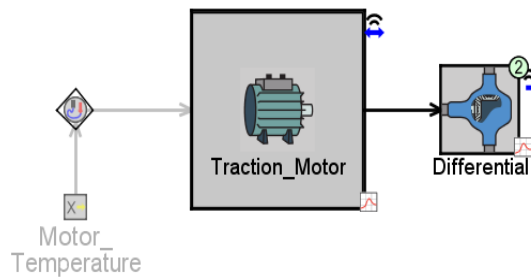


Figure 3.9: Traction motor model in GT-Suite

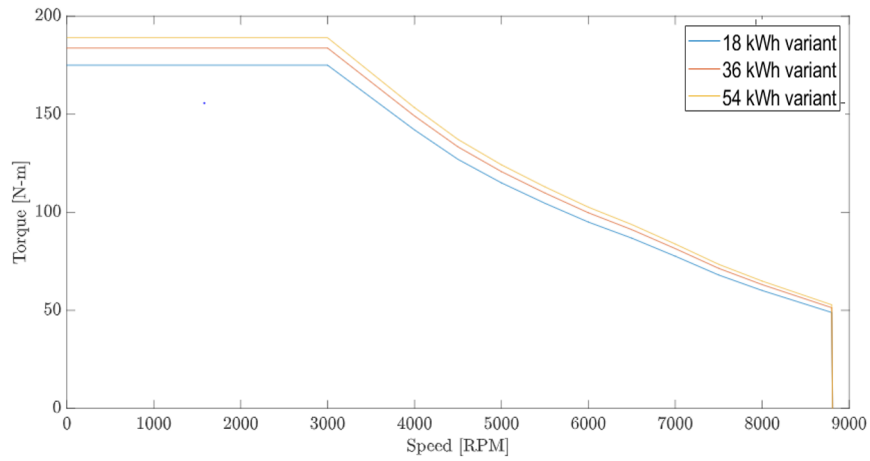


Figure 3.10: Electric machine Torque as a function speed for City driving customer

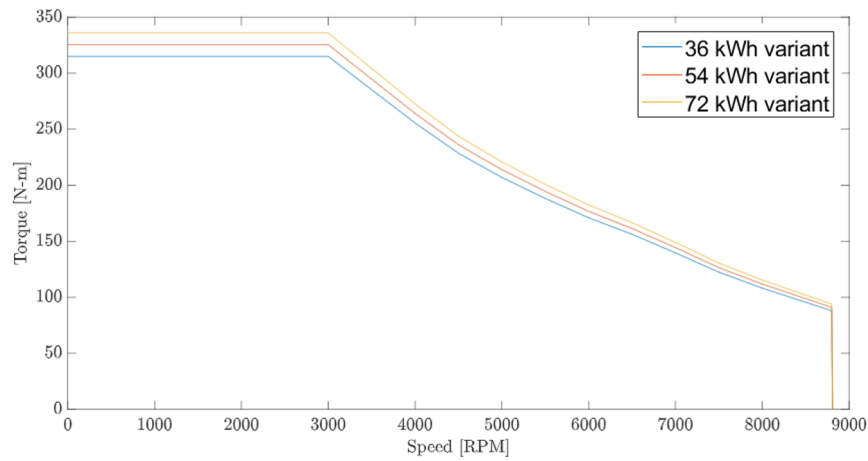


Figure 3.11: Electric machine Torque as a function speed for Mixed driving customer

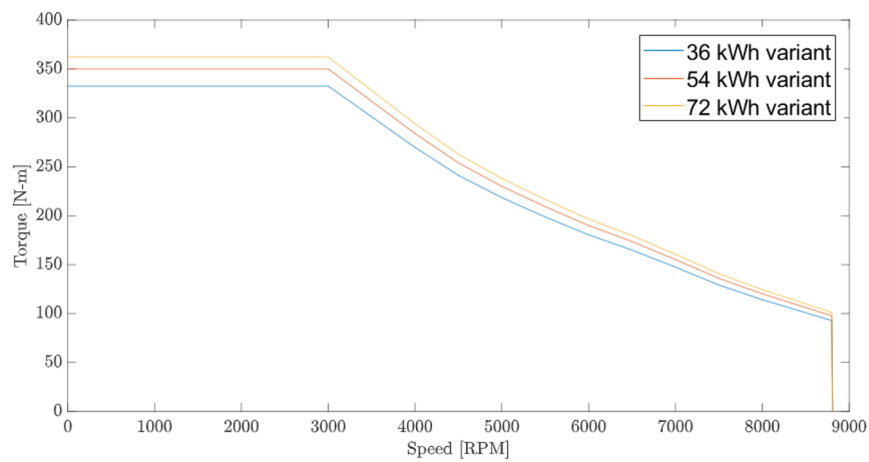


Figure 3.13: Electric machine Torque as a function speed for Shared mobility customer

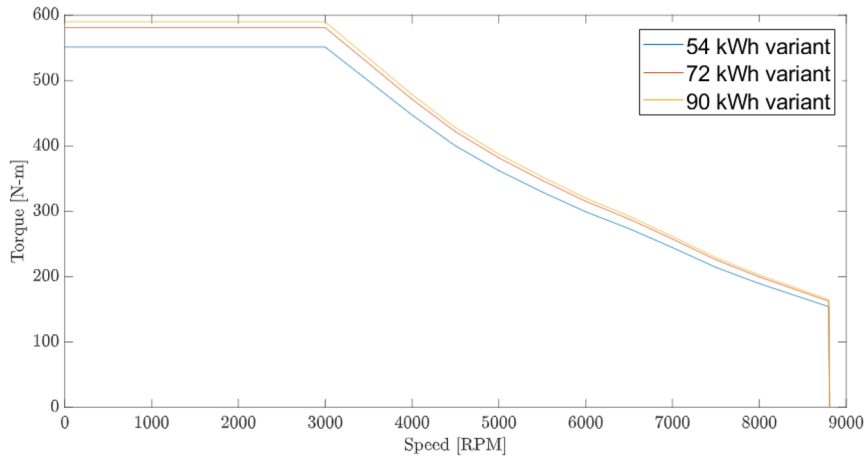


Figure 3.12: Electric machine Torque as a function speed for Long range driving customer

3.2.3 Brake Controls

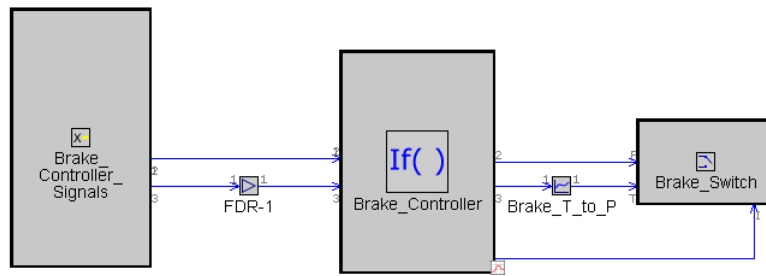


Figure 3.14: Battery controller model in GT-Suite

Generally, the braking structure of the cars will be hydraulic technology. Although this conventional braking approach causes a lot of energy waste and unwanted heat during braking. Accordingly, the development of the regenerative braking in electric vehicles has overcome these problems and help in save some energy during braking and increase in efficiency of the car. In generative mode, the traction motor acts as a generator and convert kinetic energy to electric energy to restore the batteries. And at the same time, this brake controller controls the speed of the vehicle and calculates the torque which is requested by the driver model and fed back into the batteries during regenerative mode and this helps in increasing the efficiency of the vehicle and saving some part of energy in an electric vehicle. And the simple brake controller model is shown in Figure 3.14

3.3 Battery thermal management system

Battery thermal management is the system level model which consists of following circuits

- High temperature cooling circuit (HT)
- Low temperature cooling circuit (LT)
- Intermediate refrigeration circuit
- Cabin air circuit
- Under hood air circuit.

The main aim of battery thermal model is to maintain the battery temperature within certain limits. Connection to the HT and LT circuits depends on the internal battery temperature of the battery pack. If the battery temperature is below 14° than battery pack is connected to HT circuit, if the battery pack temperature is above 14° than the battery pack is connected LT circuit. The HT and LT circuits are connected by the intermediate refrigeration circuit. Cabin air circuit and Under hood air circuit are studied but as considered as black box. The same model is used in all 12 powertrains.

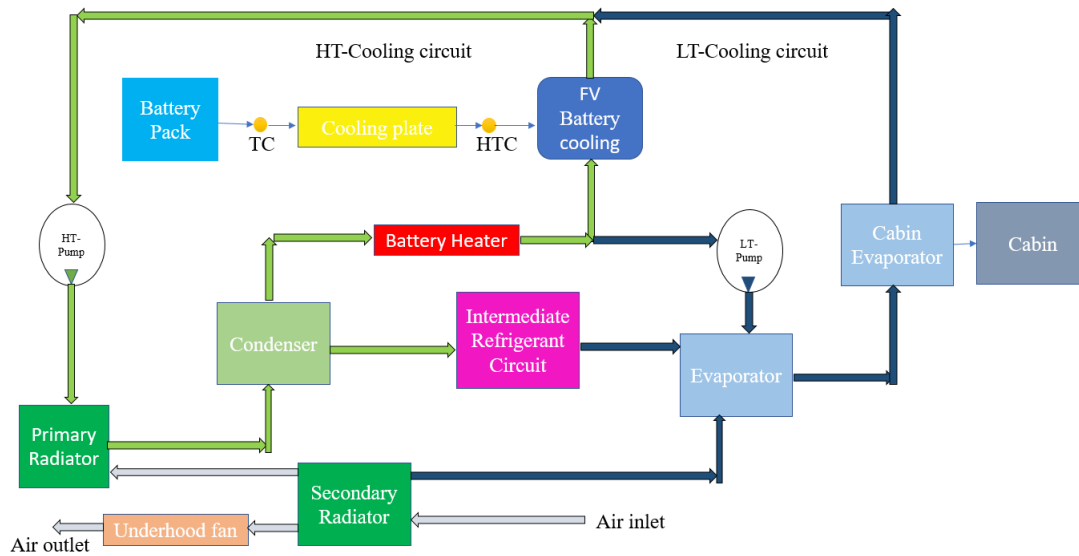


Figure 3.15: Illustration of battery thermal management as modelled in GT-Suite

Figure 3.15 represents the battery thermal management model in GT-Suite. The electric pump model in GT-Suite is based on the performance data which is inter-dependent on pump speed, flow rate, pressure rise, and efficiency. The main work of the pump is to maintain constant increase in the pressure in order to maintain the flow motion. Battery heater component is present just before the battery pack which helps in the heating the coolant before it is sent to the battery pack in case of cold start and cold ambient conditions. The heater is modelled in the straight pipes which lead to the heat addition object in GT-Suite environment. As shown in the Figure 3.15 thick arrows represents pipe connection in GT-Suite environment. Light thick green arrows represents HT-cooling circuit which consists of primary radiator, condenser, dark blue arrows represents LT-cooling circuits which consists

of secondary radiator and evaporator. Blue thin arrows are the thermal connections. Thermal conduction (TC) heat transfer takes place between the battery pack and the cooling plate and thermal convection (HTC) heat transfer takes place between cooling plate and flow valve (FV) which stores coolant when the circuit is turned off.

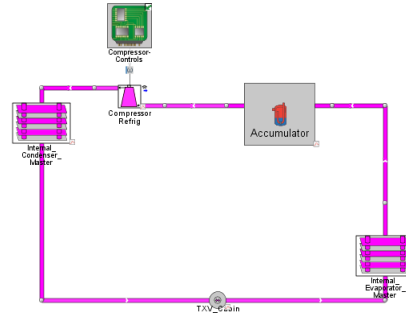


Figure 3.16: Representation of intermediate refrigerant circuit in GT-Suite

HT and LT cooling circuits are connected by intermediate refrigerant circuit which is shown in the Figure 3.16. In cooling mode evaporator removes heat from the cabin and the battery circuit. In heating mode, heat is transferred from the ambient environment through a second radiator and supplied to the HT cooling circuit, where it is used to heat the battery pack. So, HT and LT cooling circuits with battery heater helps battery to maintain the optimum working temperature.

3.4 Simulation Results

In this section, the results from the simulations of all 4 different customers with three battery variants have been presented and the analysis of each individual customer will be explained in this section. Both machine feature and driving cycle has been kept constant and all the simulation was carried under a standard temperature of 14 degrees for all the four customers to fulfil the requirements of the individual customers and the simulation results are shown in the Figures 3.17, 3.18, 3.19, 3.20 respectively. The machines were tested for a steady-state condition at a different top speed of the vehicle with the proper cooling system for all customers and performance results as shown in the above figures.

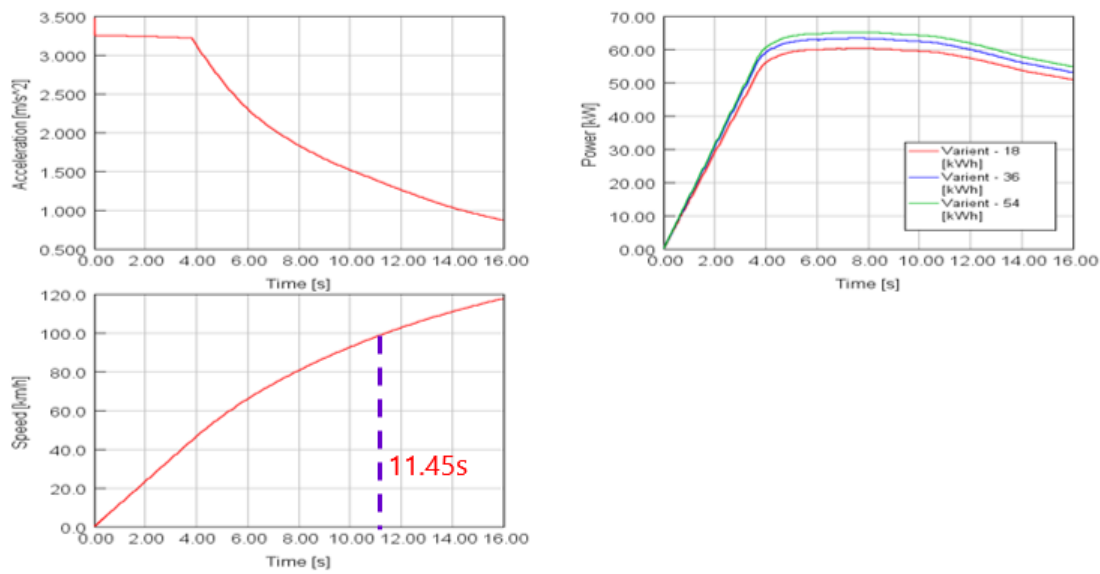


Figure 3.17: Power curves and performance results of city driving customer

The sizing of the machines is done for each customer using torque multiplier in the GT-Suite based on the requirement of the vehicle. For city driving customers the required initial acceleration is 3.5 m/s^2 and better performance in the speed curve to accelerate the vehicle speed from 0-100kmph than the requirement for city customer as mentioned in Table 2.2 this is because to meet the required performance of the electric motor. The required initial torque is 175 N/m this was fulfilled by an electric motor with the maximum speed of around 9000 rpm. Since there are some losses in the motor and in the powertrain model the simulation results were varied and the power curves and performance results of city driving customers for different variants as shown in the Figure 3.17.

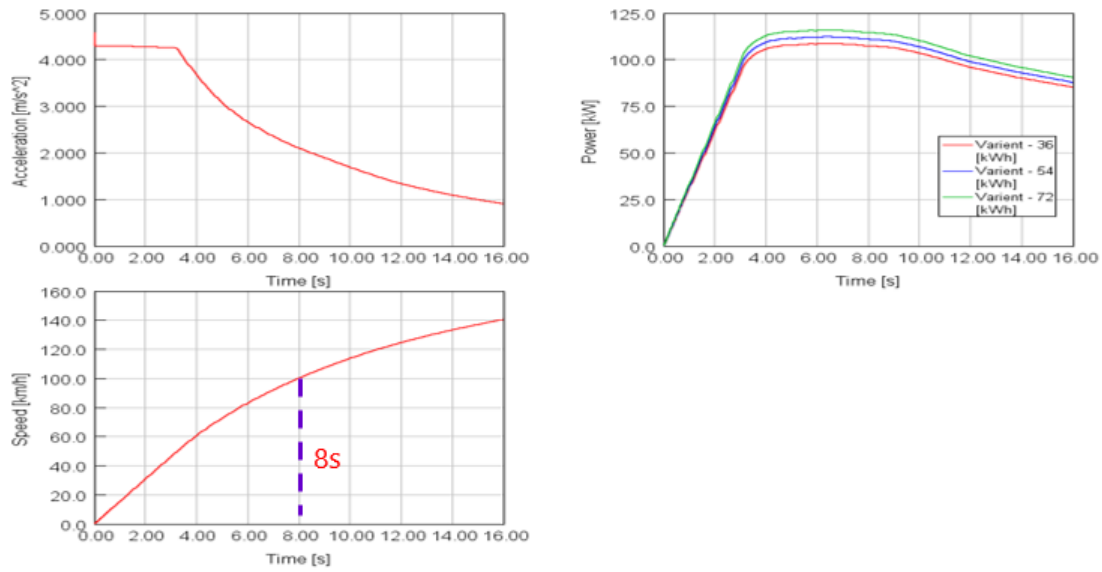


Figure 3.18: Power curves and performance results of mixed driving customer

For mixed driving customers the performance and the power requirement strategy are a bit high than comparing to city driving customers. The required initial acceleration is 4.5 m/s^2 , and speed to accelerate the vehicle from 0-100 kmph is 8s this shows better performance than the requirement shown in table 2.2, this is because to meet the required performance of the electric motor. The computed torque to accelerate the vehicle is 310 N/m and by using the torque multiplier in GT-Suite the size of the motor is increased. And the performance and power curves of different variants of mixed driving customers as shown in Figure 3.18

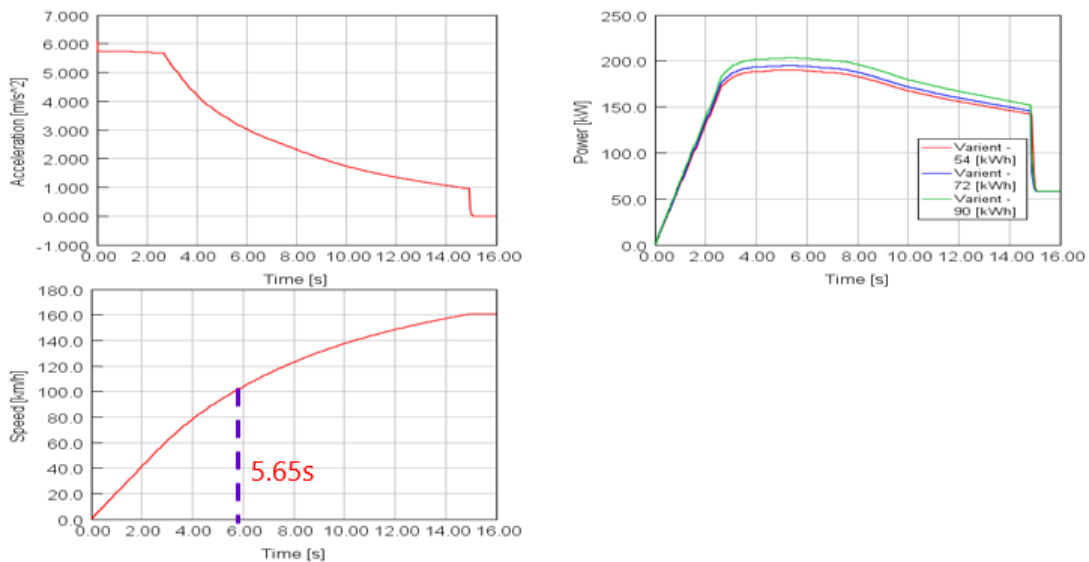


Figure 3.19: Power curves and performance results of long range driving customer

In long-range driving customer, the power and initial torque requirement is high when compared to all other three customers. Required torque of the motor was

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530N/m to drive the vehicle and this sizing has been done using torque multiplier in GT-Suite. From the simulation results of speed curve there is a noticeable changes in the acceleration performance from 0-100kmph than the requirement as shown in the table 2.2 this is because to meet requirement of electric motor. Simulated results of power curves and performance results are shown in Figure 3.19

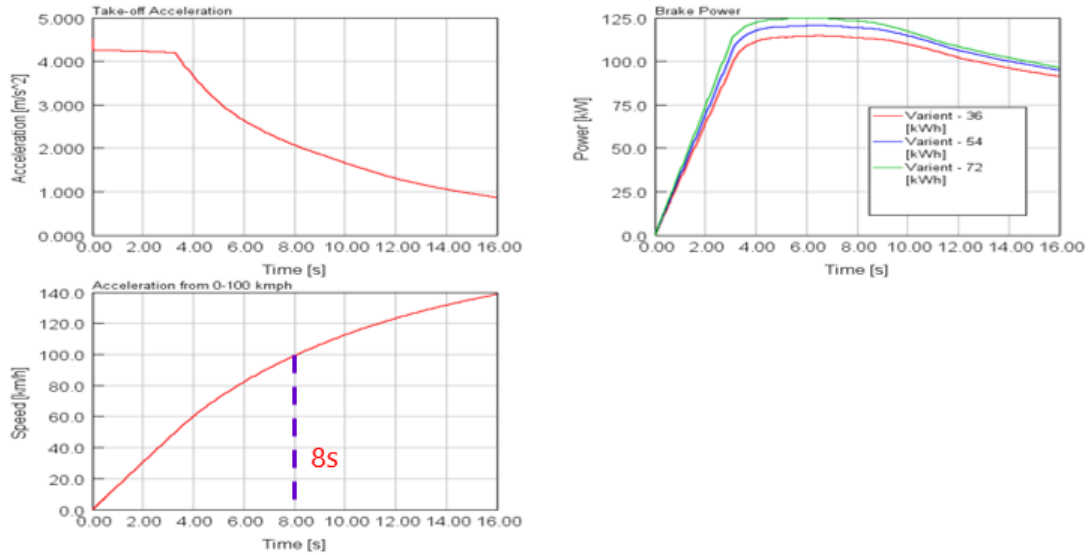


Figure 3.20: Power curves and performance results of shared mobility customer

In this shared mobility customer the battery model and the arrangements of the cells in series and parallel was kept same as like mixed driving customer only difference comes in the part of the vehicle model where the masses of the vehicle gets varied and lead to changes in the performance requirement of the vehicle. Since the mass of the vehicle is increased in this shared mobility customer the required initial torque will be more to accelerate the vehicle at 4.5 m/s^2 and to reach the acceleration from 0-100 kmph this takes 8s and seems to be better than the requirement as shown in the table 2.2 this is because to meet the required performance of the motor and simulations results of power curves for three variants and the performance results as shown in the Figure 3.20

3.4.1 Simulation results of battery model

The main objective of the simulations was to find the energy consumed by the battery per kilometer for that respective range. The overall outright of the battery-electric model is shown in Figure 3.7. The major put-in parameter of the battery model is cycles of discharge and charge currents, keeping these parameters as a reference the variation of the state of charge, battery voltage, battery current, and temperature have been examined and shown in the Figure 3.21 respectively. In this thesis project, certain parameters have been restricted to some values i.e the voltage drop in the battery model should be in between 300-330V, and distribution of a driving range of the vehicle can be calculated for 90% of SOC (95%-5%) and the input cell capacity is kept constant for all models i.e. 56Ah.

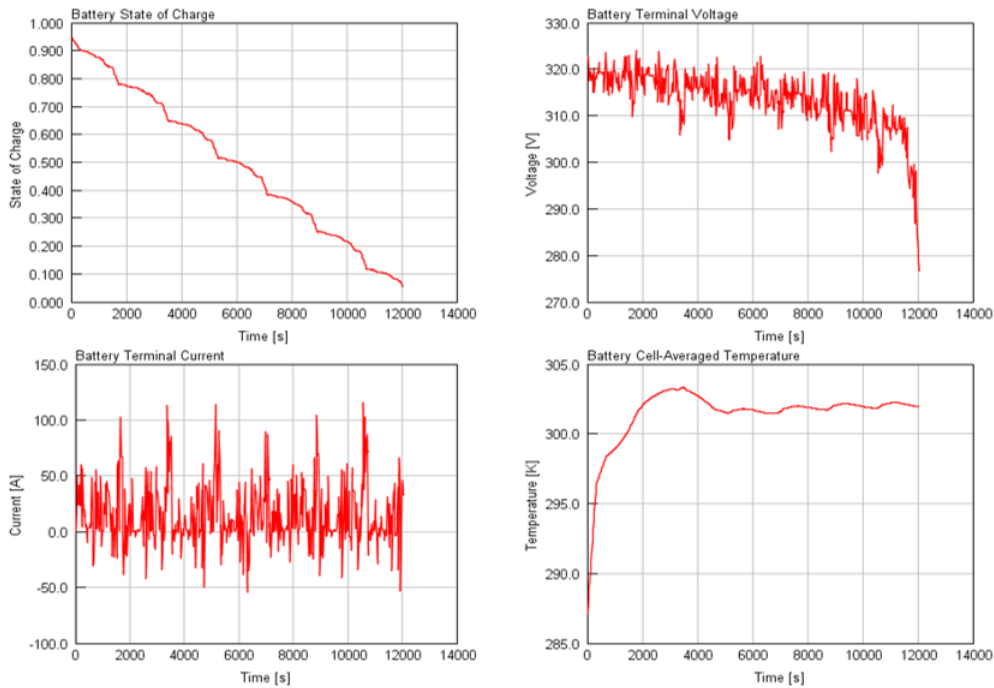


Figure 3.21: Simulation results of traction battery for city driving customer

However, the characteristics features and the properties of the cells remains the same for all 12 different models and only the arrangement of the cells is being varied for each individual customer based on the performance requirement of the vehicle, and the simulated results of each vehicle model is as shown in the Figures 3.21, 3.22, 3.23, 3.24 respectively. Since there all 12 different models with different requirements investigation was carried out to estimate the total driving range for each customer this can be done taking consideration of multiple driving cycles in the vehicle model. As mentioned in the above paragraph the main input for the battery-electric model is a cycle of charge and discharge currents. When the battery is discharging then a positive input of current is being generated and vice versa when its charging. For city driving customer the capacity of the battery is very less, since the vehicle

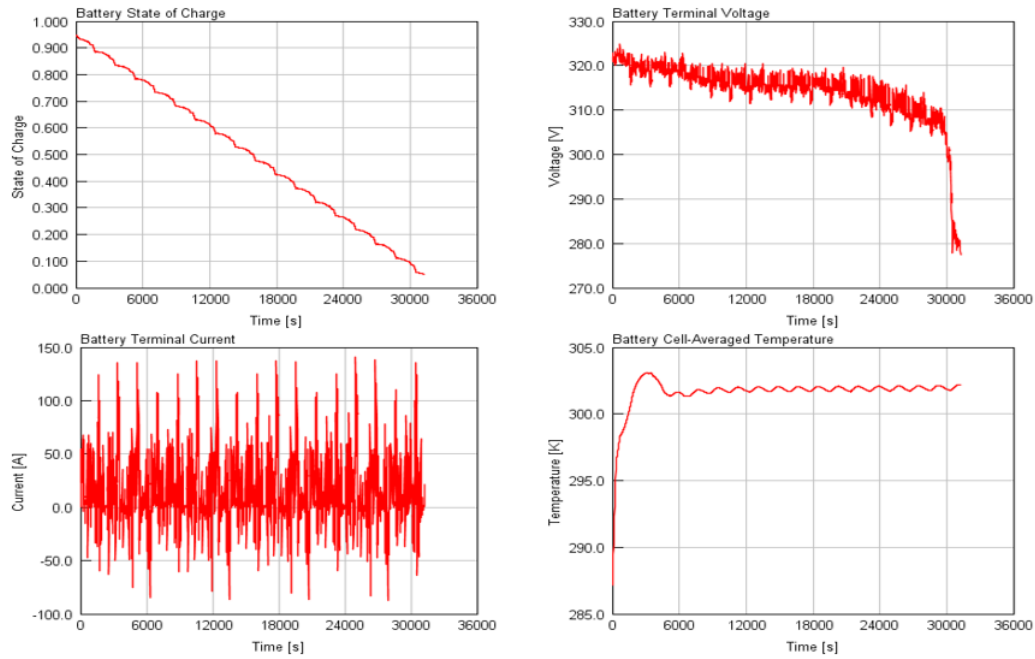


Figure 3.22: Simulation results of traction battery for mixed driving customer

moves within the city limits and this ranging from 18kWh to 56kWh, 56 cells were being connected in series and 1,2,3 cells have been connected in parallel for three different variants and the simulation has been carried out using GT-Suite. Here in this model, the state of charge can be kept constant from 95-5 % and multiple driving cycles are being used to calculate the total distance traveled by the vehicle, and the simulation results of the battery model are shown in Figure 3.21. From Figure 3.21 it is observed that there is a sudden high discharge of current after the 1800 s, during this spell there is some amount of charge that will be lost and the state of charge goes down to 5%. However all the simulation was carried out for 36019 s and vehicle will automatically stop when the battery charge goes below 5% this will be controlled using the battery controller, and the variation of the state of charge concerning to driving cycle is shown in the Figure 3.21.

Figure 3.21 also shows the variation of the temperature with respect to driving cycle. It is observed that the temperature of the battery increase high in the beginning because of insufficient cooling in the beginning and eventually constant over the period time. During discharging the voltage drops constantly from 325V to 310 V, since the voltage is a function of the discharge rate the battery is discharged at a higher rate and voltage drops quickly to 275 V and battery charge decreases to 5%. Energy consumption and depleted energy for city customer is shown in the Table 3.5

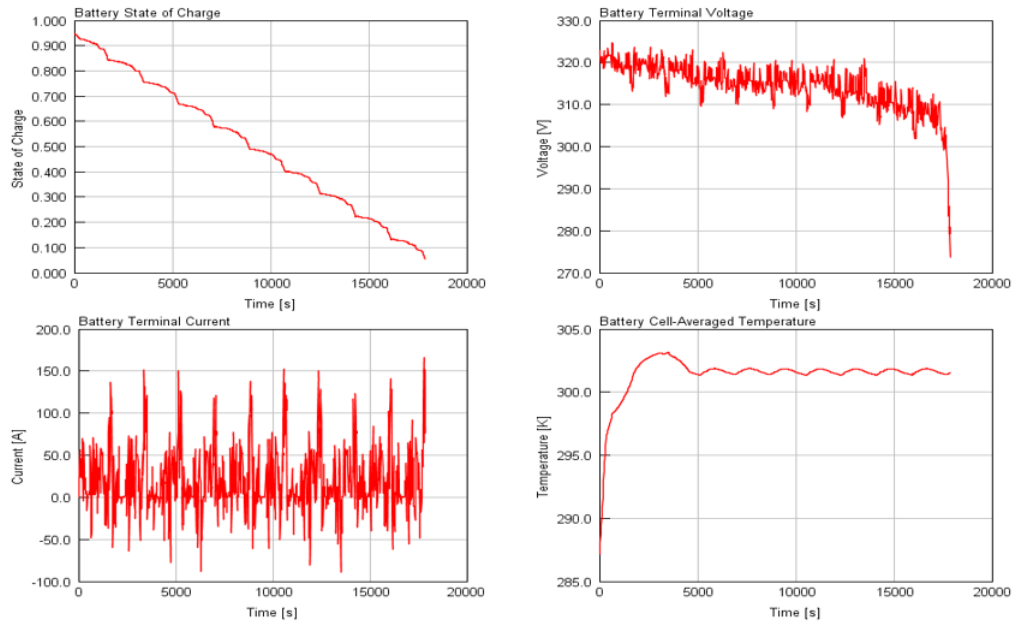


Figure 3.23: Simulation results of traction battery for shared driving customer

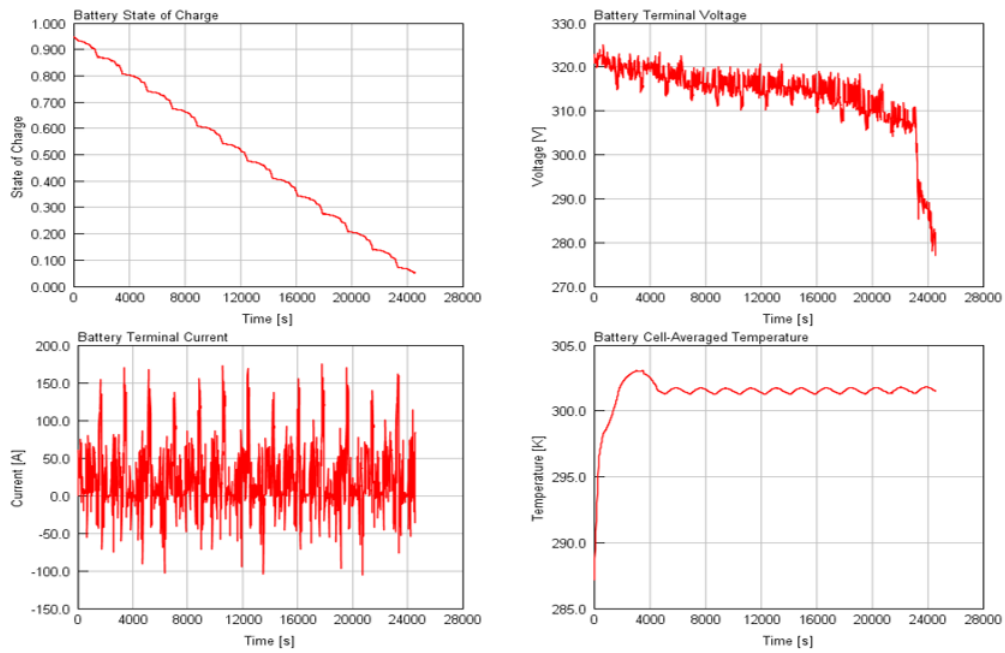


Figure 3.24: Simulation results of traction battery for long driving customer

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The simulations results for the rest of the models were almost same and shown in the figures 3.22, 3.23, 3.24 respectively. However, in these figures the variation of the current during discharging and charging, temperature and voltage drop during discharging were almost same for mixed, shared and premium customer. The difference in these figures is only between the state of charge and the simulated duration of the individual vehicle and this can be used to calculate the total driving range of the individual customer.

Table 3.5: Summary of traction battery data

Factors	City driving customer			Mixed driving customer			Long range driving customer			Shared mobility customer		
Variants (kWh)	18	36	54	36	54	72	54	72	90	36	54	72
Series cells	96			96			96			96		
Parallel cells	1	2	3	2	3	4	2	3	4	3	4	5
Nominal Voltage (V)	309			300			300			303		
Depleted energy (kWh)	16	32	48	32	47.5	63	47.5	63.28	79	31.62	47.5	63
Driving range (kWh)	151	277	394	242	341	437	311	413	465	215	298	384
Energy consumption (Wh/km)	106	115	121	132	139	144	152	154	169	148	159	164

4

Total Cost of Ownership

4.1 Introduction

Electric vehicles have high potential to eliminate green house gases and emissions of pollutants. It is expected in the future, sales of EV's to increase by 31% compound annual growth rate from 2017-2030 [17]. However it is difficult to predict the future cost of the EV's but it can be modelled by using various factors, which will be discussed in further sections. In this thesis work we examine TCO based on driving range distribution for large data set of driving profile. TCO is the cost estimate which includes the annualized capital cost for the vehicle, the annual operating cost, maintenance cost and the annual energy cost which is aimed at understanding the virtual cost of the vehicles [18]. We look at four different customer profiles, each customer with three different battery sizes and with time frame of five years to derive TCO. We then compare TCO for different customer with varying battery sizes, and this estimates will be an integral part of buying decisions made by customers. TCO is useful calculation to customers and companies alike to assess direct or indirect cost associated with the purchase [19].

4.2 Methodology

In this section we explain general approach to compute TCO for different customer profiles which is distinguish between the vehicle, battery and variables. The customers are adapted as shown in the Table 2.1 based on the driving pattern and charging preference's. Each customer is divided into five important categories based on the driving pattern and based on the charging preference's customers are divided into two variables and the values are shown in the Table 4.1. Here each of the customers use three different battery packs based on kWh capability. The general method followed in arriving TCO for different customers are,

- Collecting daily driving distance data and deriving driving range distribution curve for different customers.
- Deriving energy distribution curve from driving range distribution data. The data required for energy consumption for different driving pattern are obtained from simulations results which is presented in Table 3.5
- Integrating surface area of the energy distribution curve to find the amount energy required to satisfy the conditions of driving categories.
- Applying cost (Euros) for powertrain components and for the variables such as value of waiting time and value of having to stop.

4. Total Cost of Ownership

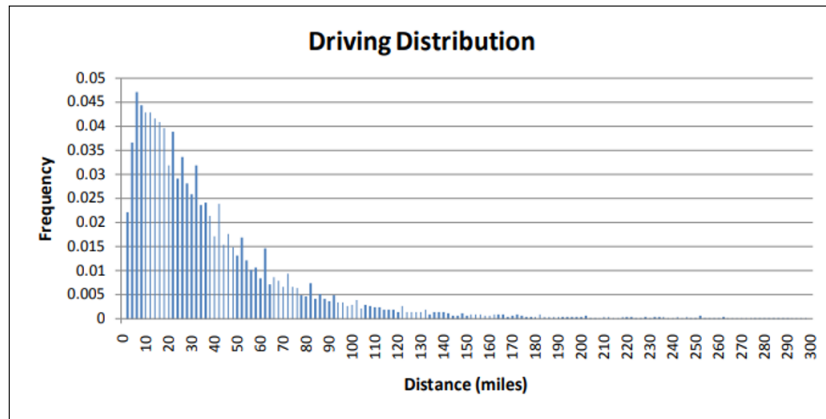
- Determining battery depreciation based on number of full cycles of the battery, electric motor depreciation and vehicle depreciation.
- The Total cost of Ownership (TCO) over five years of ownership is calculated based on driving range distribution.

Table 4.1: Customer model with different driving categories and economic priorities

Charging preference	Customers				Variables
	Cost focused customer City driving	Cost focused customer Mixed driving	Cost focused customer Long range driving	Cost focused customer Shared mobility	1.Value of waiting time: 15 €/h 2.Value of having to stop: 10 €/stop
	Premium customer City driving	Premium customer Mixed driving	Premium customer Long range driving	Premium customer Shared mobility	1.Value of waiting time: 30 €/h 2.Value of having to stop: 50 €/stop
Categories	1. Yearly driving distance: 10.000 km 2. Typical driving distance: 25 km 3. Longest driving distance: 300 4. Number of driving days per year: 200 5. Driving range distribution	1. Yearly driving distance: 15.000 km 2. Typical driving distance:49 km 3. Longest driving distance: 500 4. Number of driving days per year: 250 5. Driving range distribution	1. Yearly driving distance: 30.000 km 2. Typical driving distance: 80 km 3. Longest driving distance: 800 4. Number of driving days per: 300 5. Driving range distribution	1. Yearly driving distance: 60.000 2. Typical driving distance:90 3. Number of driving days:350 4. Longest driving distance: 500 5. Driving range distribution	

4.2.1 Driving range distribution

The driving range is key characteristic of EV, which has positive relationship with the EV market share [20]. So, driving range distribution curve is important factor in our studies and the entire computation of TCO depends on this curve. Figure 4.1 shows the distribution of daily driving distance based on national statistics and was generated using 2001 National Household Travel Survey (NHTS) database [22]. This NHTS data is used as reference data to derive the driving range distribution curve for all four customer profiles.



**Source: National Renewable Energy Laboratory*

Figure 4.1: Distribution of daily distances

Initially the data set was collected from Future Automotive Systems Technology Simulator (FASTSim), which provides information to compare powertrain in simple way [21]. From this data set frequency was normalized and miles are converted into kilometers to get a plot which is shown in Figure 4.2 on the left hand side. And depending upon the customer the number of driving days value which is mentioned in the Table 4.1 is multiplied to normalized frequency, to get driving range distribution curve which is shown in Figure 4.2 on the right hand side. The important outcomes of this curve are,

- It gives information regarding number of driving days in an year.
- The surface area under this curve gives information regarding total number of kilometers driven in an year.
- It gives information regarding the longest driving range in a year.
- Typical driving distance driven for more number day in an year.

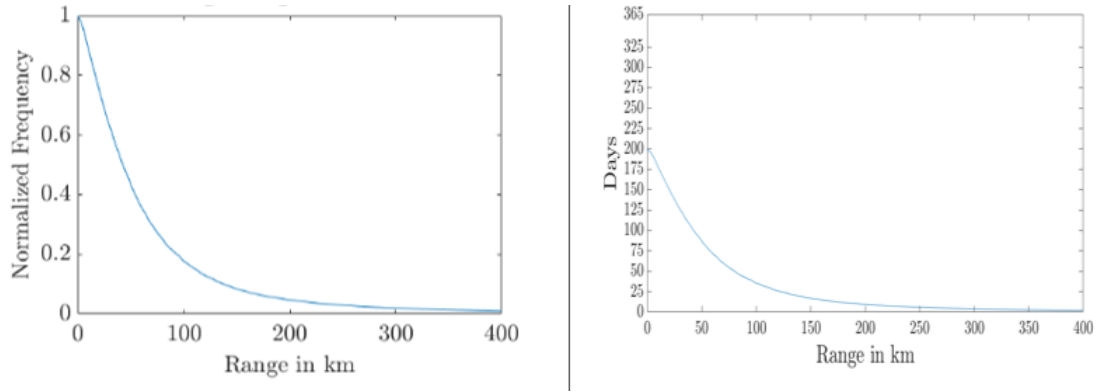


Figure 4.2: Example for driving range distribution with normalized frequency and number of days

4.2.2 Energy distribution curve

The energy distribution curve is derived from the driving range distribution plot as shown the Figure 4.3. To convert driving range distribution plot into Energy distribution curve, a set of data points of energy was derived by linear multiplication method by using depleted energy from the battery which is obtained through simulations and depleted energy values are presented in the Table 3.3.

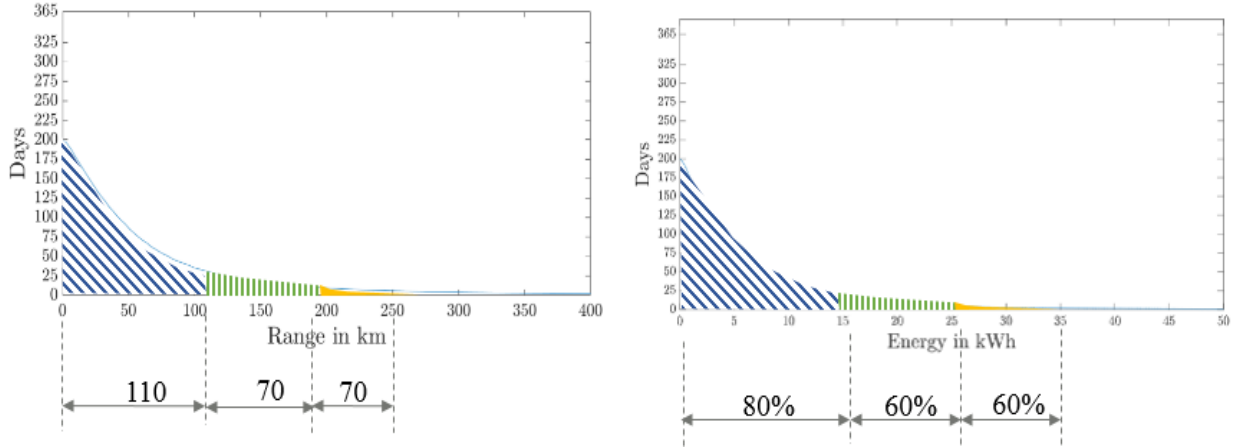


Figure 4.3: Example of energy distribution curve (right) derived from driving range distribution (left)

This study assumes, battery is always fully charged and this charge is always done at home (or over night charge at house). From house charging the BEV can consumes 80% of energy from the battery of its total available energy and the vehicle recharges upto 60% each time when battery energy capacity is totally depleted and this charge is done at fast charging stations (charge at public places), where power of the fast charging depends on the customer profile. The reason behind this, BEV is always charged before it discharges its total available energy capacity (i.e In practical BEV battery recharge is done before SOC lower limit reaches 5%) and it can be observed in the Figure 4.3. For example, consider BEV with small battery size of energy capacity 18 kWh. Suppose 18 kWh battery can go upto 110 km of range. But the destination is at 250 km, than this BEV has to charged for two times to reach the destination. Blue shade represents the range of BEV it can travel, in driving range distribution curve and in energy distribution curve it represents the energy required for the battery to travel 110 km when BEV is charged at house. Green shade represents energy required at public fast charging stations, let us call it as 'Second fast charging' which is shown n the Figure 4.3. The major outcomes of the energy distribution curve is listed below.

- The total energy required to reach the destination.
- By integrating blue shaded surface area, the amount of energy charged at home per year can be determined.
- By integrating green and yellow shaded area, the amount of energy required at fast charging can be determined.
- The number of days needed to stop and charge the car in a year can be determined.

- Waiting time for charging at public fast charging stations can be determined .

4.2.3 Charging preference variables

- **Value of waiting time for fast charging:** It is the virtual cost which reflects the different charging preferences of the customer. Important assessment carried by using this variable which presented in the Table 4.1 is how does the actual TCO varies by adding this virtual cost.
- **Value of having to stop for charge:** It is also the virtual cost which reflects the different charging preferences of customers and presented in Table 4.1. To charge an BEV while travelling most of times we don't get charging stations immediately when ever we want. So, for that sometimes we need to deviate the route, in which it costs time and money for the customers.

4.2.4 Model assumptions

A TCO analysis relies heavily on assumptions. All the assumptions of the TCO are presented in the Table 4.2. These assumptions remains same for all the customer profiles.

Table 4.2: Cost and general assumptions for TCO model

Cost assumptions	
Cost of battery pack (€/kWh)	150
EM cost (€/kW)	18
Initial Cost of vehicle without driveline for city driving customer (€)	10.000
Initial Cost of vehicle without driveline for mixed driving (€) customer	20.000
Initial Cost of vehicle without driveline for long range customer (€)	25.000
Initial Cost of vehicle without driveline for shared mobility (€) customer	35.000
Electricity cost for charging at home (€/kWh)	0,15
Electricity cost for fast charging at public places (€/kWh)	0,5
Maintenance cost (€/km)	0,03
General assumptions	
Fast charging power for city driving customer(kW)	60
Fast charging power for mixed driving customer (kW)	105
Fast charging power for long range driving customer (kW)	150
Fast charging power for shared mobility customer (kW)	105

4.2.5 TCO Model

The TCO model constructed in this study contains individual factors that have each been defined, analyzed and computed into results.

- **Actual TCO:** TCO including depreciation cost, maintenance cost and cost of electricity, and it may also be called as tradition approach of computing TCO.

$$TCO_{Actual} = \frac{D + CE + MC}{N_{years}} \quad (4.1)$$

- **Virtual TCO:** Actual TCO with cost for having to stop and cost for waiting (virtual cost). Virtual TCO is an attempt to take customer preference into account.

$$TCO_{Virtual} = \frac{D + CE + MC + WT + S}{N_{years}} \quad (4.2)$$

Where, $TCO_{Virtual}$ - Total cost of ownership of BEV with virtual cost (€/km); TCO_{Actual} - Total cost of ownership of BEV without virtual cost (€/year); D - Depreciation (€/year); CE - Cost of electricity to charge (€/year); MC - Maintenance cost (€/year) N_{years} - Number of years ownership is calculated; WT - Cost of waiting for fast charging (€/year); S - Cost of have to stop for charging (€/year).

The approach for each terms in the Equations 4.1, 4.2 will be detailed in the following subsections.

4.2.5.1 Depreciation

Depreciation rate is the difference between the initial price and the resale price of the product after a period of time. Depreciation has great importance for the new vehicle buyers. Depreciation is complex process which varies significantly with brands, driveline design and variants [19]. Depreciation is given by equation,

$$D = DB + DM + DV \quad (4.3)$$

Where, DB - Depreciation of battery (€/year); DM - Depreciation of EM (€/year); DV - depreciation of vehicle without driveline (€/year).

- **Depreciation of Battery:** Depreciation of the battery is the amount of depreciation that is taken at a certain depreciation rate to compensate for the loss of the battery after it has been used for a certain period of time [23]. Literature survey says that some analysts have made assumptions that battery may not need replacement during useful life of the vehicle, other assume that manufacturer's warranty sufficiently characterizes the expected battery lifetime. So, a review of these and other estimates of battery life leads to a conclusion that a traction battery is viable for use in electrified vehicles with advanced battery management systems for a period exceeding 4,400 battery charge/discharge cycles [24].

But, in this study we consider following equations to calculate the battery depreciation which depends on both time and number of full cycles of the battery,

$$DB = \frac{\text{Cost of battery pack} - RV}{N_{years}} \quad (4.4)$$

$$RV = \text{Cost of battery pack} * \left(1 - \frac{N_{years}}{A} - \frac{B_{cycles}}{B}\right) \quad (4.5)$$

$$B_{cycles} = \frac{E_d * Y_{distance} * N_{years}}{E_b} \quad (4.6)$$

Where, RV - Residual value (€) ; B_{cycles} - Number full battery cycles utilized in 5 years; E_d - Depleted energy form the battery (Wh/km); $Y_{distance}$ - yearly driving distance; E_b - Energy capacity of the battery (kWh).

The important assumption involved in the Equation 4.5 is:

*A = 20 years - Battery life span.

*B = 1500 cycles - Number of full cycles of battery for 20 years.

- **Depreciation of Motor:** The depreciation rate for the EM is assumed to 50%. and it is calculated by equation,

$$DM = \frac{EM \text{ cost} * DR}{N_{years}} \quad (4.7)$$

Where, DR - depreciation rate in %.

- **Depreciation of vehicle without driveline:** The depreciation rate for the vehicle without driveline is assumed to 50%. and it is calculated by equation,

$$DV = \frac{V_{cost} * DR}{N_{years}} \quad (4.8)$$

Where, V_{cost} - Initial Cost of vehicle without driveline (€)

4.2.5.2 Cost of electricity to Charge BEV

To find the cost of electricity, novel energy distribution model is used which is discussed in the section 4.2.2 . From the Figure 4.3, for simplification we consider the integrated surface area under the blue shade as A_{blue} and this depicts energy required to charge at home (E_{home}). Integrated surface area under yellow and green curve considered are as A_{yg} which depicts energy required to charge at public places (E_{public}). The sum of these two energies gives total energy required for charging BEV to reach desired destination. The energy required varies form one customer profile to other depending upon the driving categories mentioned in the Table 4.1. Trapezoidal integration method is used to integrate surface area under energy distribution curve. As depicted in the Table 4.2 we have assumed two different costs for charging at home and charging at public places. The following equations are used to calculate

the cost of electricity for Charging ($Cost_{Elc}$),

$$Cost_{Elc} = Cost_{home} + Cost_{public} \quad (4.9)$$

$$Cost_{home} = E_{home} * Electricity\ cost\ for\ charging\ at\ home \quad (4.10)$$

$$Cost_{public} = E_{public} * Electricity\ cost\ for\ fastcharging\ at\ public\ places \quad (4.11)$$

$$E_{home} = \int_a^b A_{blue} dA \quad (4.12)$$

$$E_{public} = \int_a^b A_{yg} dA \quad (4.13)$$

4.2.5.3 Maintenance Cost

Cost of the maintenance is very difficult to quantify for many reasons as depends on the individual person and there is little history on maintenance of BEV's [25]. Some vehicle owners may perform regular maintenance while other owners may follow selective maintenance. Most of the cars come with minimum three years of warranty that covers various maintenance costs, therefore it will be very less during first three years. BEVs have fewer moving parts that need no oil or filter change and less brake pad tear due to its strong regenerative braking. Maintenance and repair cost has been estimated to be lower for BEVs compared to ICEVs [19]. In this study the maintenance cost depends on the yearly driving distance and it is assumed as 0.03 €/km and given by equation,

$$MC = 0.03 * Y_{distance} \quad (4.14)$$

4.2.5.4 Cost of waiting time for fast charging

The analysis of BEV driver's charging behaviour shows that drivers are sensitive to charging costs and duration. In general, several factors including cruising range limitation, recharging duration and frequency, charging methods, availability and accessibility of charging points can lead to a distinctive travel behaviour of BEV drivers when compared to ICEV which is fairly missing in the literature. For many of the driver to choose route attributes travel time and travel cost as well as fast charging related variables such as charging time and waiting time are significant determinants, if there is any increase in the value on a specific route leads to the negative effect on the selection of that route [26]. In this study we have assumed values for waiting time which is presented in the Table 4.1 which is based the customer charging preferences. To determine waiting time and what does it actually cost for customer, energy distribution model is used which is shown in the Figure 4.3 and the following equations are given below,

$$Time_{waiting} = \frac{E_{public}}{Fast\ charging\ power\ (kW)} \quad (4.15)$$

$$Cost_{waiting} = V_{waiting} * Time_{waiting} \quad (4.16)$$

Where, $Time_{waiting}$ - Waiting time for fast charging (H); $Cost_{waiting}$ - Cost of waiting time for fast charging (€/H); $V_{waiting}$ - Value of waiting time(€/H).

4.2.5.5 Cost factor consider for have to stop for fast charging

From the studies of the report 'The International Council On Clean Transportation (icct)' says that substantial charging infrastructure investments are needed to fill the charging gap. And the charging gap analysis from icct report explains that about 4 times more public charging infrastructure is required in 2025 than in 2017 to match the expected electric vehicle market growth [27]. Due to charging gap, for drivers sometimes it is hard to find the charging stations at public places. So, they need change the route which leads in increase in the commuting distance and time to reach the destination. These are the important factors which made us to consider this cost factor.

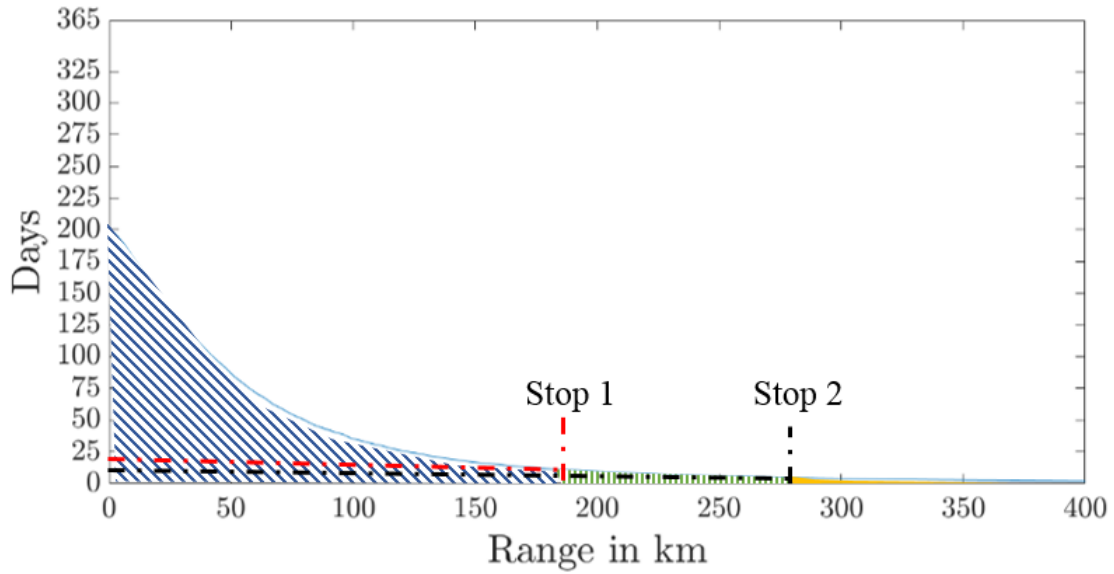


Figure 4.4: Example of energy distribution curve to read number of days have to stops in a year for charging at public places

We have assumed two different cost to stop based on the customer preferences which is mentioned in Table 4.1. Again energy distribution curve plays an important role to find this cost factor. As shown in Figure 4.4, to reach the destination two stops are required denoted by red and black dotted lines. From spotting that points on X-axis and reading the same point on Y-axis gives the number of days have to stop for charging to reach the destination and equation and the equations are given below,

$$Cost_{stop} = Value_{stop} * N \quad (4.17)$$

N - number of days have to stop for charging.

The entire TCO model is calculated by using above all equations and the results are discussed in chapter 5.

4. Total Cost of Ownership

5

Results and Discussion

We aimed to find how TCO of vehicle with different battery and EM sizing compares to each other in the 5 years of ownership model. Computation of relevant customer centric TCO model is a challenging task, especially in estimating the individual cost factor and when applying data available to customer. Depreciation rate was challenging factor to estimate as it is dependent on untold number of factors and can rapidly change over the ownership because what is on demand on the second hand car today does not necessarily to be the same in five years time. It is therefore possible that depreciation rate would be smaller or higher than what we have estimated in this thesis work. For TCO we follow the steps described in the methodology which is based on energy distribution curve. In this section results of TCO for different customer profile is presented.

From the simulations results, energy consumed by battery per kilometer for the city driving customer is different for all three variants which is shown in Table 3.5, based on the simulation result energy distribution curve is obtained. Figure 5.1 depicts the the driving range distribution for city driving customer with yearly driving distance of 10,000 km, total number of driving days 200, longest driving distance 300 km and typical commuting distance is 25 km in a day. This driving range distribution curve remains same for all the 3 variants in city driving customer profile.

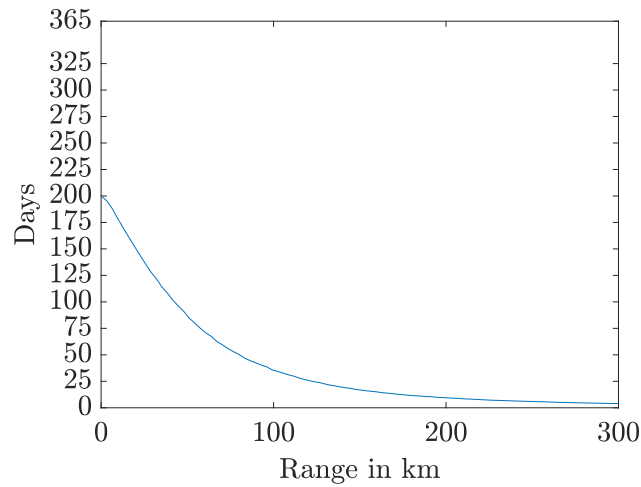


Figure 5.1: Driving range distribution for 18 kWh, 36 kWh and 54 kWh variants for city driving customer

Figure 5.2 shows the energy distribution for city driving customer with smallest battery size variant of 16 kWh. For a trip of longest commuting distance i.e. 300 km, this variant car has to be charged for two times in public fast charging station. The total energy required in a year for this driving range distribution is 1092 kWh. Energy required to charge at house is 987 kWh and at public charging stations is 105 kWh. Number of days to stop for fast charging are 13 days in a year. The total waiting time for fast charging at public places 1.75 hours.

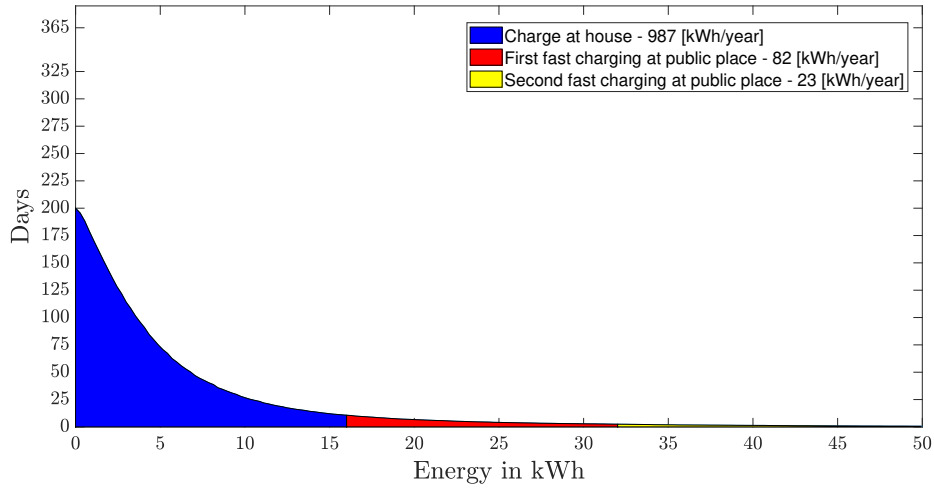


Figure 5.2: Energy distribution for city driving customer, 18 kWh variant

Figure 5.3 depicts energy distribution for city driving customer with medium battery size of 32 kWh variant. To reach longest driving distance, this variant car has to be charged for one time in public fast charging stations. Energy required to charge at house is 1004 kWh and public fast charging stations is 20 kWh. Number of day to stop for fast charging are 3 days in a year. The waiting time for fast charging 0.31 hours.

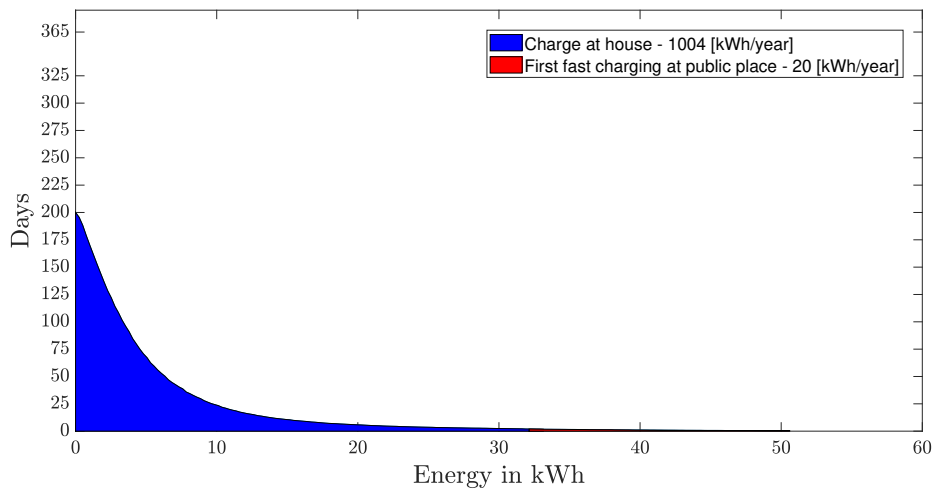


Figure 5.3: Energy distribution for city driving customer, 36 kWh variant

Figure 5.4 depicts energy distribution curve for city driving customer with large battery size 54 kWh variant. Longest driving range of 300 km can be reached without charging at public charging stations. The energy required to charge at house is 1200 kWh and the waiting time for charging at public places is zero.

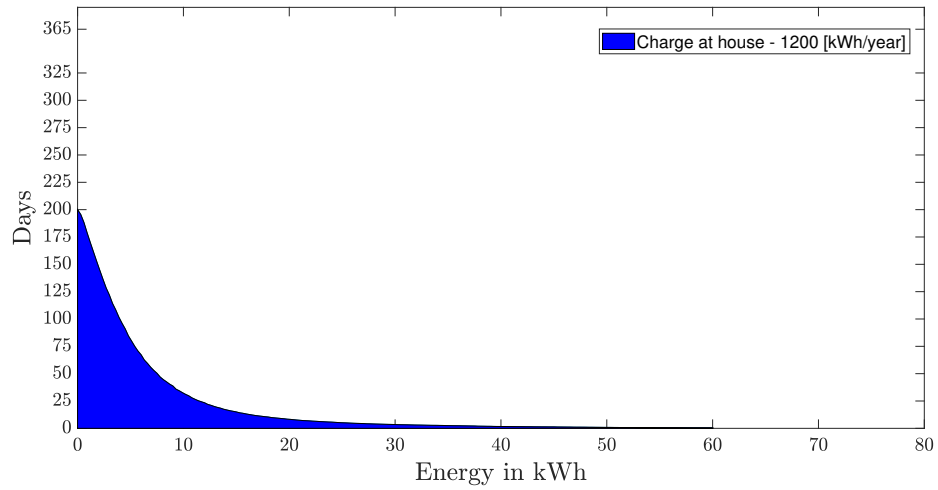


Figure 5.4: Energy distribution for city driving customer, 54 kWh variant

TCO for city driving, cost focused and premium customer with three different battery variants are depicted in the Table 5.1. The first analysis is comparison of Virtual TCO based on the battery size for both charging preferences. 36 kWh variant is clearly the most competitive BEV in this segment, although the TCO of other two variants are very close. 18 kWh variant seems to have too small battery as the result cost of waiting time is higher. 54 kWh variant has slightly higher battery size for this driving range distribution, although cost of waiting time is zero but the battery cost itself much higher than other two variants thus ending with higher TCO among all three variants. The 36 kWh (Mid-size battery) is more interesting for buying BEV. But in the second analysis i.e. between virtual TCO and actual TCO 18 kWh variant stands out to be the cheapest BEV. The actual TCO for cost focused and premium customer remains same, but for the premium customer they value more for waiting so they have higher cost for charging.

Table 5.1: TCO for city driving customer

City Driving			
Cost focused customer			
Variants (kWh)	18	36	54
Battery Depreciation (€/year)	241	385	453
EM Depreciation (€/year)	108	113.4	117
Vehicle depreciation (€/year)	1000	1000	1000
Electricity cost (€/year)	200	160	181.6
Maintenance cost €/year	300	300	300
Cost of waiting time (€/year)	26.38	4.72	0
Cost to stop for fast charging (€/year)	130	30	0
$TCO_{virtual}$ (€/year)	2006.14	1993.16	2061.67
$TCO_{virtual}$ (€/km)	0.20	0.199	0.206
Premium customer			
Variants (kWh)	18	36	54
Battery Depreciation (€/year)	241	385	453
EM Depreciation (€/year)	108	113.4	117
Vehicle depreciation (€/year)	1000	1000	1000
Electricity cost (€/year)	200	160	181.6
Maintenance cost €/year	300	300	300
Cost of waiting time (€/year)	52	9.26	0
Cost to stop for fast charging (€/year)	325	75	0
$TCO_{virtual}$ (€/year)	2227.52	2042.52	2101.67
$TCO_{virtual}$ (€/km)	0.227	0.204	0.210
TCO_{actual} (€/year)	1849.76	1958.43	2051.67
TCO_{actual} (€/km)	0.184	0.195	0.205

Figure 5.5 shows the plot for driving range distribution for mixed driving customer with yearly commuting distance of 15,000 km, longest driving distance of 500 km, with 250 driving days in year and typical daily commuting distance of 50 km.

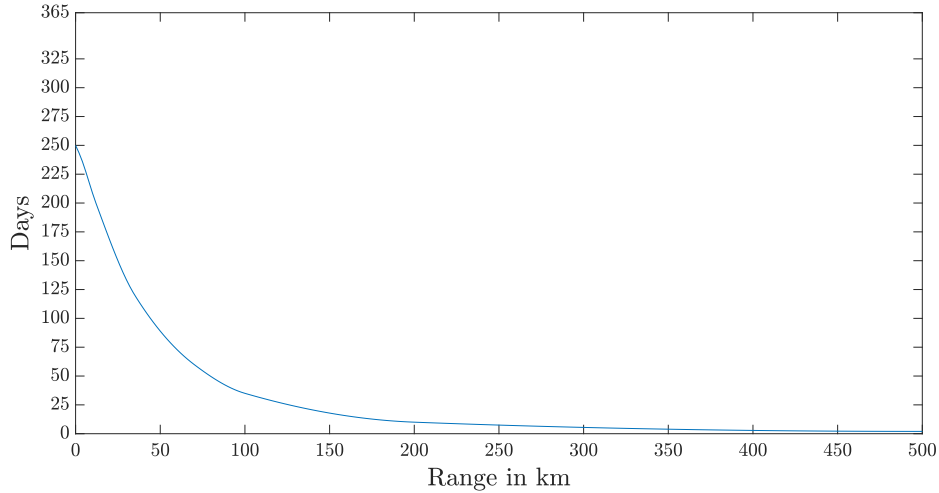


Figure 5.5: Driving range distribution of 36 kWh, 54 kWh and 72 kWh variants for mixed driving customer

Energy distributing curve for mixed driving customer 36 kWh variant which is small battery in this segment, is shown in the Figure 5.6. To commute longest distance i.e. 500 km, BEV has to charged for two times. The total energy required for above shown driving range distribution (Figure 5.5) is 2065 kWh. The energy required to charge at house 1895 kWh/year and at public fast charging stations is 170 kWh/year. Number of days have to stop for charging is 15 days in an year. The waiting time to charge BEV is 1.62 hours in a year.

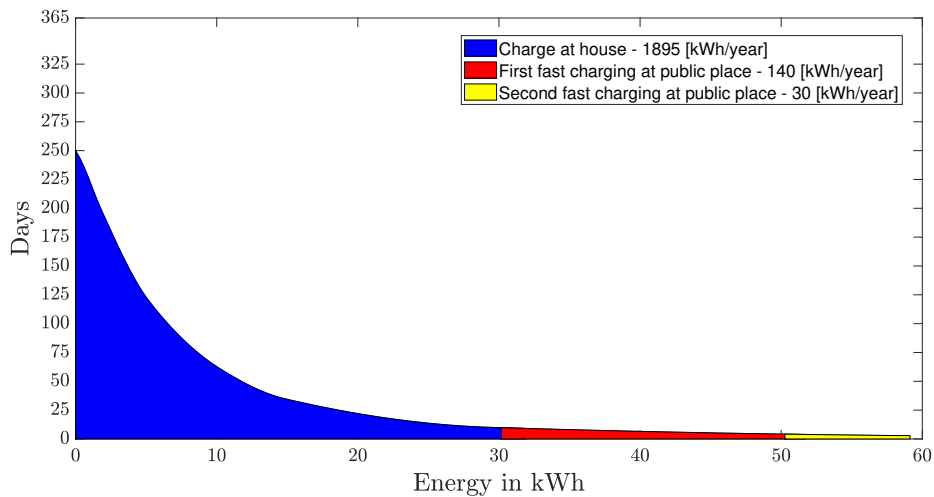


Figure 5.6: Energy distribution for mixed driving customer, 36 kWh variant

Figure 5.6 depicts the energy distribution curve for 54 kWh variant which is mid-size BEV in this segment. To commute the longest distance BEV has to charged for one

time. The energy required to charge at house 1916 kWh/year and at the public fast charging stations 65 kWh. Number of days have to stop for charging in a year is 5 days and the waiting time for charging BEV is 0.62 hours.

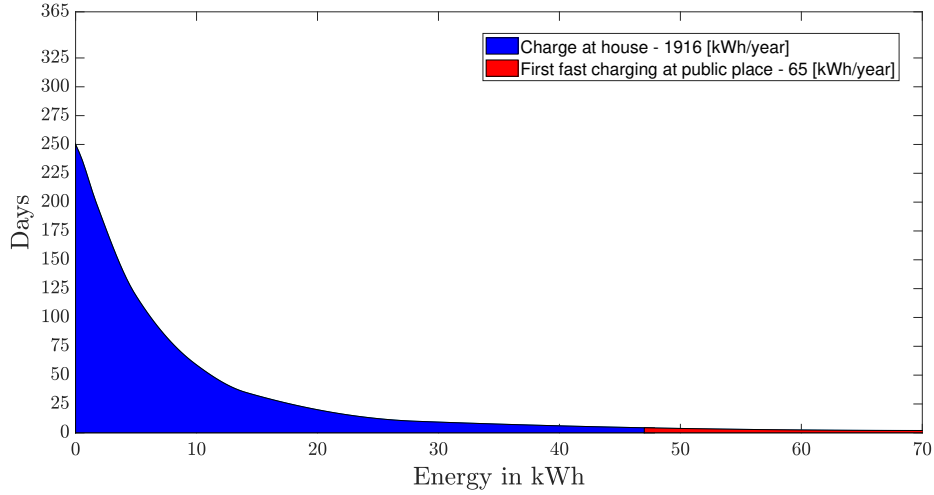


Figure 5.7: Energy distribution for mixed driving customer, 54 kWh variant

Figure 5.6 depicts energy distribution curve for the 72 kWh variant. To commute the longest distance this variant BEV has to be charged for two times. The energy required to charge at house is 2010 kWh and the public fast charging stations is 19 kWh/year. Number of have to stop for charging in a year 3 days and the waiting time for charging is 0.18 hours/year. Waiting time for this variant is very less or negligible when compared to other two variants in this segment

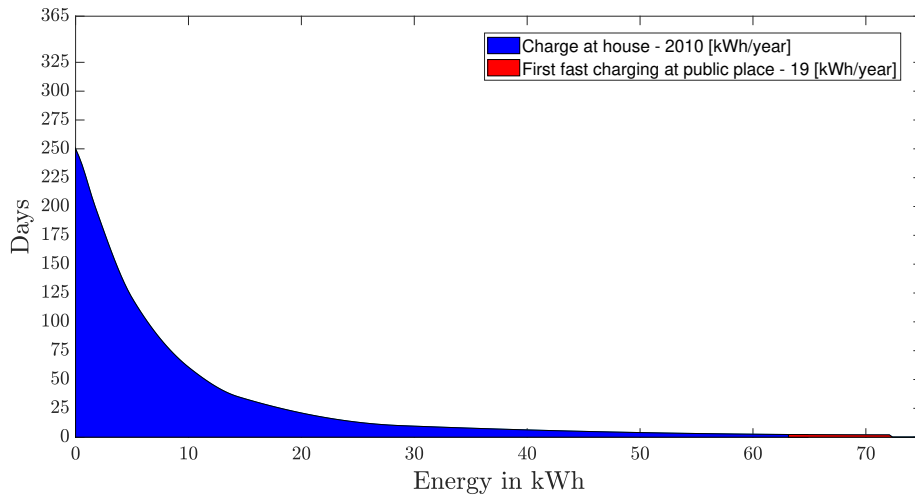


Figure 5.8: Energy distribution for mixed driving customer, 72 kWh variant

TCO for mixed driving, cost focused and premium customer is depicted in the Table 5.2. The First analysis is comparison of virtual TCO of based on the battery size. TCO for cost focused customer with 36 kWh variant and 54 kWh variant is almost equal. But the cost of waiting time, electricity cost and cost to stop for fast charging of 36 kWh variant is high when compared to 54 kWh variant. And 72 kWh variant has very less cost for the electricity but initial investment for the battery is high. Overall comparison of these three variants 54 kWh variant stands out to be interesting for buying of BEV. TCO for premium customer with 36 kWh variant is low when compared to other two variants. But the customer who values more for time than 54 kWh stands to be the best for buying of BEV as it has negligible cost for waiting time.

Table 5.2: TCO for Mixed driving customer

Mixed Driving			
Cost focused customer			
Variants (kWh)	36	54	72
Battery Depreciation (€/year)	468	614	756
EM Depreciation (€/year)	194.4	201.6	209
Vehicle depreciation (€/year)	2000	2000	2000
Electricity cost €/year	370	320	311.1
Maintenance cost €/year	450	450	450
Cost of waiting time (€/year)	24.40	9.30	2.72
Cost to stop for fast charging (€/year)	150	50	30
$TCO_{virtual}$ (€/year)	3656.47	3644.38	3758.62
$TCO_{virtual}$ (€/km)	0.243	0.242	0.25
Premium customer			
Variants (kWh)	18	36	54
Battery Depreciation (€/year)	468	613.50	756
EM Depreciation (€/year)	194.4	201	208
Vehicle depreciation (€/year)	2000	2000	2000
Electricity cost €/year	370.64	320	311
Maintenance cost €/year	450	450	450
Cost of waiting time (€/year)	49	18.6	5.45
Cost to stop for fast charging (€/year)	375	125	125
$TCO_{virtual}$ (€/year)	3907.18	3728.68	3856.35
$TCO_{virtual}$ (€/km)	0.260	0.248	0.257
TCO_{actual} (€/year)	3482.06	3585.07	3725.89
TCO_{actual} (€/km)	0.232	0.239	0.248

Figure 5.9 shows the plot for driving range distribution of long range driving customer with yearly commuting distance of 30,000 km, with 300 driving days in a year and typical driving distance of 80 km in a day.

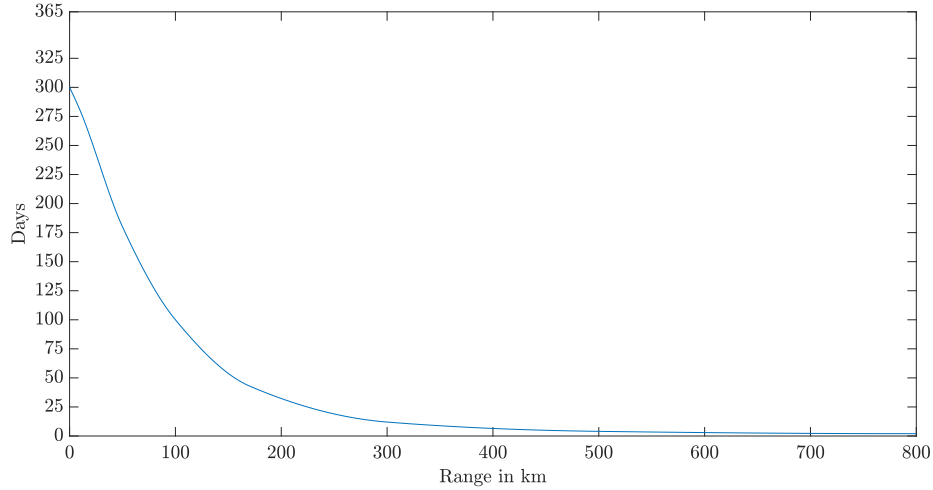


Figure 5.9: Driving range distribution for Long range driving customer

Energy distribution curve for long range driving customer with 54 kWh variant is depicted in the Figure 5.10. To commute the longest distance this variant BEV should be charged for three times. Based on the above shown driving range distribution energy required to charge BEV at house in an year is 4151 kWh and energy required for fast charging at public places is 336 kWh. Number of days have to stop for charging in an year is 25 days and the waiting time for charging is 3 hours.

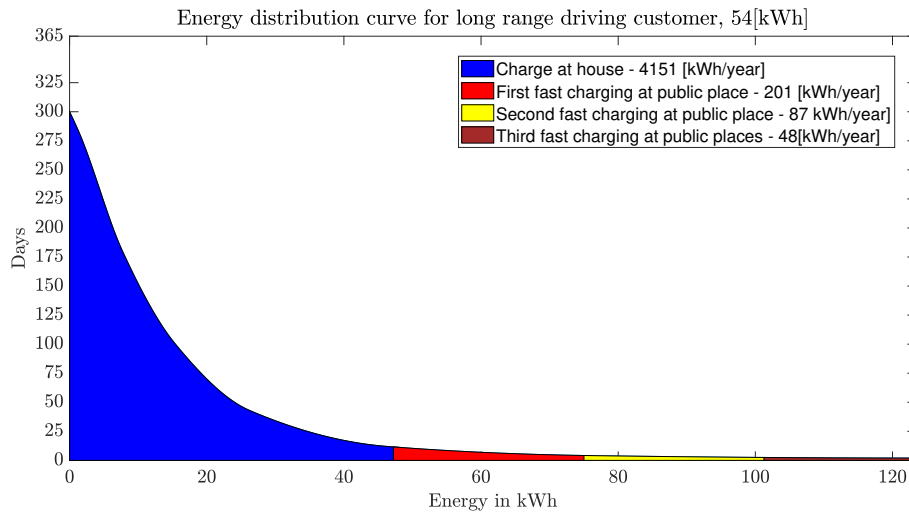


Figure 5.10: Energy distribution curve of 54 kWh, 72 kWh and 90 kWh variants for long range driving customer, 54 kWh variant

Figure 5.11 depicts the energy distribution curve long range driving customer with 72 kWh variant. To commute the longest distance the BEV has to be charged for 2 times. Energy required for charging at house in an year is 4248 kWh and energy required for fast charging at public places 191 kWh. Number of days have to stop for fast charging is 10 days and the waiting time is 1.56 hours in an year.

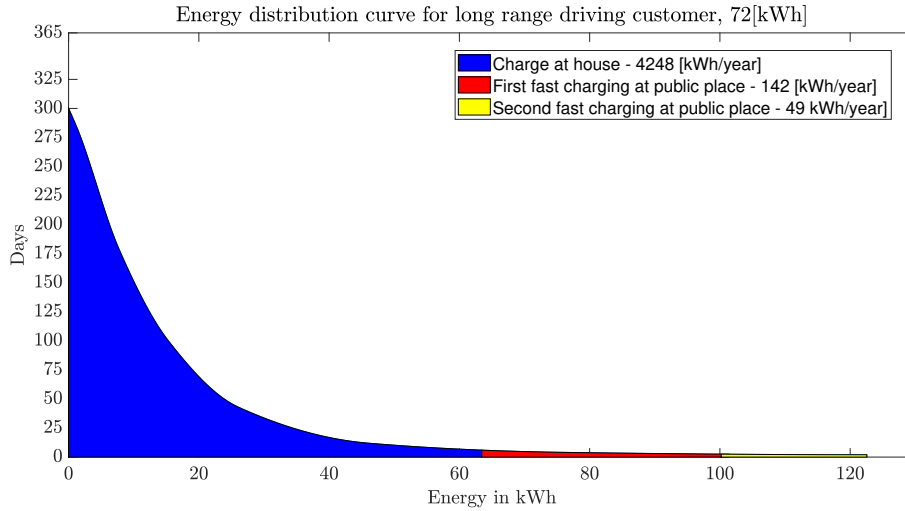


Figure 5.11: Energy distribution for long range driving customer, 72 kWh variant

Figure 5.12 depicts energy distribution curve of long range driving distance of 90 kWh variant (biggest battery size among all the variants). To commute the longest distance the BEV has to be charged for three times. Energy required for charging at house is 4647 kWh/year and for fast charging at public places is 151 kWh and waiting time for charging 1.48 hours in an year.

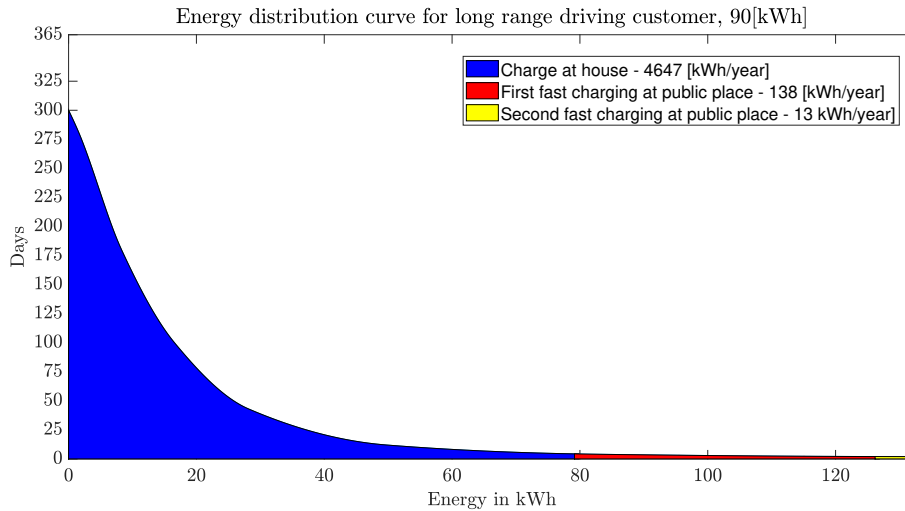


Figure 5.12: Energy distribution for long range driving customer, 90 kWh variant

TCO for long range customer with three different variants is given in the Table 5.3. Comparing and analysing the TCO based on the sizing of the battery for cost focused customer 72 kWh variant stands out be the cheapest and interesting for the customer to buy. But the factors to compare is cost of waiting and the initial investment in the battery. From the analysis of the energy distribution curve to reach 800 km in a single trip BEV has to be charged for at-least 2 times so, this applies for all three variants. Therefore, if a customer could afford high initial investments than it would be interesting to buy BEV of 90 kWh variant because it would be beneficial with less cost of waiting and also ownership cost for next five years or if the customer cannot afford high initial cost than it could be interesting for the customer to buy or 72 kWh variant based on the preference of waiting time.

Table 5.3: TCO for Long driving customer

Long Driving			
Cost focused customer			
Variants (kWh)	54	72	90
Battery Depreciation (€/year)	930	1032	1266
EM Depreciation (€/year)	342	349	365
Vehicle depreciation (€/year)	3500	3500	3500
Electricity cost €/year	791.09	732.5	772.3
Maintenance cost €/year	900	900	900
Cost of waiting time (€/year)	45	23.4	22.30
Cost to stop for fast charging (€/year)	250	100	90
$TCO_{virtual}$ (€/year)	6746.77	6632.78	6708.79
$TCO_{virtual}$ (€/km)	0.224	0.221	0.230
Premium customer			
Variants (kWh)	54	72	90
Battery Depreciation (€/year)	930	1032	1266
EM Depreciation (€/year)	342	349	365.4
Vehicle depreciation (€/year)	3500	3500	3500
Electricity cost €/year	791.09	732.5	772.3
Maintenance cost €/year	900	900	900
Cost of waiting time (€/year)	90	46.80	44.61
Cost to stop for fast charging (€/year)	625	250	225
$TCO_{virtual}$ (€/year)	7155.44	6801.86	7058.85
$TCO_{virtual}$ (€/km)	0.238	0.226	0.235
TCO_{actual} (€/year)	6463.09	6513.70	6803.73
TCO_{actual} (€/km)	0.215	0.217	0.226

Driving range distribution for Shared mobility customer is depicted in the Figure 5.13 with yearly driving distance of 60,000 km, longest driving distance of 500 km, with 350 days of driving in year, and typical commuting distance of 90 km per day.

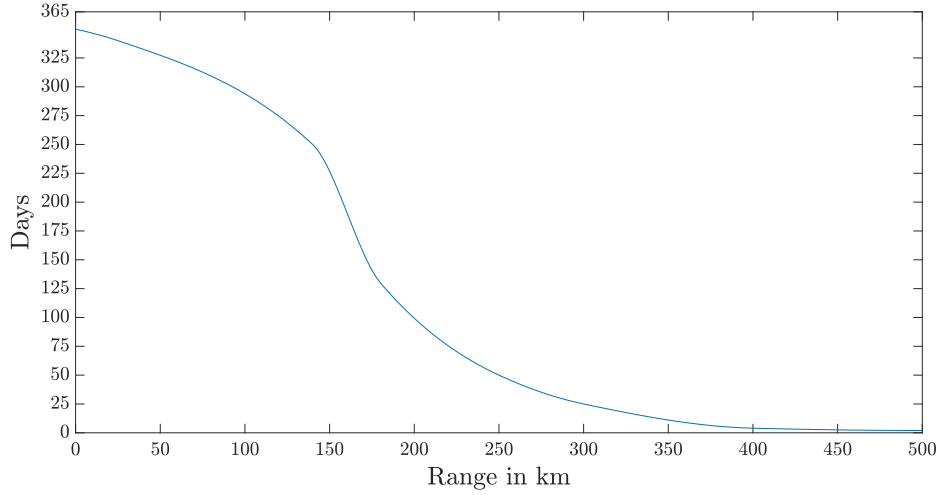


Figure 5.13: Driving range distribution for shared mobility customer

Figure 5.14 depicts the energy distribution curve of shared mobility customer of 36 kWh variant. To commute the longest distance this BEV has to charged for two times. Energy required to charge at house is 8191 kWh/year and energy required for fast charging at public places is 855 kWh/year and the waiting time for fast charging is 8.14 hours in year.

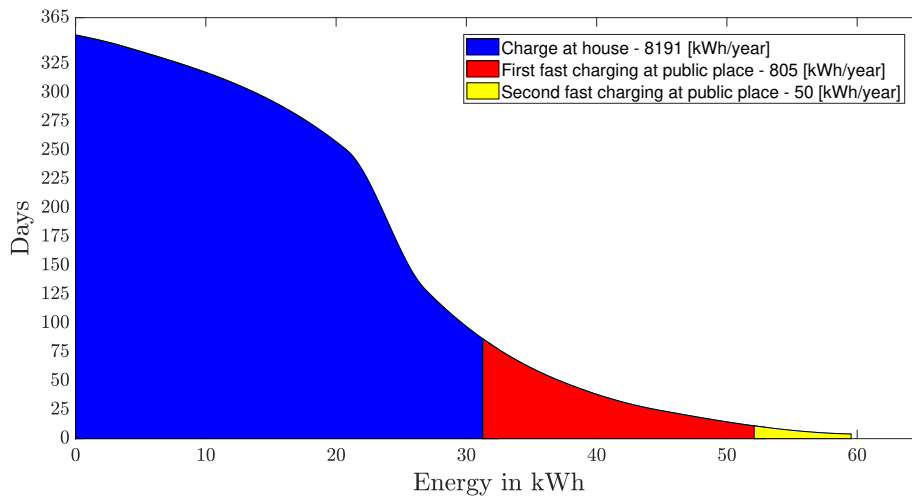


Figure 5.14: Energy distribution curve of 36 kWh, 54 kWh and 72 kWh variants for shared mobility customer, 36 kWh variant

Figure 5.15 depicts the energy distribution curve of shared mobility customer of 54 kWh variant. To commute the longest distance this BEV has to charged for one time. Energy required to charge at house is 9380 kWh/year and energy required for fast charging at public places is 246 kWh/year and the waiting time for fast charging is 2.34 hours in year.

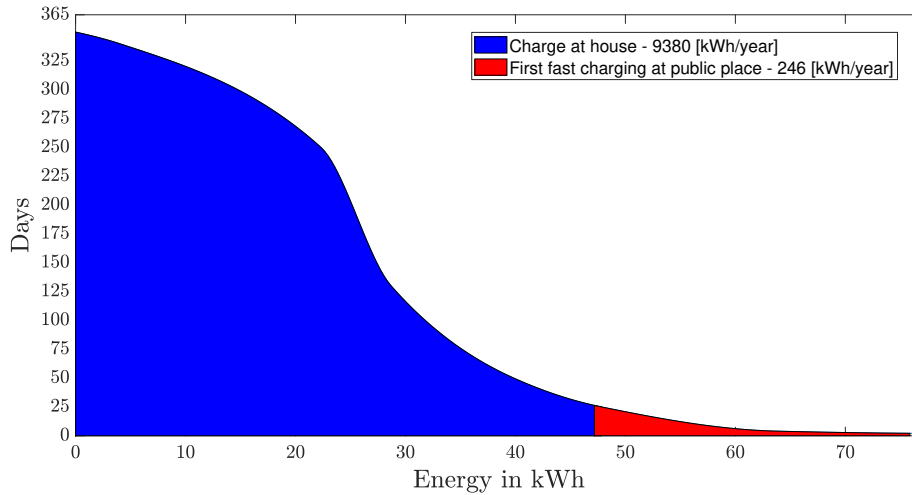


Figure 5.15: Energy distribution curve for shared mobility customer, 54 kWh variant

Figure 5.14 depicts the energy distribution curve of shared mobility customer of 36 kWh variant. To commute the longest distance this BEV has to charged for two times. Energy required to charge at house is 9571 kWh/year and energy required for fast charging at public places is 38 kWh/year and the waiting time for fast charging is 0.36 hours in year which is negligible for this variant.

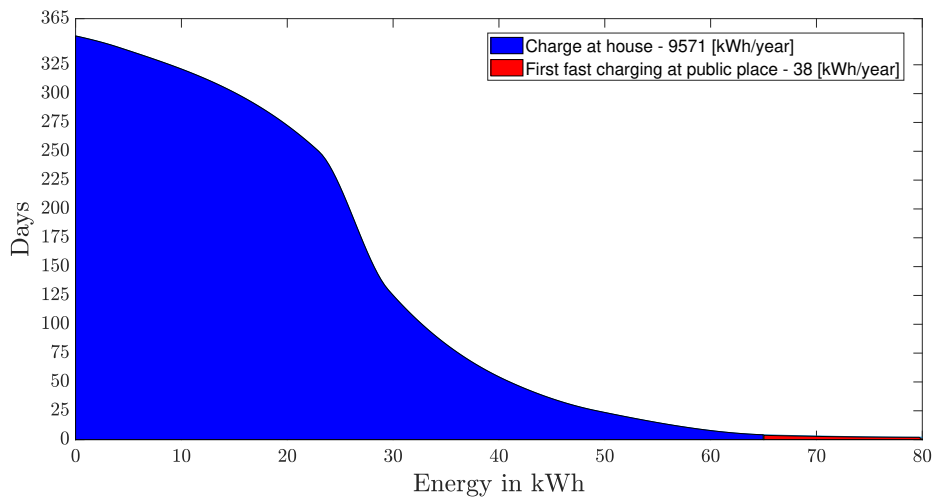


Figure 5.16: Energy distribution distribution curve for shared mobility customer, 72 kWh variant

TCO for shared mobility customer with 3 different variants is depicted in the Table 5.4. Comparing the Virtual TCO based on the battery size for cost focused customer shows that 36 kWh variant has less TCO per km. But for shared mobility battery size of this variant could be small and cost for waiting time is very high compared to other two variants. 54 kWh and 72 kWh variants could be interesting for customer to buy as they have almost equal TCO and cost for waiting time is less.

Table 5.4: TCO for Shared driving customer

Shared Driving			
Cost focused customer			
Variants (kWh)	36	54	72
Battery Depreciation (€/year)	1062	1317	1524
EM Depreciation (€/year)	207	216	225
Vehicle depreciation (€/year)	2500	2500	2500
Electricity cost €/year	1656	1530	1454
Maintenance cost €/year	1800	1800	1800
Cost of waiting time (€/year)	122.2	35.19	5.48
Cost to stop for fast charging (€/year)	960	260	50
$TCO_{virtual}$ (€/year)	8307.61	7658.24	7559.90
$TCO_{virtual}$ (€/km)	0.13	0.127	0.125
Premium customer			
Variants (kWh)	36	54	72
Battery Depreciation (€/year)	1062	1317	1524
EM Depreciation (€/year)	207	216	225
Vehicle depreciation (€/year)	2500	2500	2500
Electricity cost €/year	1656	1530	1454
Maintenance cost €/year	1800	1800	1800
Cost of waiting time (€/year)	244.40	70.38	10.96
Cost to stop for fast charging (€/year)	2400	650	125
$TCO_{virtual}$ (€/year)	9869.23	8083.43	7639.86
$TCO_{virtual}$ (€/km)	0.164	0.134	0.127
TCO_{actual} (€/year)	7225.41	7363.05	7503.90
TCO_{actual} (€/km)	0.120	0.122	0.125

Figure 5.17 and 5.18, shows the comparison between virtual TCO and actual TCO for all customer profiles with all different variants.

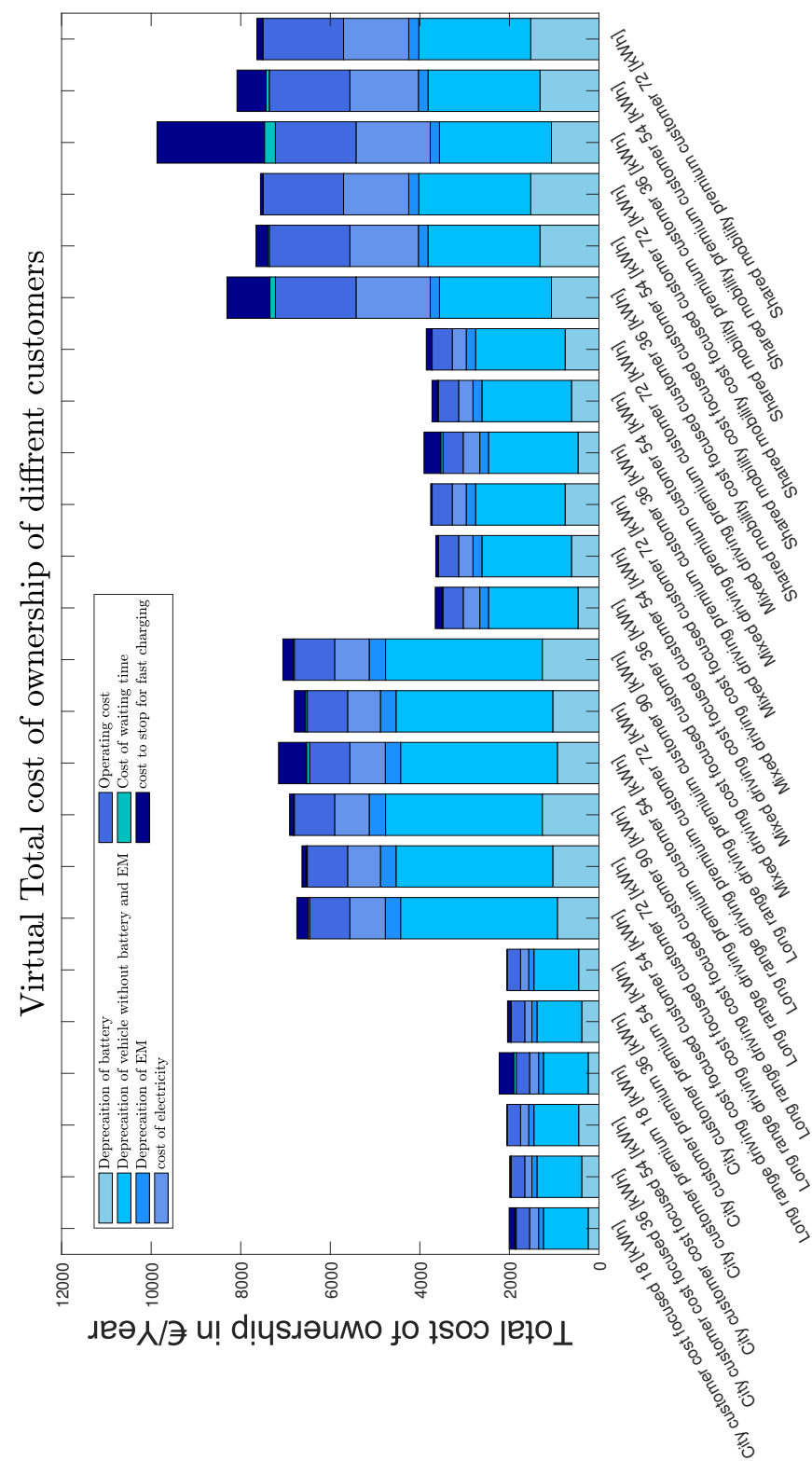


Figure 5.17: Virtual TCO for customer profiles and different variants

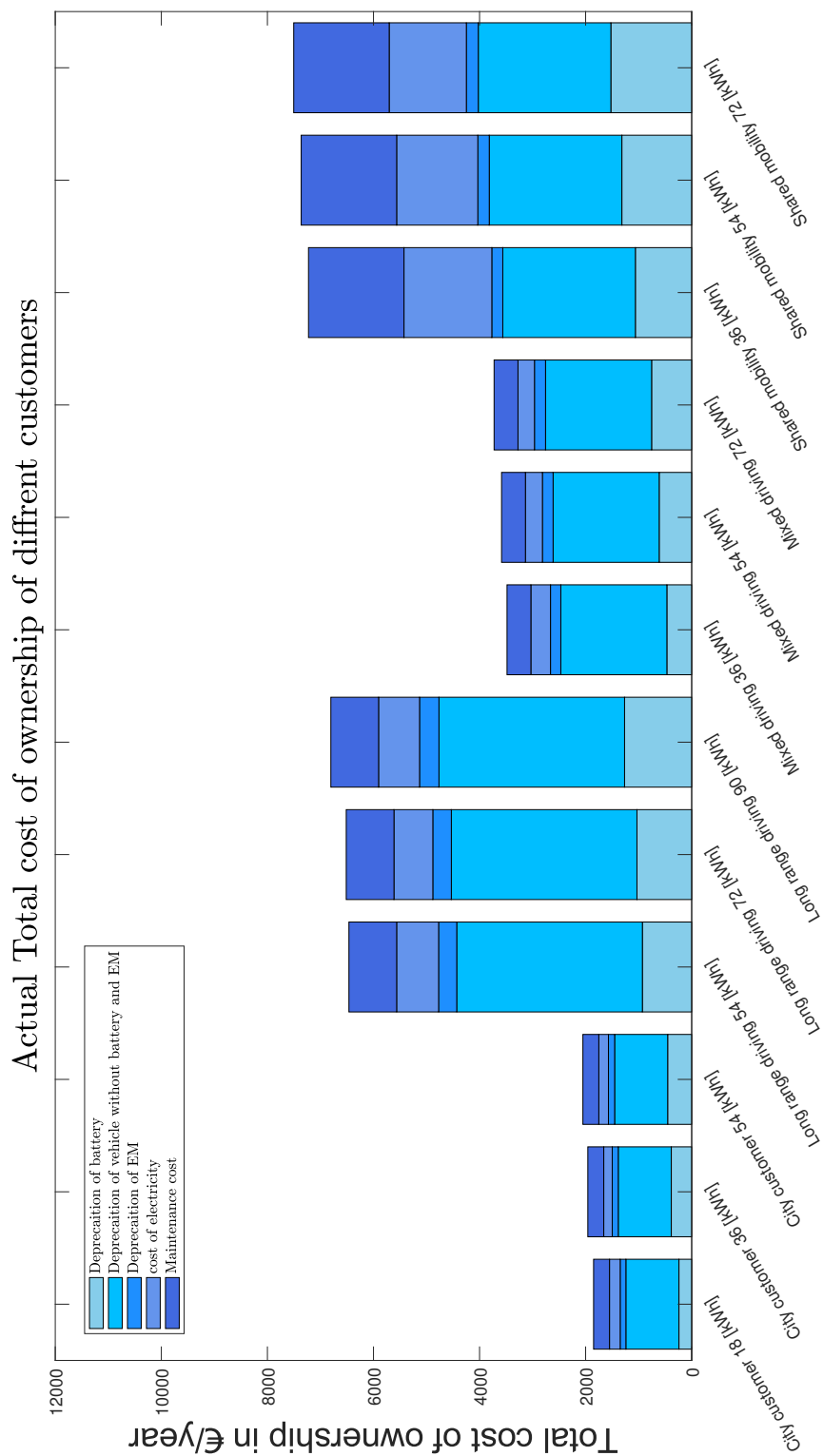


Figure 5.18: Actual TCO for customer profiles and differents variants

6

Conclusion

This study intend to demonstrate the customer centric TCO model. The results suggest that comparative cost efficiency of BEV is strongly dependent on the driving range distribution of the customer. Calculating the customer centric TCO model is challenging task as it dependent on the relevant data for different factors and reasonable assumptions about the cost of those factors. This study suggests that considering TCO for BEV is important since their initial cost might be higher than conventional vehicles but the cost of driving BEV is lower due to low cost of electricity and higher efficiency of the vehicle. The results imply three main insights.

- Driving range distribution and energy distribution curve from this study is the major contribution towards the calculation of virtual costs and the TCO. Surprisingly results suggest waiting time and cost for fast charging is very low and in some cases it is negligible. So these results gives good impact on buying a BEV and remove wrong notion of the customer regarding waiting time for fast-charging.
- Customers should think and make smarter choices in buying BEV and drop the concept of always buying a big size battery car, because our results suggest that medium battery size cars have less TCO (€/km) (City driving, mixed driving, long range driving), which would help to reduce the initial purchase cost of the customer and also reduces the ownership cost over five years. But for shared mobility customers (buyers who use for commercial purpose) big size battery is useful as they commute long distances in a day.
- Customers should be educated regarding TCO model based on their choice of the BEV by relating it to driving distances. Otherwise customer might automatically consider the initial cost of BEV and develop inappropriate assumptions related to the purchasing cost of BEV. We believe our model of explaining TCO could be the strong way of educating the customer which actually helps them making of smarter decisions in buying BEV which also in-turn helps in making better society. Other way is educating the customers about TCO by explaining them orally in the showroom itself or by providing online platform where they can calculate TCO which will give better picture. In future if companies implement TCO in their business model it may increase the competitiveness of the vehicles in the market.

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