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Minimal design of battery storage for electric vehicles

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by

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Danksagung

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Gracias

Abstract

There are ambitious greenhouse gas emission (GHG) targets for the means of transport. Promising powertrain technologies using electricity as an energy source should made they more efficient and would help to reduce the GHG emissions. Battery electric vehicles show features to improve the transportation system. However, the battery component due to the high production cost and its effect on the total vehicle price make it a challenge worthy to be analyse. The present master thesis gives an overview of battery electric vehicles (BEV) and setted that some electric vehicles use batteries larger than necessary to perform their tasks. The use of a minimum battery capacity where the range matches correctly drivers needs, would be much more friendly with the available resources and could reduce the acquisition price.

With the abstraction of three vehicles classes (Passenger cars, Buses and Freight trucks) it is possible to define and design a method that describes the minimum capacity of batteries needed. This method takes into consideration driver specifications for the desired vehicle, mileage quantity and distribution and battery degradation for the fulfilment of the previously defined mileage at the end of the vehicles lifespan. The basis of the master thesis was to set the most important parameter for the different vehicle classes. As well an application of a linear regression for the description of energy consumption.

The results show that for passenger cars, the mileage requirements of all nowadays persons in different European countries could be met by all evaluated electric cars and in the most cases surpass it. For all bus sizes the battery capacity are low but with the use of extra infrastructure can be optimized for met different routes length. In the freight vehicles mode, the last-mile and the short-haul mode in logistic are met by all listed vehicles. The long-haul still a problem since the mileage demanded for this category is very high but the use could be implemented as batteries improve and charging infrastructure expands. In addition, recommendations for Original Equipment Manufacturers (OEMs) to use modular sizes of battery capacities have been developed to meet different driver requirements.

Kurzfassung

Für die Transportmittel gibt es ehrgeizige Ziele um Treibhausgasemissionen (GHG) zu verringern. Vielversprechende Antriebstechnologien, die Elektrizität als Energiequelle nutzen, sollten sie effizienter machen und dazu beitragen, die Treibhausgasemissionen zu reduzieren. Batteriebetriebene elektrische Fahrzeuge weisen Merkmale zur Verbesserung der Transportsysteme auf. Jedoch stellt die Batteriekomponente, aufgrund der hohen Produktionskosten und ihrer Auswirkung auf den Gesamtfahrzeugpreis, eine Herausforderung dar, die es wert ist, analysiert zu werden. Die vorliegende Masterarbeit gibt einen Überblick über batteriebetriebene elektrische Fahrzeuge (BEV) und legt fest, dass einige Elektrofahrzeuge Batterien verwenden, die größer sind als zur Erfüllung ihrer Aufgaben erforderlich ist. Die Verwendung einer minimalen Batteriekapazität, bei der die Reichweite den Anforderungen des Fahrzeugbetreibers entspricht, wäre mit den verfügbaren Ressourcen viel freundlicher und könnte den Anschaffungspreis senken.

Mit der Abstraktion von drei Fahrzeugklassen (Personenkraftwagen, Busse und LKWs) ist es möglich, eine Methode zu definieren und zu entwerfen, die die Mindestkapazität der benötigten Batterien beschreibt. Bei dieser Methode werden die Kundenspezifikationen für das gewünschte Fahrzeug, die Fahrleistung und -verteilung sowie die Batteriedegradation berücksichtigt, um die zuvor festgelegte Fahrleistung am Ende der Fahrzeuglebensdauer zu erreichen. Grundlage der Masterarbeit war die Festlegung der wichtigsten Parameter für die verschiedenen Fahrzeugklassen und die Anwendung einer linearen Regression für die Beschreibung des Energieverbrauchs.

Die Ergebnisse zeigen, dass bei Personenkraftwagen die Fahrleistung aller heutigen Personen in verschiedenen europäischen Ländern von allen bewerteten Elektroautos erreicht und meist übertroffen werden. Für manche Busgrößen ist die Batteriekapazität nicht ausreichend, aber mit der Verwendung zusätzlicher Infrastruktur kann sie für unterschiedliche Streckenlängen optimiert werden. Für die Klasse der Lastkraftwagen werden die Kategorien Last-Mile und der Shorthaul von allen gelisteten Fahrzeugen erfüllt. Die Longhaul-kategorie der LKWs ist hingegen immer noch ein Problem, da die für diese Kategorie erforderliche Fahrleistung sehr hoch ist. Der

Einsatz bei höheren Fahrleitsungen könnte implementiert werden, wenn sich die Batteriekapazität verbessert und die Ladeinfrastruktur erweitert. Darüber hinaus wurden Empfehlungen für Originalausrüstungshersteller (Original Equipment Manufacturers, OEMs) entwickelt, um modulare Batteriekapazitätsgrößen zu verwenden und somit unterschiedliche Fahreranforderungen zu erfüllen.

Contents

1 Introduction

The reduction of greenhouse gas (GHG) emissions and petroleum consumption is the major challenge for the transport sector. Transport is responsible for about 20% of total GHG emissions in the EU in 2015 [1]. There are ambitious GHG emission targets for the means of transport. In 2011, the European Commission set very ambitious targets for CO_2 emissions reductions[2], stating: "Emissions from transport could be reduced to more than 60% below 1990 levels by 2050.". In this context, vehicles manufacturers, are required to decrease or eliminate the CO_2 emissions of new vehicles. Promising powertrain technologies using electricity as an energy source should make vehicles more efficient and would help to reduce the GHG emissions and achieve this goal.

Years ago, we made the transition to a better and more efficient metro system and higher speed trains using electricity as an energy source. For other types of transport modes, for example on roads, petroleum products are still the most used energy source (see Figure-1.1).

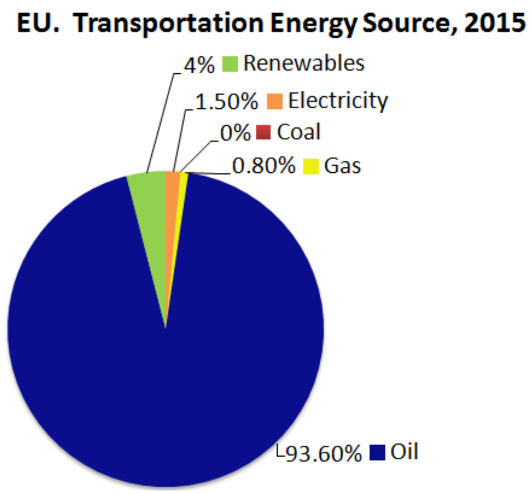

Figure 1.1: Use of fuels in transport, EU-28, 2015. Data extracted from Eurostat in December 2017

Since 1990, electric cars became the focus of more and more reinvention and a better electric setup was designed. In recent years, batteries went through radical changes, evolving from lead-acid batteries and nickel-iron batteries to the current lithium batteries which multiplied the potential range of battery electric vehicles (BEVs) by 10, giving rise to big companies like VW, Ford, Mercedes or Nissan to begin manufacturing BEVs. Other areas where EV success was very unexpected, include the transport of goods by road (last mile, short-haul and long-haul) and the fleets of electric buses that already circulate in cities like Barcelona, Paris or London.

The present master thesis gives an overview of battery electric vehicles (passenger cars, buses and freight trucks) and setted that some electric vehicles use batteries larger than necessary to perform their tasks. The use of a minimum battery capacity where the range matches correctly drivers needs, would be much more environment-friendly with the available resources and could reduce the acquisition price.

Due mainly to these arguments, this thesis focuses on the evaluation of the minimal design of battery storage for BEVs.

1.1 Core objectives of this work

In this thesis, the minimal battery storage of a vehicle is designed from the perspective of a driver. At the starting point of the model, there is no defined daily travel distance. Rather, daily travel distance may be freely chosen depending on the use, for example a taxi through the city, delivery service car, vehicle with mixed consumption in city and highway, bus route through the city center, peripheries, etc.

The number of existing models of the three selected vehicle is a advantage. Different companies offer different models and different sizes. In the created database are for the passenger cars 57 models available covering a whole spectrum. For the buses 29 different model where listed with different lengths and for the freight trucks 17 different models with different characteristic. This number of vehicles allowed to calculate the best possible solution, considering engine power, energy consumption and the installed battery capacity of each vehicle.

The database includes the information about engine power, installed battery capacity and other characteristic values. This information was taken from the respective vehicle manufacture.

The special focus on passenger cars was set on the spatial distribution of the mileage (consumption in city and in highway), by using a specific driving cycle. The average consumption provided by the vehicle manufacture represent only an average value of the different spatial distribution (real consumption depends on driving style, road conditions, etc.). For the buses and trucks vehicles a differentiation was made depending upon where the mileage happens only paying attention to the operation speed (heavy city or down-town, easy city with middle traffic, and city periphery).

To evaluate different driver behaviour for demanded mileage, a reasoning close to a real case was made and the results were presented.

The model presented here recommend the minimal cost solution for the battery capacity of each evaluated vehicle in the corresponding power category. This model, the evaluation of the different driver behaviour and the database created here, can be used for different analyses. The listed vehicles can be easily extended and updated, the local conditions related to mileage are variables to configure and the values taken here are representative for a clear explanation.

Seeing the goals that the governments have regarding the reduction of CO_2 emissions and the advance in the technologies used by BEVs (battery, new curb materials, electronic, etc.), it was decided as main task for this thesis, to make an model to identify the minimal battery setup in BEVs. Engine power, energy consumption and battery capacity as well as the driver amount of mileage and the distribution (route, city, highway, etc.) are taken into account. In the process, the influence of various criteria on the minimum battery choice are investigated.

- The presented master thesis enables to:

- Identify the battery capacity for passenger car, bus and freight truck drivers with different driving profiles.
- Present the possible use of battery electric vehicles in the different transport modes

1.2 Methodology

Based on the current literature and to complement the studies based on econometric analysis, this thesis aims to take as a starting point the vehicle models available in the market and their characteristic values (see Table-1.1.)

Table 1.1: Classes and vehicles characterization

Vehicle Class	Characteristic values
Passenger cars	Engine power
Buses	Battery capacity
Road freight trucks	Energy consumption

The different type of collected vehicles where separated in classes and the characteristic values data was obtained from the respective vehicle manufacturers and driving cycles with an aim to take values as real as possible to be able to guarantee the validity of the results.

After having a representative database that includes most of the models available in the market with the characteristic values of the different classes (passenger cars, buses, and freight trucks), a categorization was made in order to adjust the number of available vehicles in the different areas of use (smalls cars for city use, long buses for heavy city sectors, small trucks for last mile, etc.). This categorization was done empirically with similar values of engine power $[kW]$ for passenger cars, with similar vehicle lengths $[m]$ for buses and similar payloads $[kg]$ for the road freight trucks.

The energy consumption was defined like a function by the characteristic values, battery capacity and engine power (Function-1.1). The battery capacity was also defined as a function of the range and energy consumption (Function-1.2).

$$EC_i = f(P_i, QB_i) \tag{1.1}$$

$$QB_i = f(s_i, EC_i) \tag{1.2}$$

Where EC_i describe the energy consumption obtained from the driving cycle in kWh/km, QB_i equals the net battery capacity in kWh. P_i the engine power of each vehicle in kW and the variable s_i the individual driving mileage of the user.

Since the value of the engine power does not vary too much within the category, average values for the engine power were taken to define the category and to evaluate the obtained model.

The driver chooses the desired vehicle class: passenger cars (C), buses (B) or road freight trucks (T) and a desired category: small for compact cars, midibuses or last-mile trucks, medium for family/medium cars, urban buses or short-haul trucks or big: for Tesla's cars, articulated buses or long-haul trucks. After that, depending on their driving behaviour or route (e.g $40 km/day$, $100 km$ route, etc.) the daily mileage demand. This model inputs, results in the recommended value of the necessary battery capacity of the vehicle that is being requested. For the total calculation against ageing an extra battery capacity value is added (see Subsection-3.3).

The Figure-1.2 present the general form of the method used to achieve the objectives of this work. Here we explain in a general way how in the first instance the driver chooses a vehicle class to perform a task (passenger car, bus or freight truck T) and a category i determined by the power of the engine. Then the driver according to their needs (route length, payload, etc.), driving behaviour (city, highway or mix driving profile) or wishes (personalized mileage) choose a daily mileage and become a net value for the battery capacity. After that, the ageing factor of the battery is added, so that the vehicle at the end of its useful life continues to meet the conditions demanded. These analysis results in a recommended minimum value for the vehicle and its tasks.

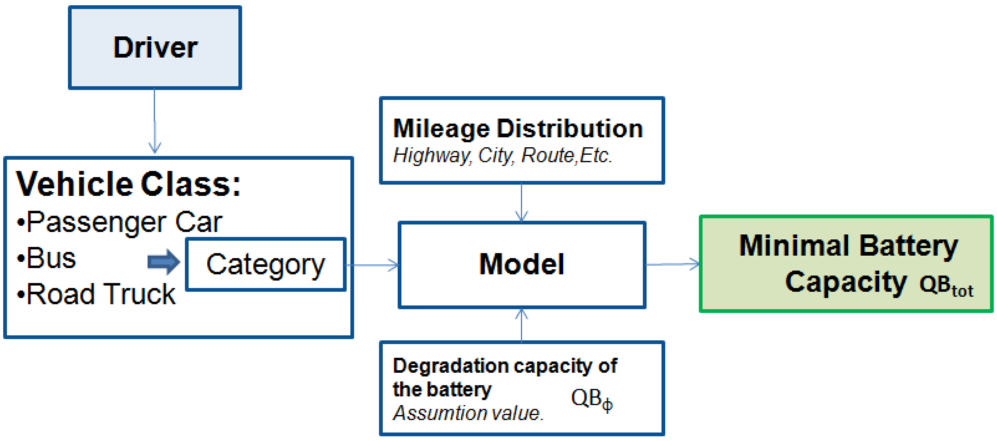

Figure 1.2: General method of the battery capacity minimization for BEV.

The box "Model" presented in Figure-1.2 is a linear regression with the dependent variables presented in Function-1.1 and Function-1.2. The linear regression as econometric analysis was the appropriate technique in the analysis, because the two metric dependent variables whose value depends on one independent variable.

The problem is modelled in Microsoft Excel® 2007. A linear regression is one of the most commonly used statistical tests in industry, and Excel includes this tool for this calculation.

For the realization of this analysis, a database were collected for three vehicle classes:

- Class *C* - Passenger cars
- Class *B* - Buses
- Class *T* - Road freight trucks

1.3 Structure of the thesis

The structure of this thesis is divided into six chapters and an Appendix:

- Chapter 2 provides an overview of the state of the art in the field of EVs, and describes the starting position of this work.

- Chapter 3 describes the modelling process. This includes the description of the mathematical model, its parameters and their origin. It also discusses which assumptions are included in the model.

- Chapter 4 describes the results obtained by applying the minimization model and the variation of different case studies. The results and statements are derived within the case studies, as well as the comparisons with the solutions from other categories.

- Chapter 5 summarizes, discusses and interprets the results.

- Chapter 6 present conclusions that can be gained from the results.

2 Literature and data used

Since 1990 Electric vehicles got their second change. The "California Zero Emission Vehicle (ZEV) rule" [3] a controversial air quality policy prompted different models of Battery Electric Vehicles on the market. This opened an evolution into clean automotive technology with cars like *Chevrolet S-10*, *Solectria Geo Metro*, *Ford Ecostar* and the *eRanger* among others. Today in the 21st century, the electric car continues growing to be incorporated in different areas of the transport mode.

The mobility of people and goods was formerly a relatively straightforward undertaking. Vehicles were chosen by purpose (how big should it be or how many people should it be able to transport), appearance and functionality (green, blue, air conditioning, sound system, etc) and the purchase decision by economy calculation, prestige, brand fidelity, etc. The consideration of which fuel technology they used was applicable to only two options: gasoline or diesel. Acorrding to the publication from the organization Deloitte Touche Tohmatsu Limited in 2014[4] now, however, this is a very dynamic purchase decision, not only the Internal Combustion Engines (ICE) are available, different technologies of fuel are now on the market. Vehicles like Hybrid Electric Vehicles (HEV), Range Extended Electric Vehicles (REEV), Plug-in Hybrid Electric Vehicle (PHEV) that combine an electric engine and an internal combustion engine or Fuel Cell Hybrid Electric Vehicle (FCHEV) and use fuel cells as a source of energy and in this scope of this work, Battery Electric Vehicles (BEV) that use an electric engine and battery-powered energy.

The current geopolitical situation and unconventional oil production are making different fossil fuels available at lower prices. With oil at approximately USD 60 barrel (December 2017) [1], other energy sources like batteries face strong competition. BEVs are becoming politically more and more popular and because of their high efficiency, many governments see a greater use of BEVs as an important way to meet their environmental goals and increase the efficiency of transportation systems.

[1] `https://markets.businessinsider.com/`

2.1 Literature

After a period of introduction, EVs are now an established part of the transport mode. The goal to reduce greenhouse gas (GHG) in transport would not be achievable without the use of new fuel technologies including electrical vehicles and their high energy efficiency compared to normal internal combustion vehicles. The National Research Council [5], completed one of the most comprehensive studies of how a transition could be done and how to achieve the goals of reducing petroleum consumption and GHG emissions. In this study, broad topics are tackled, starting with alternative vehicle technologies, alternatives fuels, possible future uses, etc. Then follows an evaluation about consumer purchasing patterns, consumer attitudes, car-buying motivations and also possible barriers to owning a car. In the final part, this work explains the role of government and its different types of policies (land, environmental, energy, etc.).

Also how a possible optimal design of battery storage for electric passenger cars looked from an economic cost perspective was investigated in the "Report of the Committee on Transitions to Alternative Vehicles and Fuels" [6]. This paper proposes a total cost of ownership (TCO) model for battery sizing of plug-in hybrid electric vehicles (PHEVs). It was determined with data from Germany [7] "to customize the battery size with respect to the driving behaviour of the user to make hybrid electric vehicle more cost competitive and attractive for different driver types". The researchers took into account parameters such as heterogeneity amongst drivers, trip distribution,driver profile, and energy prices among others. They came to the conclusion "that OEMs should develop modular design for their battery packs that allows adapting capacity to meet different driver requirements (instead of "one size fits all" product strategy) and that the analysis of the driving profile of the user has priority because optimization depends therefore strongly.

A similar conclusion also comes from the article "Battery Sizing for Plug-in Hybrid Electric Vehicles in Beijing: A TCO Model Based Analysis" [8] with data from Beijing. They also conclude that fuel and battery price are the two most significant economic parameters. With regard to this, the analysis "Lithium-ion Battery Costs and Market Squeezed margins seek technology improvements and new business models" [9] shows very clearly that the trend is towards reducing battery price: "BNEF forecasts lithium-ion battery pack prices will continue to fall short of $73 USD/kWh$" now because of the oversupply and in the future by improving company strategy.

The Institute for Energy and Transport from the European Commission Joint Research Center [10] makes a comparison with national travel survey data and analysis of driving behaviour. The report analyzed car mobility patterns derived from direct surveys in five European Union member states (France, Germany, Italy, Poland, Spain) and the United Kingdom. In particular, the information on average number of car trips per day, daily travel distance, daily travel time, trip distance, distribution of parking and driving, distribution of parking places, trip purposes, duration of parking and many other parameters per member state are analyzed and presented in this report. Another very extensive report was made by the Federal Ministry of Transport Construction and Urban Development in Germany [7]that characterizes the detailed mobility behaviour of more than 50,000 German households in 2008 and is used as an important data source for drive value and drive distribution. Germany represents a good average value of all the countries surveyed in the European Commission survey driving report. Thanks to this report, it can be concluded that for passenger cars, the current range that batteries offer is enough for the average driver.

For the public transport, many reports have also been done. A report called "ZeEUS" for "eBus report an overview of electric buses in Europe" [11] was conducted offering an overview of electric buses in Europe with participation from 40 consortiums in over 20 countries and 60 cities. This report was presented in 2017 to test electrification solutions for the urban bus networks. The importance of this project was that it was evaluated in real zones and with real routes, this with the purpose of facilitating the market uptake of electric buses in Europe. Although this project focuses on plug-in hybrid buses (PHEB), full battery electric buses (BEB) and battery trolleybuses, it gives a very clear idea of the scope and possibility of introducing BEB (21 BEB vs. 11 PHEB) in the bus transport mode for different types of cities.

Regarding the freight transport mode, it is possible to divide the analysis in two parts: on the one hand "Light Duty Vehicles" (LDV) that describe the last mile and short-haul transport modes and on the other hand the "Heavy Duty Vehicles" (HDV) that represent the long-haul mode. For the LDV it can be affirmed that electric vehicles are fitting to the requirements of urban logistics in small and medium cities for the same reasons passenger vehicles (engine efficiency, health, pollution, emissions of greenhouse gases, etc.). There are many studies that attempt to compare small sized electric vehicles with traditional petroleum fuel vehicles. The article "Comparing the Use of Small Sized Electric Vehicles with Diesel Vans on City Logistics" [12] concluded that in the best scenario, the on-road electric freight systems represent a niche of the market and that they are only feasible as a compliment to conventional vehicles. However, there are other studies that recognize the disadvantages of BEVs and show that the electric freight vehicles in the urban logistics (the main use of LDV) needs to evolve [13], as seen by operators paying attention to how to adapt logistics processes to lower ranges [14]. On the side of the heavy duty vehicles or long-haul vehicles there are very few studies. The large range that this system demands these days is not economically and technically viable. For example there are only a very small number in the market of vehicles class 8 or in Europe class "CE", besides these offer much lower ranges (see table-2.4)[2] and times of recharge much higher compared to those that need traditional petroleum fuel.

The success of the lithium-ion battery is now assured and has found wide application in the area of consumer electronics. It's a well-know technology and is a reason why nowadays this technology forms part of the electro-mobility industry. Compared with other used batteries, lithium-ion batteries offer high energy density, high power density, long life and environmental friendliness. Also different important control parameters have been sufficiently evaluated and detected, management systems like battery state estimation, charge control, thermal management, State of Charge (SoC) estimation algorithm, etc. are explained in "a review on the key issues for lithium-ion battery management in electric vehicles" [15].

A complex task in this model was to identify the ageing mechanism of the lithium-ion battery. Important parameters such as temperature, charging cycle (speed, frequency, voltage, current, etc.) and the chemical itself are difficult to evaluate for a model. All these parameters are very important to find an optimal method of estimation and are presented from the Journal of Power Sources [16] [17] as a review of the battery ageing mechanisms, and their consequences, occurring during a battery life.

Starting for previous work in this area places, this thesis focus on BEVs over other technologies to design a minimal battery storage. Its also present a possible solution to achieve the governments goals regarding the reduction of CO_2. Emissions with a econometric analysis for the energy consumption of an electric vehicle with the analysis unit power engine and battery capacity.

[2]Between 150 and 250 [km]

2.2 Data overview

Batteries are the key component of electric vehicles. They determine whether vehicles are perceived as attractive, interesting by customers and therefore, whether they become popular. They determine the range, price, recharge, speed and lifespan of the vehicle, fundamental aspects that still restrain many users. This technology offers lower levels of pollution and emissions of GHG, all things which favour human health, ecosystems, and the climate. All of these are clear benefits of the new, more efficient transport system technologies.

The different Battery Electric Vehicles models on the market were listed with characteristic values, power peak, battery capacity, energy efficiency (fuel/energy consumption) and some other important parameters obtained from each manufacture for easy categorization.

This list was classified and separated into three parts where each part presents a class with their categories.

- The first part is for the passenger cars C_i with the category $C1$ for compact size, $C2$ for the medium size and $C3$, $C4$ for the Teslas. At the moment there are a considerable amount of vehicles in this class. For this work, 58 vehicles were taken with their above-mentioned characteristic parameters (P_i, QB_i, EC_i), see Table-2.1 [3].

[3]Manufacturer's suggested retail price (MSRP) from `https://www.motortrendgroup.com/`

Table 2.1: Overview of passanger cars

Category	Vehicle	P_C $[kW]$	QB_C $[kWh]$	$EC_{C\ City}$ $[kWh/km]$	$EC_{C\ HW}$ $[kWh/km]$	MSRP $[USD]$
C1	2017 Mitsubishi i-MiEV	49	16	0.17	0.21	22995
	2016 Mitsubishi i-MiEV	49	16	0.17	0.21	22995
	2016 Smart for2 e-drive convertible	55	17.6	0.17	0.23	28000
	2016 Smart for2 e-drive coupe	55	17.6	0.17	0.23	25000
	2017 Smart for2 e-drive convertible	60	17.6	0.19	0.23	25200
	2017 Smart for2 e-drive coupe	60	17.6	0.17	0.22	25000
C2	2017 BYD e6	75	82	0.26	0.29	40000
	2016 Nissan Leaf (24 kWh)	80	24	0.17	0.21	36790
	2016 Nissan Leaf (30 kWh)	80	30	0.17	0.21	36790
	2017 Kia Soul Electric	81	27	0.17	0.23	35950
	2016 Kia Soul Electric	81	27	0.17	0.23	35950
	2017 Fiat 500e	82	24	0.17	0.20	31800
	2016 Fiat 500e	82	24	0.17	0.20	31800
	2016 Volkswagen e-Golf	85	24.2	0.17	0.20	35595
	2017 Hyundai Ioniq Electric	88	28	0.16	0.17	32500
	2017 Volkswagen e-Golf	100	35.8	0.17	0.19	35595
	2016 Chevrolet Spark EV	105	21	0.16	0.19	25510
	2017 Ford Focus Electric	107	33.5	0.18	0.22	29120
	2016 Ford Focus Electric	107	33.5	0.19	0.21	29170
	2017 Honda Clarity	120	25.5	0.17	0.20	59000
	2016 BMW i3 BEV	125	22	0.15	0.19	42400
	2017 BMW i3 BEV (60 Ah)	125	22	0.15	0.19	42400
	2017 BMW i3 BEV (94 Ah)	125	33.2	0.16	0.20	44450
	2017 Mercedes-Benz B250e	132	28	0.17	0.26	41450
	2016 Mercedes-Benz B250e	132	28	0.17	0.26	41450
	2017 Chevrolet Bolt EV	150	60	0.18	0.19	40905

Table 2.2: Overview of Tesla vehicles

Category	Vehicle	P_C $[kW]$	QB_C $[kWh]$	EC_{City} $[kWh/km]$	EC_{HW} $[kWh/km]$	MSRP $[US\$]$
C3	2017 Tesla Model S (60 kWh)	285	60	0.21	0.21	68000
	2016 Tesla Model S (60 kWh)	285	60	0.21	0.21	66000
	2016 Tesla Model S (70 kWh)	285	70	0.22	0.23	70000
	2017 Tesla Model S (75 kWh)	285	75	0.22	0.21	69500
	2016 Tesla Model S (75 kWh)	285	75	0.22	0.21	74500
	2016 Tesla Model S (85 kWh)	285	85	0.24	0.23	80000
	2016 Tesla Model S (90 kWh)	285	90	0.24	0.23	85000
	2017 Tesla Model S AWD-100D	386	100	0.24	0.21	85700
	2017 Tesla Model S AWD-60D	386	60	0.21	0.20	73000
	2016 Tesla Model S AWD-60D	386	60	0.21	0.20	71000
	2016 Tesla Model S AWD-70D	386	70	0.21	0.21	75000
	2017 Tesla Model S AWD-75D	386	75	0.21	0.21	74500
	2016 Tesla Model S AWD-75D	386	75	0.21	0.21	79500
	2016 Tesla Model S AWD-85D	386	85	0.22	0.22	80000
	2017 Tesla Model S AWD-90D	386	90	0.21	0.21	78200
	2016 Tesla Model S AWD-90D	386	90	0.21	0.21	89500
	2017 Tesla Model X AWD-60D	386	60	0.23	0.23	100150
	2016 Tesla Model X AWD-60D	386	60	0.23	0.23	83000
	2017 Tesla Model X AWD-75D	386	75	0.23	0.23	82500
	2016 Tesla Model X AWD-75D	386	75	0.23	0.23	83000
	2017 Tesla Model X AWD-90D	386	90	0.23	0.23	93500
	2016 Tesla Model X AWD-90D	386	90	0.23	0.23	95500
C4	2017 Tesla Model S AWD-P100D	568	100	0.25	0.24	134500
	2016 Tesla Model S AWD-P100D	568	100	0.25	0.24	134500
	2016 Tesla Model S AWD-P85D	568	85	0.24	0.23	85000
	2017 Tesla Model S AWD-P90D	568	90	0.24	0.24	87500
	2016 Tesla Model S AWD-P90D	568	90	0.25	0.25	112000
	2017 Tesla Model X AWD-P100D	568	100	0.26	0.23	135500
	2016 Tesla Model X AWD-P100D	568	100	0.26	0.23	159000
	2017 Tesla Model X AWD-P90D	568	90	0.24	0.23	143950
	2016 Tesla Model X AWD-P90D	568	90	0.24	0.23	115500

- The second part is for the evaluated class Buses B_i and the three different categories $B1$ for the midibuses, $B2$ for the urban buses and $B3$ for the articulated. 29 Buses were taken and parametrized. This second class was used for its importance in the transportation of people. It is a mature class and has already been implemented in some cities in Europe [4]. This class is listed in Table-2.3.

Table 2.3: Overview of bus vehicles

Category	Vehicle	P_B $[kW]$	QB_B $[kWh]$	EC_B $[kWh/km]$	l $[m]$
B1	OTOKAR Electra	103	170	0.80	9
	SOR LIBCHAVY EBN 10.5	120	172	0.80	10.37
	SOR LIBCHAVY SPOL EBN 11	120	172	0.95	11.1
	OPTARE Solo EV	150	138	0.95	9.9
	OPTARE Metrocity EV	150	138	0.80	10.8
	eVOPRO C68e	160	144	0.90	7.98
	eVOPRO C88e	160	84	0.82	9.46
	SOLARIS Urbino 8.9 LE	170	160	0.94	8.95
	TEMSA MD9 electric	200	200	1.10	9.3
	SAFRA Businova Midibus	200	132	1.10	10.5
	OPTARE Versa EV	200	138	1.20	11.1
	BOZANKAYA A.S. Sileo S10	240	200	1.30	10.7
B2	CRRC C12	150	201	1.20	11.95
	BLUEBUS BEV	160	240	1.23	12
	RAMPINI CARLO SPA E12	160	180	1.13	12
	ŠKODA Perun HE	160	230	1.20	12
	URSUS Bus City Smile	170	175	0.95	12
	URSUS Ursus Bus Ekovolt	170	120	1.10	11.96
	BYD AD Enviro200EV	180	324	1.20	12
	BYD BYD 12m China	180	324	1.08	12
	BYD BYD Double Decker	180	345	1.05	12
	HEULIEZ BUS HEULIEZ BUS GX 337	190	349	1.25	12
	SAFRA Businova Standard	200	132	1.10	12
	EBUSCO B.V. Ebusco 2.1	220	311	1.30	12
	BOZANKAYA A.S. Sileo S12	240	230	1.30	12
	SOLARIS Urbino 12 electric	250	240	1.30	12
B3	EBUSCO B.V. Ebusco 18M	250	414	1.28	18
	SOLARIS Urbino 18 electric	270	240	1.60	18
	BOZANKAYA A.S. Sileo S24	400	300	1.50	24

[4] `http://bydeurope.com/innovations/future/index.php#/list`

- For the third class T_i, which represents road freight trucks, 17 vehicles were listed. Here, one can see well-known brands such as *Renault*, *Nissan*, *Daimler* and *BYD* among others. A class that represents a large market and of interest to manufacturers, governments and participants of the logistics system in general. The Table-2.4 shows a list of class T vehicles currently available (December 2017). With the characteristic value "Payload" it is possible to have an idea of the different sizes available.

Table 2.4: Overview of freight vehicles

Category	Vehicle	P_T $[kW]$	QB_T $[kWh]$	EC_T $[kWh/km]$	Payload $[kg]$
T1	Renault Kangoo Maxi Z.E.	44	33	0.31	640
	emovum E-Ducato L1H2	60	43	0.43	940
	Nissan eNV200	80	24	0.51	695
T2	Emoss EMS 712	120	120	0.75	4600
	Emoss EMS 304	135	42	0.45	5000
	Emoss EMS 307	135	72	0.48	5000
	Emoss EMS 508	135	84	0.48	5000
	Emoss EMS 1008	150	80	0.8	5265
	Emoss EMS 1212	150	120	0.8	6550
	Emoss EMS 1220	150	200	0.8	5422
T3	Emoss EMS 1612	150	120	0.96	9992
	Emoss EMS 1620	150	200	0.95	8930
	Daimler AG Fuso eCanter	185	70	0.7	7500
	Emoss EMS 1820	230	200	1.05	10666
	Emoss EMS 1824	230	240	1.04	10430
	E-Force E18	300	240	1.1	10000
	BYD T9	359.42	188	1.27	7000

2.3 State of the art

Based on the aforementioned literature and obtained data, an overview of the passenger cars market, buses and trucks, and batteries is presented below.

- Passenger cars

With passenger cars we can conduct a close analysis of stock, range and battery capacity as well as battery costs in relation to car price.

The global stock of passenger BEVs reached almost 2 million in 2017, with an increase of almost 60 % compared to the previous year (see Figure-2.1).

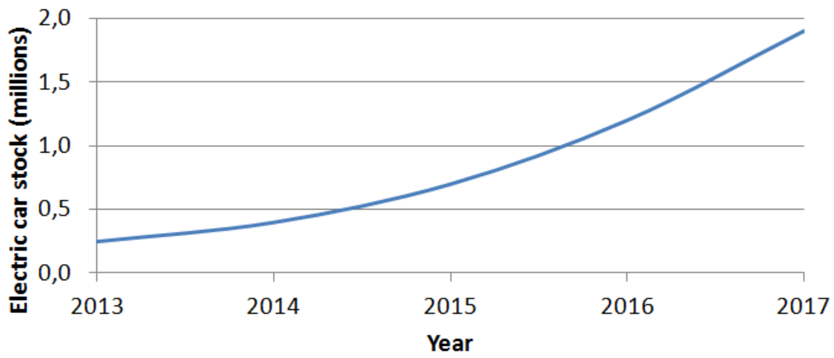

Figure 2.1: Cumulative electric vehicle sales for 2013–2017 since 2005[18]

All technological progress as well as cost reductions to certain components (e.g. power electronics and batteries) make this exponential growth possible. Different policies (purchase and tax incentives, parking, etc.) as well as improved availability of charging infrastructure are other important factors to take into account.

BEVs use mostly lithium-ion batteries because they offer relatively high energy density, have a high specific energy and good life cycle. Battery lifetime today is compatible with the expected lifetime for passenger cars [19] and their costs are getting progressively lower (see Figure2.2).

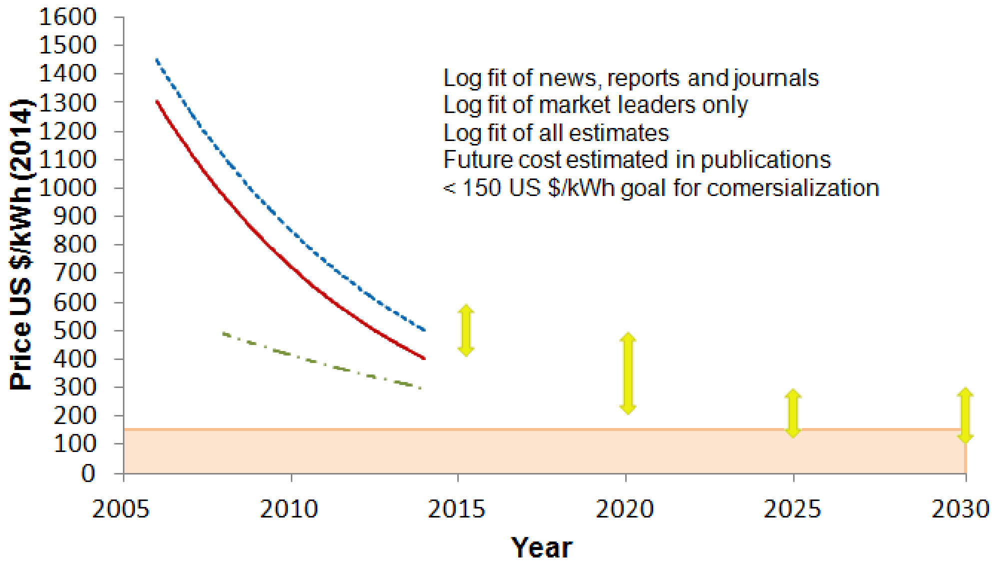

Figure 2.2: Estimates of costs of lithium-ion batteries for use in electric vehicles[20].

Taking 300 USD/kWh, a value close to the average battery cost projected for 2020, installed battery capacity and the manufacturer's suggested retail price (MSRP) (see Table-2.1 and Table-2.2) make possible to calculate an approximate percentage of the battery cost in relation to MSRP (see Figure-2.3).

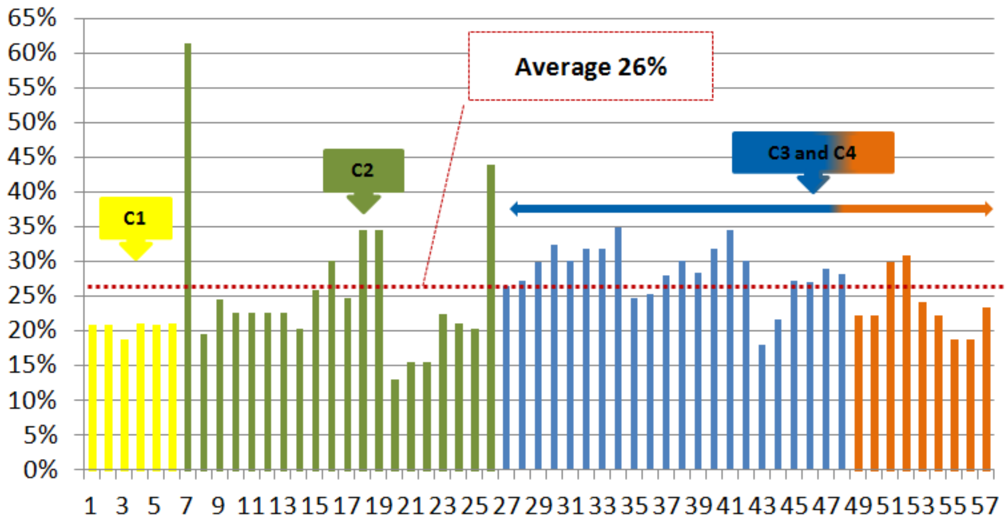

Figure 2.3: Battery costs (300 USD/kWh) and installed battery capacity in relation to the MSRP

Figure-2.3 shows that this ratio ranges from 16% for the BMW i3, to 44% for the Chevrolet Bolt, peaking at 62% with the model e6 made by Chinese manufacturer BYD. The average value across these models is 26% of the MSRP.

With the goal for commercialization cost (see Figure-2.2) of USD 150/kWh for full battery packs it would reduce the ratio between battery cost and MSRP to an average of 13%. This represents the point at which the overall purchase plus energy costs of a BEV become competitive with ICE vehicles [10]. Studies show that this commercialization point will be reached in 2025. One way to reduce this ratio between battery cost and MSRP before is using a minimal battery capacity.

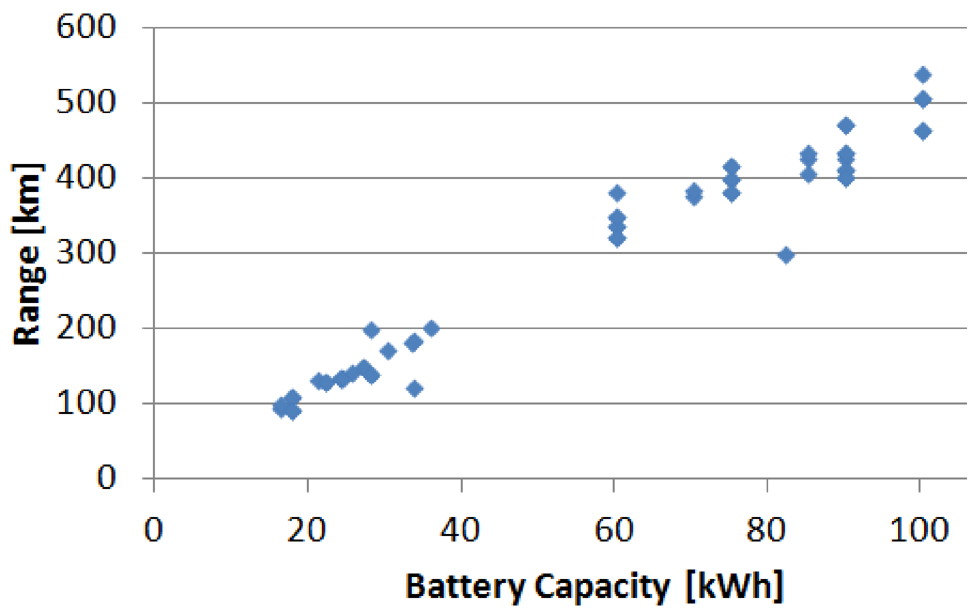

Figure 2.4: Offered battery capacity/driving range for BEVs.

Figure-2.4 shows, for the BEVs sold in different countries during 2016 and 2017, battery capacity and the rated driving range as function of the city energy consumption listed in Table-2.1. BEVs typically have average ranges of 150km for compact and medium sized C1 and C2 vehicles and 410km for Tesla C3 and C4 vehicles.

- Buses

The promising advances for passenger cars have opened new opportunities for the electrification of buses and other modes of transportation . Public buses with regular schedules and routes are early targets for electrification [18]. A growing number of cities are building pilot projects to make public transportation systems operate on electric power. The already mentioned ZeEUS project shows that some European cities have already expanded operations beyond the pilot and have BEB fleets operating as normal transport. Examples include Barcelona, Paris and London, however such formal implementation is not limited to European cities, with China, USA and Japan also adopting the new technology to power its bus fleets [21].

In Europe there are a variety of manufacturers making electric buses, which results in a wide variety of models available in the European market (see Table-2.3). OEMs can design buses to operate with "overnight charging" for a full day of operations on a single battery charged at night or as "opportunity charging," which relies on fast chargers at the terminals or along a bus route. The benefits of "opportunity charging" are that the electric bus require much smaller batteries,resulting in lower purchase prices, less weight. The downfalls include more infrastructure and maintenance costs compared to the overnight charging [22].

- Freight trucks

Similar to buses, until now the use of electric trucks has been limited to fleets of commercial and service trucks that operate in urban environments with regular routes and schedules [18]. A example is the "Solar energy powered electric trucks in Amsterdam" in beverage distribution being carried out by Heineken in the Netherlands [5].

The current use of medium and heavy duty electric trucks with work cycles such long-haul operations are carried out on a pilot scale [18]. The trucks offered so far (see Table-2.4) have a maximum range of $250km$ with a future incorporation planned for long-haul electric heavy freight trucks. [6].

[5]https://www.theheinekencompany.com/
[6]e.g. Tesla Semi, Daimler eCascadia and eM2

3 Method

In this chapter the method to obtain the minimal battery capacity has been discussed. In order to figure out the recommended minimal battery capacity, three different vehicle classes, passenger cars (C), buses (B) and trucks (T), were used. To calculate the minimal battery capacity, a energy consumption equation had been established and described. The effects and measurement methods for the battery ageing effect are explained at the end of the chapter.

3.1 Modelling minimal battery capacity

To identify the minimal battery capacity for a new electric vehicle from the perspective of a driver, it is necessary to separate the analysed vehicles in classes and categories. The vehicles have been separated in three classes passenger cars, buses and trucks. Each class have different categories representing the size of the vehicle, the number one have a lowest engine power in the class cars, the shorted buses and the last-mile trucks. The category two represent the medium size, family cars, urban buses and short-haul trucks. The third category is larger than the others, car with bigger engine, articulated buses and trucks with more payload. The category four is only for the passengers cars and is for the available Teslas model S and model X with all wheel drive (AWD). The index that accompanies each abbreviation represents which vehicle is being referenced (e.g C1 = small car). This was made to be able to adapt better the demand of the different drivers and to refine the results. The categorization was made empirically taking into account the engine power as it relates to passenger cars, the length for buses and the payload for trucks.

This categorization is explained with more details in each section, for the passenger cars in Subsection-3.2.1, for the buses in Subsection-3.2.2 and for the road freight mode in Subsection-3.2.3. A summary is presented in Table-3.1.

The task of identifying the minimal battery capacity is focused on the needs of a driver taking into account the vehicle models available at the moment[1].

Table 3.1: Categorization by power

Vehicle Class	Categories: Average engine power
Passenger cars	$C1 : 55kW$ $C2 : 102kW$ $C3 : 354kW$ $C4 : 568kW$
Buses	$B1_{(8-11m)} : 160kW$ $B2_{(12-14m)} : 195kW$ $B3_{(18-25m)} : 400kW$
Road freight trucks	$T1_{(lastmile)} : 60kW$ $T2_{(shorthaul)} : 142kW$ $T3_{(longhaul)} : 261kW$

To illustrate the various case studies for the passenger cars, the data presented in the report "Driving and parking patterns of European car drivers - a mobility survey" was selected [10]. This work was considered to create the possible specifications that a driver can have in their mileage. In the case of buses and road freight trucks it was a bit more difficult to create a case study since this depends on the mileage of the route where it is used.

Buses have in general defined operation speeds according to a time table in a route. The operation times for buses were chosen based on the public service schedules offered in an average European city (14 hours for the city periphery and easy city and a 19 hour service schedule for the heavy city).

For the road freight trucks with the $T1$ category, a labour day of 8 hours was taken as reference along with different average speeds in the city to give an idea of the mileage needed. In categories $T2$ and $T3$ analogous reasoning was used with different values for speed and work schedules.

A big advantage of the three selected vehicle classes is the number of existing market models (see Table-3.2) and the variety of engine power available. Small and medium-sized cars with an optimal design for the city, luxury cars with higher engine power and a low aerodynamic drag, buses with different lengths for use in the urban traffic, as well as large, medium and small trucks for freight transport. On a smaller and larger

[1] December 2017

scale, all mobility vehicles are present in the collected data and the use of this amount of current market models is beneficial to the validity of the results.

Table 3.2: Number of sampled vehicles in each class

Vehicle	Class	Quantity
Passenger cars	C_i	57
Buses	B_i	29
Road freight trucks	T_i	17

To measure the energy consumption of each vehicle, a driving cycle was used. A driving cycle determines which vehicle operating speed sequences and conditions determine energy or fuel consumption. This should create transparency in comparing energy consumption between different models. The driving cycle results are independent of manufacturer and vehicle type. In general terms, a given speed and acceleration profile (see Figure-3.1) checks all vehicles under the same conditions and the determined energy consumption can thus be used to compare the different models.

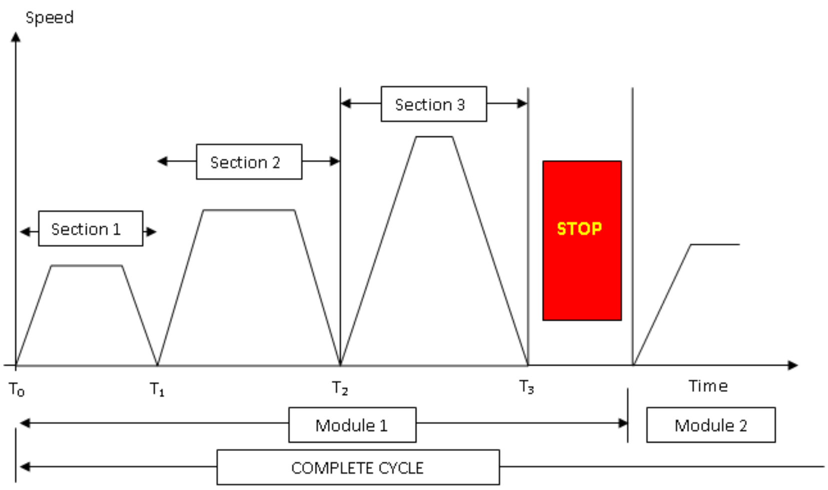

Figure 3.1: General description of a driving cycle. Sections, that specify the vehicle speed and acceleration.

In general every vehicle accelerates and stops several times in the same way until the last final stop is made.

For passenger cars, the data on energy consumption there were different options to choose from, with two being the most common. The EPA (Environmental Protection Agency) and the NEDC (New European Driving Cycle). Both driving cycles defines the energy consumption for city transit and on highways. The use of the EPA [2] driving cycle in passenger cars for energy consumption is preferred, because of its accuracy compared to the New European Driving Cycle or NEDC [3]. In general, when comparing the data given by these two cycles, in most cases the NEDC cycle shows higher values than the EPA (see Figure-3.2).

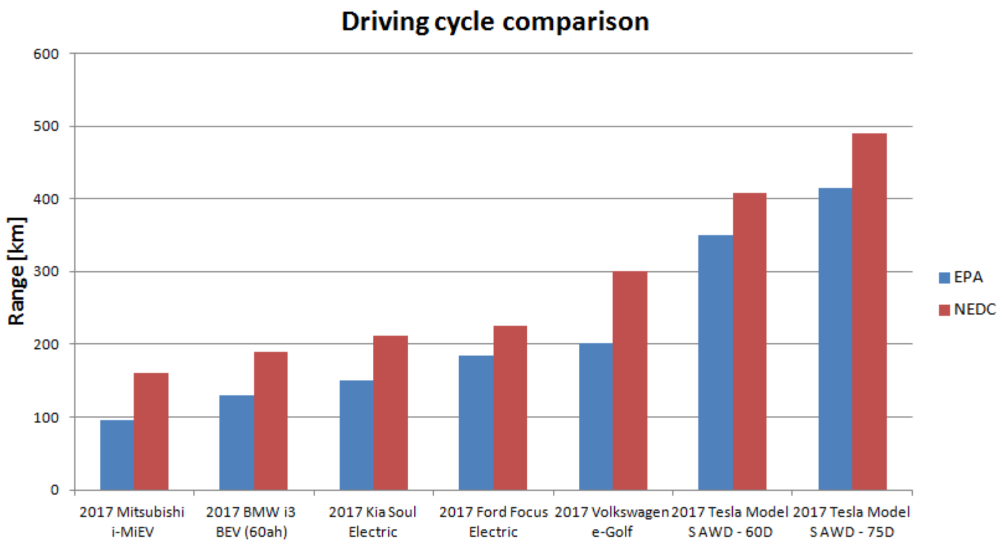

Figure 3.2: Comparison between the most used diving cycles NEDC vs. EPA

The EPA specification is determined from values that have arisen from practical laboratory conditions. Here a scenario "city" and scenario "highway" are driven in warm weather with air conditioning and cold weather with heating. The values under NEDC are also determined in the laboratory but at room temperature. In this test NEDC, a maximum of $50 km/h$ is driven four times in the city and an overland cycle is carried out. The most important difference, however, is that in the NEDC driving cycle, heating and air conditioning are not taken into account, so it should be noted that the NEDC value does not underlie real conditions such as temperature, weather conditions and driving style. For this reason, the use of the EPA driving cycle is preferred.

Buses instead are determined by the driving cycle SORT (Standardised On-Road Test Cycles). The driving cycle was developed by the International Association of Public Transportation UITP (Franz: Union Internationale des Transports Publics). Here its also drove through different modules with defined speeds (see Table-3.3).

[2] `http://www.epa.gov/`
[3] `http://www.unece.org/trans/main/welcwp29.html`

Table 3.3: Test cycles - SORT and UITP use average speed

Cycle	Description	Average speed $[km/h]$
SORT 1	Heavy urban	12
SORT 2	Mixed or Easy urban	17
SORT 3	Easy suburban or Periurbain	27

To obtain the total consumption, all modules are drove (SORT 1, 2, 3) and an average value is calculated. Different to the passenger cars the driving cycle includes the opening and closing of the doors every stop, the bus has to be at least at half passenger capacity, having the standard basis equipment and being in nominal tuning, etc.

For the road freight trucks there is no established driving cycle for the measurement of energy efficiency and all values are dictated by the respective vehicle manufacturer.

Table-3.4 present an overview of the different used driving cycles of the different classes.

Table 3.4: Driving cycle data source

Class	Vehicle	Driving cycle
C	Passenger cars	EPA
B	Buses	SORT
T	Road freight trucks	Manufacturer

To calculate the matching battery capacity, the driver, in addition to choosing the vehicle class (passenger car, bus or freight truck), is also choosing a desired size of the vehicle choosing one of the categories from Table-3.1. Then, with daily mileage consumption determined by their own behaviour or by the route, the model yields a result of net value for battery capacity.

For the total battery capacity (QB_{tot}), a degree of degradation (QB_{φ}) is added so that at the end of the battery lifespan the demanded mileage is still potentially satisfied. This lifespan means that 20% of the battery capacity is lost as a result of battery degradation [16].

The aim of this regression analysis is to find a relation between the vehicle energy consumption, engine power, battery capacity and mileage. In this way, select a recommended minimum size in the battery capacity and save acquisition cost.

The development of the model used for this formal analysis is described in more detail in the next section (see Section-3.2).

Due to the large selection of vehicles, average engine power is used for the respective categories and classes, and the driver is presumed to be rational and has the objective to select the minimal cost solution to meet desired needs.

There are differences in the chemistry of lithium ion batteries. The batteries are named after their active materials. This material gives special characteristics to the battery like voltages, specific energy, cycle life, etc. The most used in the automotive industry are Lithium Manganese Oxide ($LiMn_2 O_4$) and the Lithium Iron Phosphate ($LiFePO_4$) in larger vehicles. As all lithium-ion batteries have a common name and similar properties, the general term "lithium-ion battery" will be used.

3.2 Formal framework

Equation-3.1 to Equation-3.7 are used to calculate minimal battery capacity. Additional parameters used are described in Table-3.5 below.

Table 3.5: Overview of decision variables and parameters used in the methodology.

Parameter	Unit	Description
EC_i	[kWh/km]	Energy efficiency
d_i, e_i, f_i	[−]	Coefficients obtained from the econometric analysis
i	[−]	Index for the vehicle category
P_i	$[kW]$	Engine peak power
QB_{φ}	$[kWh]$	Degradation capacity of the battery (aging factor)
QB_i	$[kWh]$	Nominal capacity of the battery
QB_{tot_i}	[kWh]	Total capacity of the battery
s_i	$[km]$	Vehicle range
φ_{deg}	[−]	Degradation factor

As a first step, for the theoretical and methodological contributions and to determinate the current knowledge and the substantive findings a literature research was made. The different features of batteries and EVs mentioned before were listed and analysed, and all technical features, energy features and their dependencies with the energy consumption lead to Equation-3.1.

$$EC_i = d_i + e_i \cdot P_i + f_i \cdot QB_i \tag{3.1}$$

Where d_i, e_i, f_i are the obtained coefficients from the regression analysis, EC_i describe the energy consumption obtained from the driving cycle in kWh/km, QB_i equals the net battery capacity in kWh. P_i the engine power of each vehicle in kW and the variable s_i the individual driving mileage of the user.

That means that energy consumption is defined by a linear equation with engine power (P_i), nominal battery capacity (QB_i) and weighted with several coefficients (d_i, e_i, f_i).

- Engine power (P_i): Larger engines increase vehicle mass, volume and weight, but they are also more efficient [23]. Larger engines have the properties to increase acceleration and driving-style dynamics, making the vehicles flexible and making it possible to drive in a more dynamic way.

- Battery capacity (QB_i): A change in this parameter also brings a change in the weight and volume of vehicles.
  These parameters reflect in some way the aerodynamic drag and the weight of the car curb, representing a possible increase or reduction in the energy efficiency of the vehicle.

With the collected data and the regression analysis the coefficients d_i, e_i and f_i have been calculated (see Chapter-1, Section-1.2).

After the linear regression, the battery capacity was defined (see Equation-3.2). This definition was made in order to achieve a relationship between battery capacity QBB_i, mileage s_i and energy consumption EC_i to create a equation system with the energy consumption (Equation-3.1).

$$QB_i = s_i \times EC_i \tag{3.2}$$

In this relationship (Equation-3.2) it is possible to solve the energy consumption EC_i and substitute this parameter in the Equation-3.1. (Equation-3.3 in Equation-3.4).

$$EC_i = \frac{QB_i}{s_i} \tag{3.3}$$

$$\frac{QB_i}{s_i} = d_i + e_i \cdot P_i + f_i \cdot QB_i \tag{3.4}$$

By making this substitution (Equation-3.4) and solving QB_i from the equation, the expected model for calculating the minimal battery capacity QB_i is obtained (see Equation-3.5).

$$QB_i = s_i \cdot \frac{d_i + e_i \cdot P_i}{1 - f_i \cdot s_i} \tag{3.5}$$

Equation-3.5 would give the answer of the minimization model without taking into account the total life of the battery and the ageing effects that impact battery life. If the minimal value given only by the approximation model for a given consumption is used, such capacity decline would result in the mileage offered by the battery being insufficient over time (see Subsection 3.3).

To counteract this effect, an extra value (QB_{φ}) was added to net battery capacity, giving the total required capacity as a result (see Subsecction-3.3).

3.2.1 Data overview of passenger cars

The first class analysed in this work corresponds to passenger cars. This class has the advantage of being the largest market and with a tendency to increase in relation to the number of existing models and technical advances.

26 cars of different manufacturers (BMW, Chevrolet, Ford, Hyundai, Mercedes-Benz, etc.) and 31 cars from the company Tesla for a total of 57 vehicles were analysed in this class, representing a significant sample that covers most of the cars available in 2016 and 2017.

According to the categorization of this study, in this class are all kinds of models from small cars to luxury cars. The categorization was done empirically by the author (see Figure-3.3) and similar models with similar engines power and use were grouped to make an analysis easier.

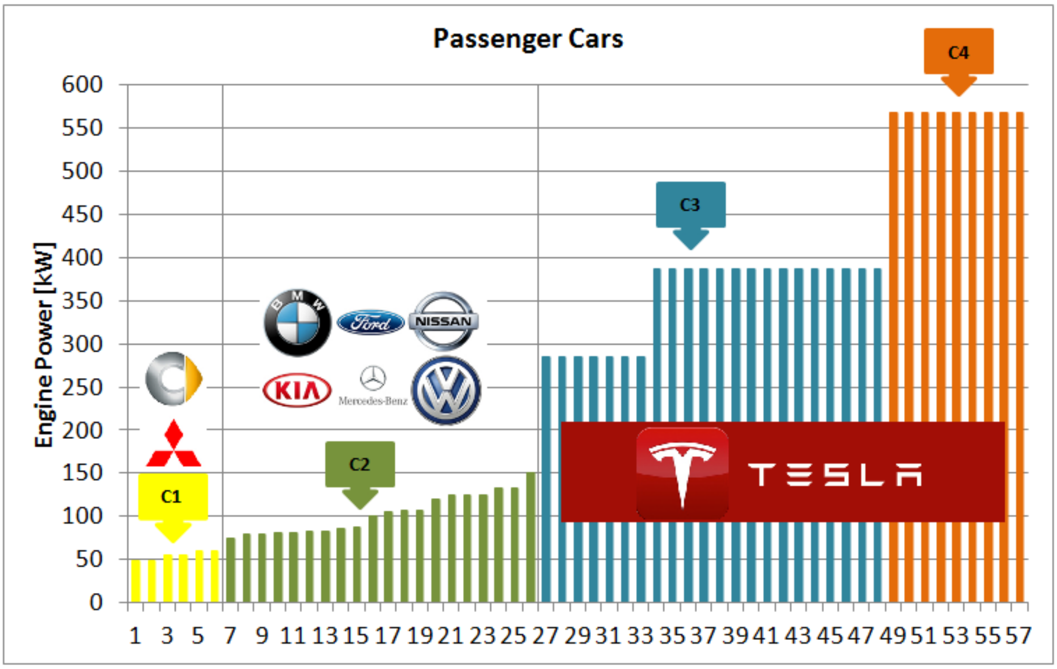

Figure 3.3: Sample passenger cars and categorization by engine power

- *C*1 is the compact class with engine power that range from 49 to 60kWh. There are very successful models in this class such as *Smarts* that are very common in heavy urban environments where vehicle size and agility are of greater importance.

Average engine power for category $C1$

$$P_{C1} = 55kW$$

- $C2$ is the second class taken and the most diverse in terms of models and brands. There are many brands competing in this category such as *BMV, Ford, VW,* etc. These are cars with wider uses than those of the $C1$ class because of the number of seats and space available.

Average engine power for category $C2$

$$P_{C2} = 102kW$$

- $C3$ and $C4$ are the luxury categories and it is important to note that the only participant in this class is Tesla. Focus on Figure-3.4 the models offered by this brand represent more than 50 percent of the database.

Since the applied model is similar to the other two categories and the consumption rate shows very similar values for city and highway (see Table-2.1), the same consumption rate values for the model was used for both driving profiles.

Average engine power for categories $C3$ and $C4$

$$P_{C3} = 354kW$$
$$P_{C4} = 568kW$$

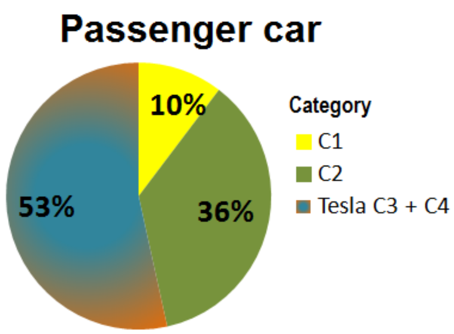

Figure 3.4: Percentage of distribution by classes, C3 and C4 are from the company Tesla

Table 3.6: Overview of the passenger car category

Category	Average engine power $[kW]$
$C1$	55
$C2$	102
$C3$	354
$C4$	568

3.2.2 Data overview of buses

The second class evaluated are buses (B), a transport mode of great interest since much of public transport in Europe belongs to the state. In this class, 29 bus models were taken and divided as before into 3 categories depending on the length of the buses (see Figure-3.5).

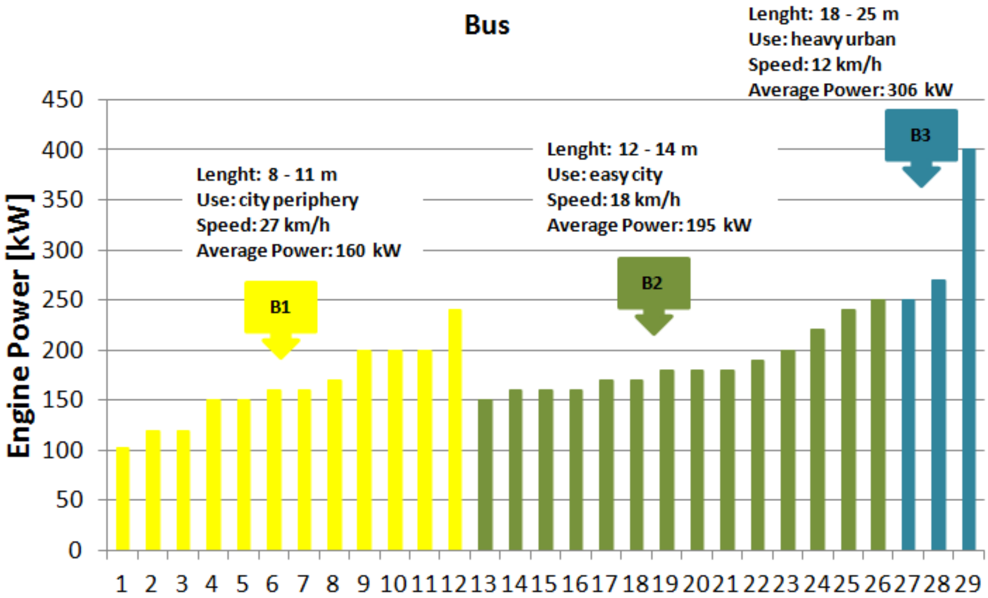

Figure 3.5: Sample bus and categorization by use

- $B1$ includes buses seen in periphery areas where population density is lower or buses are used to connect the city with nearby towns. These buses range from 8 to 11 meters long and with engine powers between 103 and $200kW$.

$$\text{Average engine power for the category } B1$$
$$P_{B1} = 160kW$$

- $B2$ are larger and more versatile buses. Class $B2$ buses can be used in urban areas as well as peripheral areas. These are between 12 and 14 meters long and have engines similar to those of class $B1$ with powers between 100 and $270kW$. This category with almost half of the buses in the sample (14 from 29 in total) shows the versatility previously mentioned and makes it of great interest.

$$\text{Average engine power for the category } B2$$
$$P_{B2} = 195kW$$

- $B3$ are the longest buses on the market, ranging from 18 to 25 meters long and with larger engines between 240 and 480kW. This category has three models and is used in heavy urban environments.

Average engine power for the category $B3$

$$P_{B3} = 306kW$$

These three categories ($B1$, $B2$ and $B3$) also agree with the three cycles used to measure the consumption of buses developed by the International Association of Public Transportation UITP (see Table-3.3).

3.2.3 Data overview of road freight trucks

Last but not least is the road freight trucks. Some time ago it was thought that this transport mode was going to be difficult to electrify due to demanding mileage, but with advances in the logistic and the increase in the energy density of batteries, there is more interest and more investment in this mode [4].

17 models were used in this sample, and the division was made taking into account the payload capacity of each vehicle Figure-3.6.

[4] https://www.tesla.com/semi

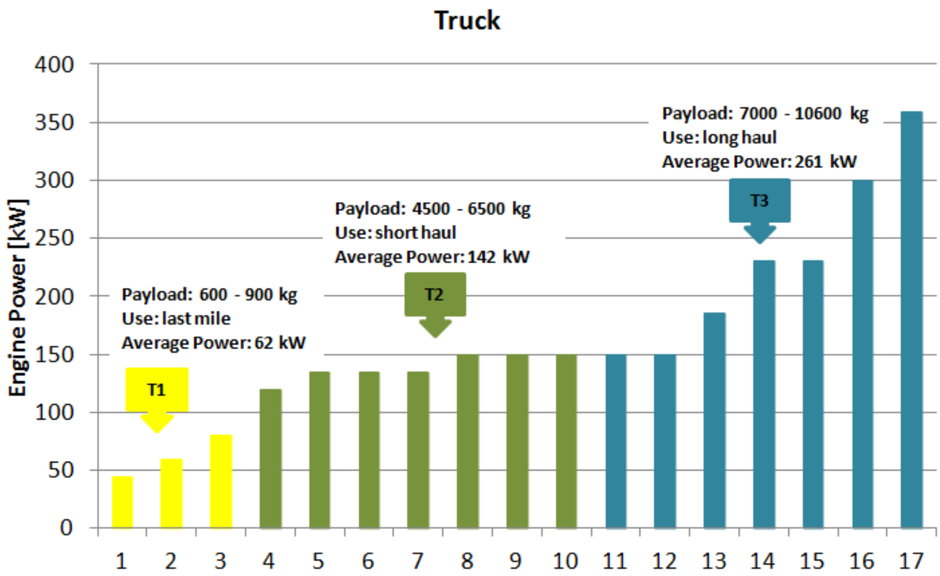

Figure 3.6: Sample trucks and categorization by use in the supply chain

To effectively cover a wide variety of transport modes, three categories were created and characterized by engine power P_{Ti} (see $T1$, $T2$, $T3$ in Figure-3.6).

- $T1$ represents the "last mile" transport mode. In a logistic system, this means the transport to the front door of the customer. The vehicles here are small trucks with a payload between 605 and 940kg.

$$\text{Average engine power for the category } T1$$
$$P_{T1} = 62kW$$

- $T2$ represents vehicles intended for longer distances and payload greater than those in the T1 category. These vehicles have payload between 4500 and 6500kg.

$$\text{Average engine power for the category } T1$$
$$P_{T2} = 142kW$$

- $T3$ are the vehicles with more payload compared to the other two classes, starting at 7000kg up to more than 10000kg. This category should be the one that need the highest range, but due to cost or technology issues, it offers very similar ranges to category $T2$.

$$\text{Average engine power for the category } T3$$
$$P_{T3} = 261kW$$

3.3 Modelling and assumption for the battery aging

Identifying the aging mechanism of commercial lithium ion batteries is an important and complex task. A very comprehensive article about lithium-ion batteries[16] describing the ageing mechanisms and their estimations for automotive applications. Each of the different methods offers advantages and disadvantages and it becomes necessary to accept compromises to estimate battery ageing.

Table-3.7 taken from this article, lists a review of the ageing mechanisms for lithium-ion batteries, explaining that there are few basic mechanisms that can describe the general phenomena of ageing due to the difficulty in quantification.

For examples an estimation for battery ageing can be made by direct measurement of its capacity. This method is very precise and one does not need to have recorded data to employ it, however, it has the disadvantage of not being able to make accurate predictions about battery behaviour. Other possibility is the statistical method has good precision but a certain amount of available data is necessary for its proper functioning. This method is able to make good predictions for ageing behaviour.

Table 3.7: Battery ageing estimation methods performances comparison for five principal aspects [16].

Method	Precision	Operate without data	Prediction
Direct measurement	Excellent	Excellent	Very poor
Equivalent circuit	Fair	Good	Fair
Electrochemical	Excellent	Fair	Fair
Performance	Good	Poor	Good
Analytical	Good	Poor	Poor
Statistical	Good	Very poor	Good

There are few studies that consider ageing as a consequence of all interactions between environmental factors. Lithium-ion batteries are complex systems and their ageing processes, which are even more complicated, strongly depend on operating conditions. For this reason vehicles manufactures use batteries bigger and the lower and upper battery capacity is used to maintain the offered range.

$$QB_{\varphi} = QB_i \times 20\% \tag{3.6}$$

In this work an extra 20% value is added to counteract the ageing effect and compliance with the requirements presented by the driver at the end of the useful life of the vehicle (see Equation-3.6).

This means the total battery capacity (QB_{tot}) needed in a vehicle results from the Equation-3.5 and the addition of the value that counteracts the ageing of the battery QB_{φ} (see Equation-3.7).

$$QB_{tot} = QB_i + QB_{\varphi} \tag{3.7}$$

The total battery capacity meets the vehicle's necessary mileage at the end of its useful life and can be managed in different ways to meet the demand on the vehicle's mileage, whether the vehicle is new or at the end of its useful life (see Figure-3.7).

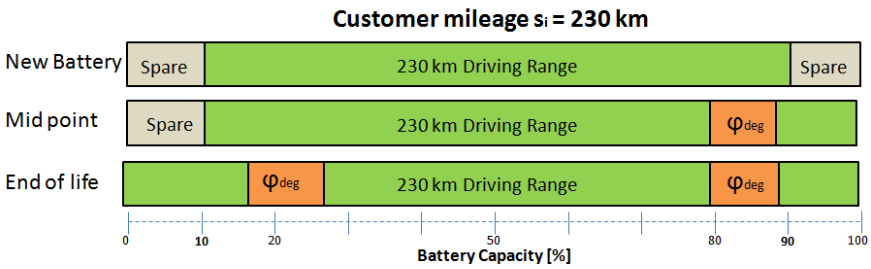

Figure 3.7: Example - Management of value QB_{tot} for $s_i = 230km$ [24]

Figure-3.7 shows an option of how vehicles manufacture the battery capacity of a new battery management. The battery is not fully charged and not fully discharged when the battery is new. As the degradation factor (φ_{deg}) increase and the battery fades, the bandwidth expands to maintain the same driving range.

4 Results and discussion

In this chapter all model results of the minimization model introduced in Chapter 3 are illustrated and discussed. Apart from the different case studies, which demonstrates today's challenges in the transport sector, case scenarios with higher mileage and with mixed distribution are included. In each case study the results are rounded and include the ageing factor (see Equation-3.7).

As previously stated, the importance of handling the available resources responsibly and the goal of lowering acquisition prices of BEV, makes necessary a method that describes how to calculate the minimum capacity required in the battery for a BEV. The battery is an important component that can unnecessarily increase the price of a vehicle. Therefore, and as described in the Chapter-3, the presented model in this thesis helps to solve this task and presents possible results for minimum battery capacity.

4.1 Passenger cars

The regression analysis of this class was divided in two parts. The different manufacturers (BMW, Chevrolet, Ford, Hyundai, Mercedes-Benz, etc.) part with a 26 vehicles samples and the part from the company Tesla with 31 vehicles.

- Passenger cars different manufacturers

For the passenger cars the category $C1$ and $C2$, the linear regression was only made with the characteristic parameters (EC_i, QB_i) of all collected vehicles. The engine power P_i has a lower correlation in the statistical results (see Figure-4.1).

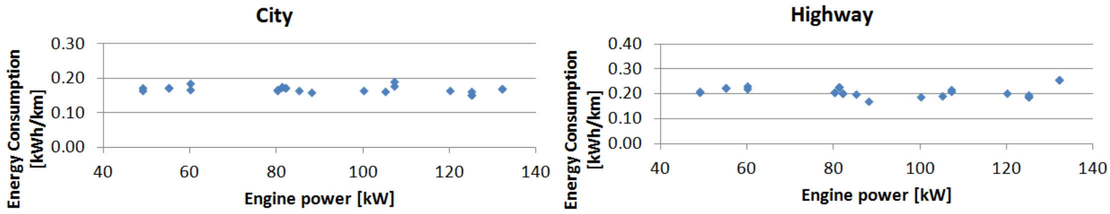

Figure 4.1: Horizontal course between energy consumption vs. engine power

The almost horizontal course between energy consumption and engine power, shows a lower dependency between both parameters. The consumption is almost constant in the different models of cars (Average value city 0.20 and 0.22 kWh/km for highway), causing the coefficient e_C to be almost zero.

The other coefficients d_C, f_C obtained in the regression analysis and the consumption of a vehicle (EC_i) describe now a linear equation depending only on the battery capacity QB_i (see Equation-4.1).

$$EC_C = d_C + f_C \cdot QB_C \tag{4.1}$$

For the Equation-4.1 the obtained coefficients (see Table4.1) from the regression were replaced and the two different equation for the city and highway profile presented (Equation-4.2 and Equation-4.3).

Table 4.1: Regression statistics for passenger cars $C1$ and $C2$ with city consumption profile.

Coefficient	Value	t-statistic
d_B	0.1434	24.9912
f_B	0.0011	5.8173

Table 4.2: Regression statistics for passenger cars $C1$ and $C2$ with highway consumption profile.

Coefficient	Value	t-statistic
d_C	0.1932	17.8927
f_C	0.0007	2.0972

For the City driving profile are expected lower speeds, high number of stops and goes and short driving times. The Equation-4.2 describes the passenger car consumption in categories $C1$ and $C2$ that only go through the city. Examples of this type of car may include a small or medium taxi cab, car sharing service, food delivery vehicles, some promotional cars, cars for personal use belonging to people with defined urban life, etc.

$$EC_{C_{City}} = 0.1434 + 0.0011 \cdot QB_C \tag{4.2}$$

The highway driving profile has higher cruising speeds, few acceleration and longer driving times. The Equation-4.3 specifies a profile of highway driving. Although the interesting analysis is the combination of the two driving profiles (City and Highway), here is possible to represent drivers who live in peripheries or villages, travel to the city and then use public transportation services.

$$EC_{C_{HW}} = 0.1932 + 0.0007 \cdot QB_C \tag{4.3}$$

As explained in the previous chapter (Chapter-3), it is now possible to take the relationship between the energy consumption EC_i, the mileage s_i and the battery capacity QB_i (see Equation-3.2) to obtain by substitution the model that describes the recommended minimum capacity QB_i (see Equation-4.4).

$$QB_i = \frac{s_i \cdot d_i}{1 - f_i \cdot s_i} \tag{4.4}$$

The two evaluated category was the compact cars category $C1$ (e.g. "Smart for2 e-drive") and the medium cars category $C2$ (e.g. BMW i3, Nissan Leaf).

The Equation4.5 and Equation4.6 describe the battery capacity QB_C as a function of the range s_C for the city and highway driving profile. These are represented in Figure-4.2.

$$QB_{C_{CITY}} = \frac{s_i \cdot 0.1434}{1 - 0.0012 \cdot s_i} \tag{4.5}$$

$$QB_{C_{HW}} = \frac{s_i \cdot 0.1932}{1 - 0.0007 \cdot s_i} \tag{4.6}$$

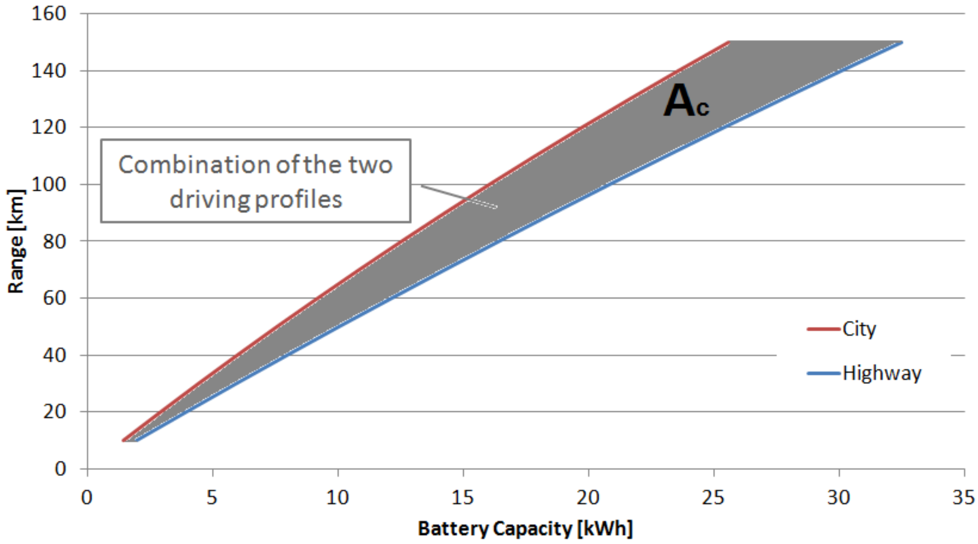

Figure 4.2: City and highway functions for category $C1$ and $C2$

The functions presented in Figure-4.2 limit an area A_C where a mix of different types of driving behaviour may fit. In the case studies for the passenger car class in the Subsection-4.1.1 the different combinations are shown to see in a better way the needs that drivers for the categories $C1$ and $C2$ could have.

- Passenger cars Tesla manufacture

Evaluating the linear regression with the characteristic parameters (P_i, EC_i and QB_i) of all collected Tesla vehicles, the coefficients $d_{TESLA}, e_{TESLA}, f_{TESLA}$ are obtained. The consumption of a vehicle (EC_{TESLA}) in function of the engine power (P_{TESLA}) (see Equation-3.1) and the capacity of the battery QB_{TESLA} (see Equation-3.2) are now evaluated.

For the categories $C3$ and $C4$, where Tesla is the only supplier of passenger cars, (see Subsection-3.2.1 and Figure-3.4) it was possible to make a econometric analysis with all characteristic parameters. These two categories represent a sufficiently large sample and can be evaluated separately to obtain more related coefficients and make the model more precise in case the driver wants to choose this category.

This analysis with the characteristic values (P_{TESLA}, EC_{TESLA}, QB_{TESLA}) generates coefficients (d_{TESLA}, e_{TESLA}, f_{TESLA}) and gives the description for the consumption.

The consumption profile for passenger cars of category $C3$ and $C4$ is presented in the Equation-4.7.

$$EC_{C_{TESLA}} = d_{TESLA} + e_{TESLA} \cdot P_{tot} + f_{TESLA} \cdot QB_C \tag{4.7}$$

The relationship between the energy consumption EC_i, the mileage s_i and the battery capacity QB_i is also used and the model that describes the recommended minimum capacity QB_i its obtained (see Equation-4.8).

$$QB_i = s_i \cdot \frac{d_i + e_i \cdot P_i}{1 - f_i \cdot s_i} \tag{4.8}$$

For the Equation-4.8 the coefficients were replaced and evaluated with the average engine power of each category. Taking the driver demanded range s_i as the only dependent variable.

The Tesla's categories $C3$ ($P_{C3_{TESLA}} = 354kW$) and $C4$ ($P_{C4_{TESLA}} = 568kW$) was evaluated together to recognise common relationships and the obtained coefficients are listed in Table-4.2

Table 4.3: Regression statistics for Tesla

Coefficient	Value	t-statistic
d_B	12.7214	6.2926
e_B	$5.7020 \cdot 10^{-5}$	2.3273
f_B	0.0005	2.8481

The category $C3$ and $C4$ are the luxury category, has engines with power between $P_i = 285kW$ and $P_i = 568kW$ and all models are from the Tesla company. The categories are analysed as explained in the Chapter-3 and evaluated using the average engine power of $P_{C3} = 354kW$ for the category $C3$ and $P_{C4} = 568kW$ for the category $C4$ (see Equation-4.9 and Equation-4.10).

$$QB_{C_{TESLA_{CITY-HW}}} = s_{C_{TESLA}} \times \frac{0.1683 + 0.0003433 \cdot 354kW}{1 + 0.001293 \cdot s_{C_{TESLA}}} \tag{4.9}$$

$$QB_{C_{TESLA_{CITY-HW}}} = s_{C_{TESLA}} \times \frac{0.1683 + 0.0003433 \cdot 568kW}{1 + 0.001293 \cdot s_{C_{TESLA}}} \tag{4.10}$$

Here only the City driving profile is evaluated. City energy consumption and highway energy consumption are not differentiated since according to the EPA, driving cycles yield very similar values (see Table-2.2) unlike the categories $C1$ and $C2$.

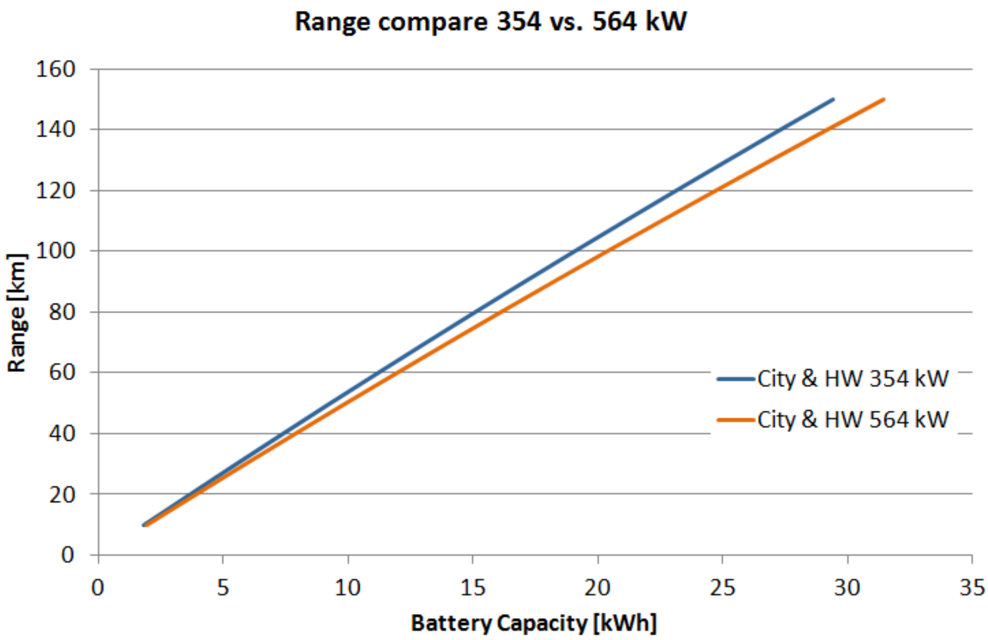

Figure 4.3: Functions for the $C3$ and $C4$ category $P_{C3} = 354kW$ and $P_{C3} = 568kW$

The efficiency of the big engines is remarkable [23], the $C4$ engine is $200kW$ more powerful than the $C3$ category and even so, its functions have similar curve shape (Figure-4.3).

4.1.1 Passenger cars: Case study

In order to complete a successful analysis for this case study, the consumption of mileage in this document was based on the study "Driving and parking patterns of European car drivers - a mobility survey"[10] carried out to describe the behaviour of drivers at European levels. This study shows the Figure-4.4 and the average amount of mileage required by users in different European countries over a week.

Based on this information, it is possible to create appropriate case studies for near constant mileage and have results that are close to a real user.

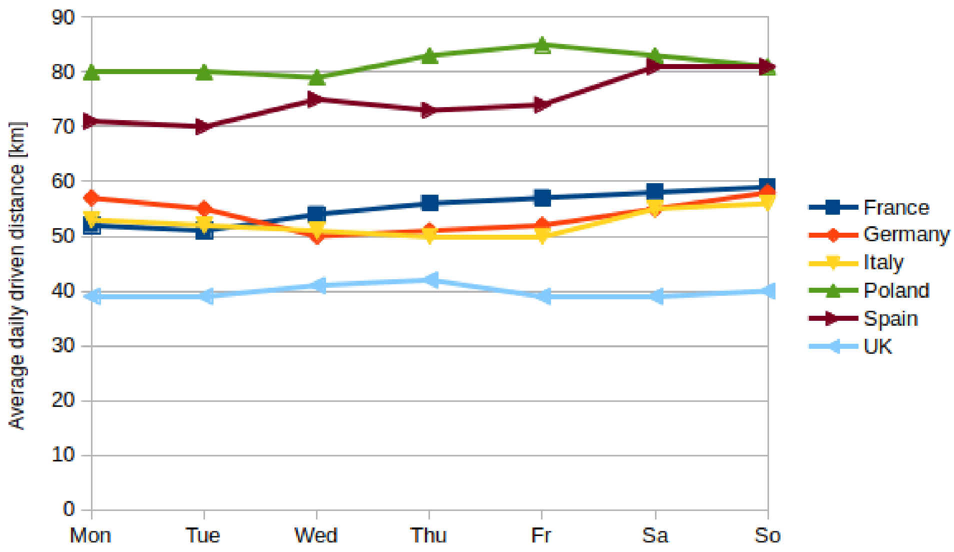

Figure 4.4: Overview summary for the week mileage of 5 countries [10]

Highlighting the extremes of the graph, usually one can see that $40 km/day$ represents a minimum range and $90 km/day$ a maximum range. In order to represent a large number of drivers in the category C_i, four cases with different driving distributions are presented (see Table-4.4).

Table 4.4: Case study - Distribution between city and highway mileage

	Total Range $[km/d]$	City [%]	City $[km]$	Highway [%]	Highway $[km]$
Case 1	40	80	32	20	8
Case 2	60	65	39	35	21
Case 3	90	50	45	50	45
Case 4	100	100	100	0	0

- Case 1: Represents a user with $40 km/day$ mileage. 80% of the user's driving is done in the city and the remaining 20% on the highway. This could represent the profile of a person living on the periphery of a common European city and describe the round trip from the home to work and back.

- Case 2: Represents a user with $60 km/day$ daily mileage, which is consumption typical of a citizen from France, Italy or Germany. The assumed distribution is 65% in the city and the remaining 35% on the highway.

- Case 3: Represents the highest mixed consumption of 90km/day where 50% of driving is done in the city and 50% on the highway. This case represents the highest average consumption documented in Europe.

- Case 4: Shows values for a city-only profile of 100km/day. Related profiles would be taxis cabs, car suppliers, other private passenger transportation services, car sharing, etc.

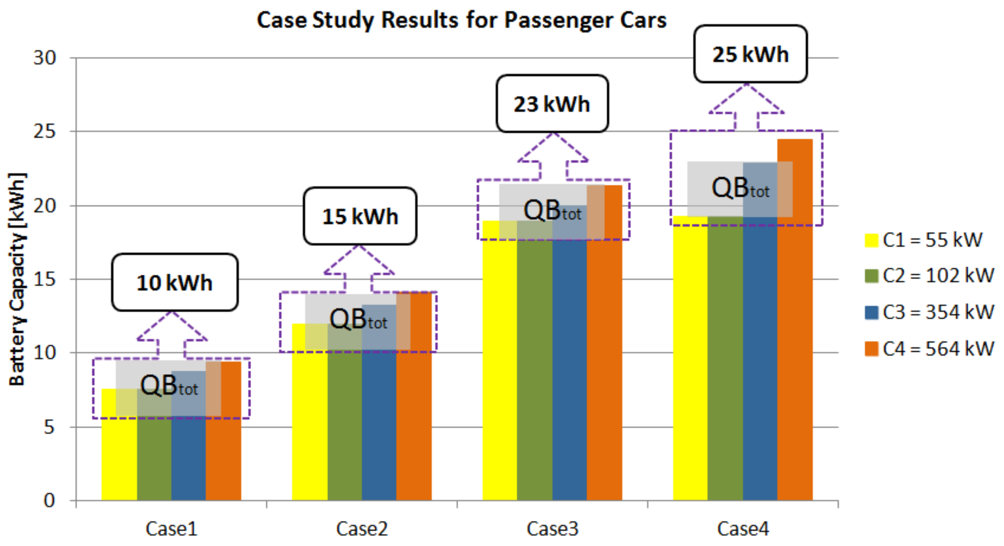

Figure 4.5: Rounded and the recommended values for each case QB_{tot}

The Figure-4.5 shows the recommended minimum battery capacity including ageing for the different categories and the different case studies. The recommended values for each case are listed in Table-4.2.

Table 4.5: Recommended values for battery capacity

	Range [km]	Total Battery Capacity (QB_{tot}) [kWh]
Case 1	40	10
Case 2	60	15
Case 3	90	23
Case 4	100	25

Similar to the figure already shown above (see Figure-4.2), the results for different cases analysed are displayed in Figure-4.6.

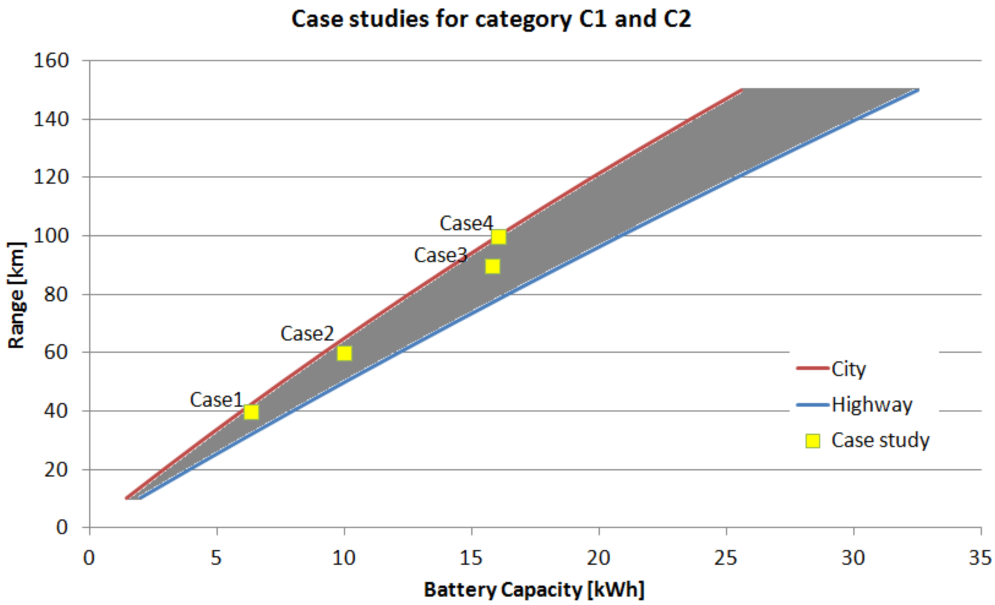

Figure 4.6: Net battery capacity for Cases, category $C1$

4.2 Buses

After the regression analysis, the obtained coefficients (see Table-4.6) are used to evaluate the equation that describes the consumption of the listed buses.

Table 4.6: Regression statistics for buses $R^2 = 0.6758$

Coefficient	Value	t-statistic
d_B	0.5266	6.2926
e_B	0.0024	5.5316
f_B	0.0006	2.0506

The Equation-4.11 describes the bus consumption of the listed vehicles.

$$EC_B = 0.5266 + 0.002416 \cdot P_{Bi} + 0.0006207 \cdot QB_B \tag{4.11}$$

Where EC_B describe the energy consumption the bus kWh/km, QB_B equals the net battery capacity in kWh and P_i the average engine power of the category kW.

For buses, only one driving consumption profile was taken because the manufacturers offered value is the average result of the three consumption profiles: heavy city (SORT1), easy city (SORT2) and city periphery (SORT3).

Similar to the Subsection-4.1, the energy consumption (see Equation-4.11 was substituted with the defined equation (see Equation-3.2) to obtain the minimization model:

$$QB_B = s_B \times \frac{0.5266 + 0.002416 \cdot P_{Bi}}{1 - 0.0006207 \cdot s_B} \tag{4.12}$$

The Equation-4.12 was evaluated for the different bus categories ($B1$, $B2$, $B3$) with the respective average engine power P_{Bi}.

The results obtained are represented in Figure-4.7.

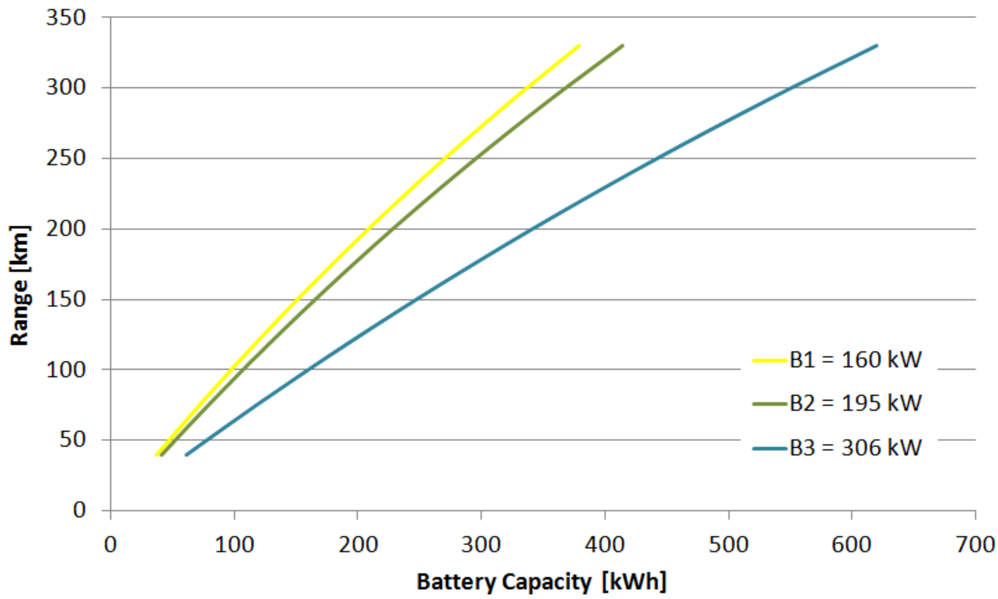

Figure 4.7: Categories functions $B1$, $B2$ and $B3$

4.2.1 Buses: Case study

The case studies in the category Bus (B_i) were evaluated by dividing them by their operation use, according to their size and operation speed (See Figure-4.8).

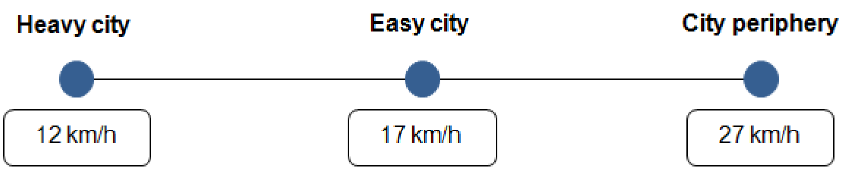

Figure 4.8: Bus driving speed in different use profiles used for the UITP

For its evaluation, three cases were taken for each category:

- Case 1: The category of Midibus $B1$ buses are the smallest analysed. With lengths between 8 and 11 meters, are used in smaller cities and in peripheral areas of large cities where population density is low. For this case, an 8-hour workday and two drivers were taken for a total of 16 work hours. It is assumed that each driver drives 6 effective hours for 12 hours total of transit (average time lapse in which public transport works in the city peripheries). The defined speed according to the SORT cycle is $27km/h$, resulting a $324km$ mileage.

$$s_{B1} = 27\frac{km}{h} \times 12h \tag{4.13}$$

$$s_{B1} = 378km \tag{4.14}$$

- Case 2: $B2$ is a category with a 12 meters average length. Its use is generally for a area between city and periphery called by the International Association of Public Transportation (French: the Union Internationale des Transports Publics (UITP)) "easy city". For operation time, the reasoning is similar to Case 1 but with an extra hour of driving for each driver ($2 \times 7h = 14h$). The defined speed for "easy city" according to the UITP is $17km/h$. The result is a route with $238km$.

$$s_{B2} = 17\frac{km}{h} \times 14h \tag{4.15}$$

$$s_{B2} = 238km \tag{4.16}$$

- Case 3: $B3$ is the bus category and the longest on the market, with lengths ranging from 18 to 25 meters. In many cities the $B3$ category is exclusively for use in downtown areas, where tourists and residents have to share public transportation. The number of mobilized individuals in this area is higher than in any other part of the city. This area of operation is called by the UITP "heavy city" and is characterized by a $12km/h$ speed, and longer driving times ($19hours$) resulting in a mileage of $228km$.

$$s_{B3} = 12\frac{km}{h} \times 19h \tag{4.17}$$

$$s_{B3} = 228km \tag{4.18}$$

All journeys are designed to be travelled without taking into account additional infrastructure (battery change, charging at stations, etc.), therefore the journey is made starting with the full load and operates until the end of the day.

A summary of the categories, their average engine power and the to travel mileage in each case is summarized in Table-4.7.

Table 4.7: Case study - Overview Range Bus

Category and Case	Average Power $[kW]$	Speed $[km/h]$	Operation time $[h]$	Range $[km/d]$
$B1_{Case1}$	166	27	12	324
$B2_{Case2}$	182	17	14	238
$B3_{Case3}$	314	12	19	228

Evaluating these mileages with the Equation-4.12, battery capacity (QB_{tot}) values are obtained.

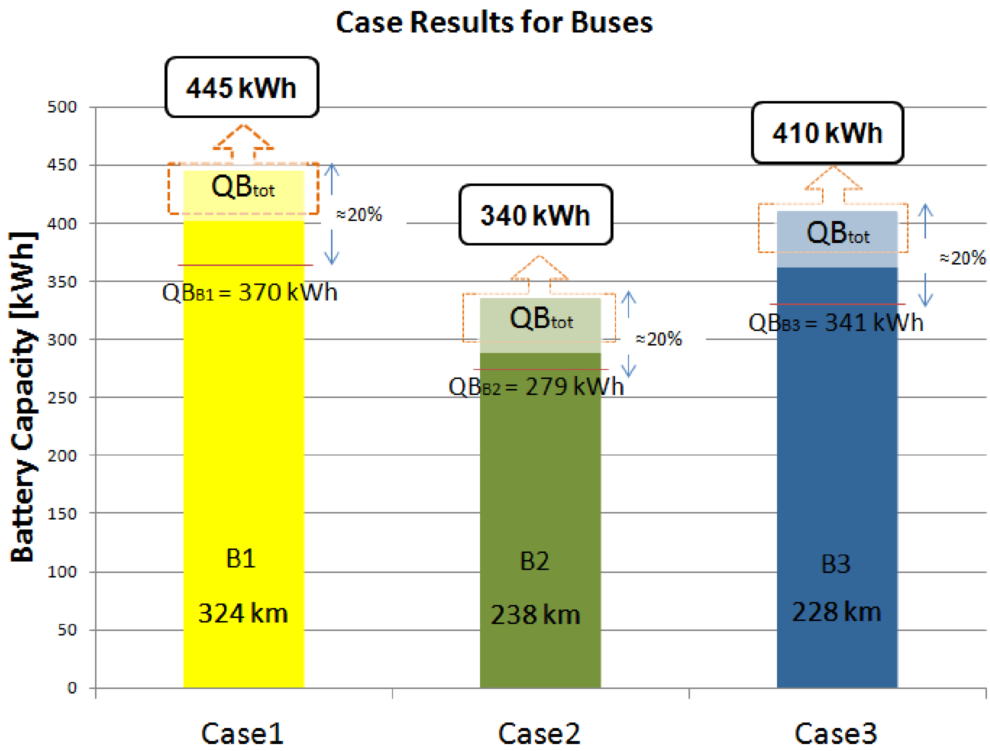

Figure 4.9: Results for the case studies in class B (without ageing factor)

In this class the results of the model are presented in the Figure-4.9. The values QB_{B1}, QB_{B2}, QB_{B3} are the results of the Model without the ageing of the battery. QB_{tot} are the total rounded values, including the 20% ageing factor. The minimum recommended values for each case are listed in Table-4.8.

Table 4.8: Recommended values for the battery capacity in class B

Case	Range $[km]$	Battery Capacity QB_B $[kWh]$	Total Battery Capacity QB_{tot} $[kWh]$
Case 1	324	370	445
Case 2	238	279	360
Case 3	228	341	420

An extra case study was made to evaluate the three categories $(B1, B2, B3)$ with a constant route length $s_{Bi} = 250km$.

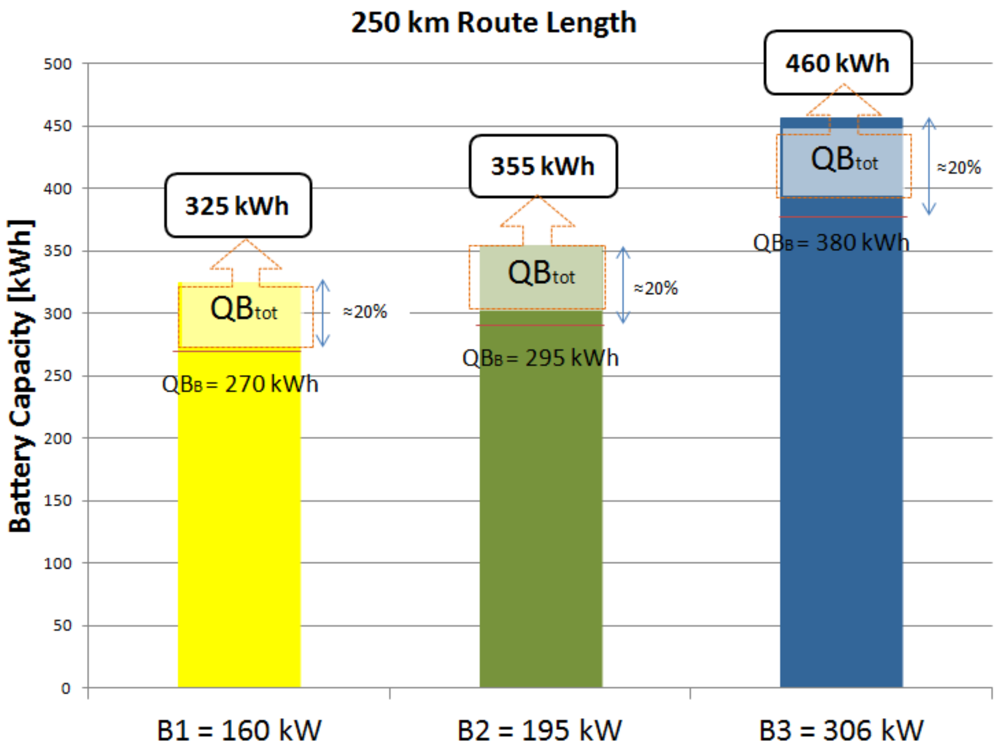

Figure 4.10: Case study $s_B = 250km$ route for all bus categories

The results shown in Figure-4.10 are summarized in Table-4.9 and show the expected trend that at higher power and bus length, more battery is needed for a defined route.

Table 4.9: Recommended values for the battery capacity in a 250 km route

Case	Range $[km]$	Battery Capacity QB_B $[kWh]$	Total Battery Capacity QB_{tot} $[kWh]$
B1	250	270	325
B2	250	295	355
B3	250	380	460

4.3 Road freight trucks

The road freight trucks class (class T_i) is very similar to the buses. In this section, the Equation-4.19 describes the average consumption of the trucks.

$$EC_T = 0.25166 + 0.001697 \cdot P_{Ti} + 0.001888 \cdot QB_T \tag{4.19}$$

The obtained coefficients from the regression analysis are listed in Table-4.10,

Table 4.10: Regression statistics for freight trucks $R^2 = 0.8474$

Coefficient	Value	t-statistic
d_T	0.2573	3.9984
e_T	0.0017	3.1866
f_T	0.0018	3.1346

and the minimal battery capacity model is described in Equation-4.20.

$$QB_T = s_{Ti} \times \frac{0.25166 + 0.001697 \cdot P_{Ti}}{1 - 0.001888 \cdot s_{Ti}} \tag{4.20}$$

Inserting the category average engine power (P_{Ti}), Figure-4.11 shows the curve running the three freight trucks functions.

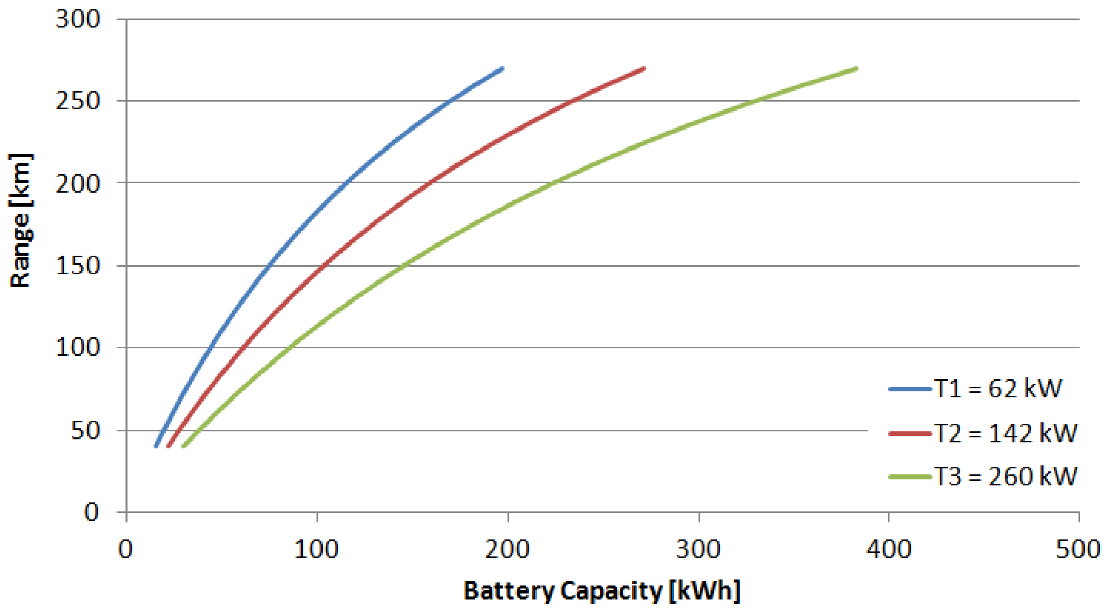

Figure 4.11: Categories functions $T1$, $T2$ and $T3$

4.3.1 Road freight trucks: Case study

For the road freight trucks, an analysis similar to that of the buses was made, operation times and traffic speeds are comparable and additional values are taken to see the possible battery capacities.

- Case 1: Here the category $T1$ vehicles are evaluated, $T1$ are fleets of small vehicles, used in the city for logistics tasks (e.g. mail, small business logistic, last mile services, etc.). A driver with 8 hours of daily work and 6 hours of effective driving is assumed. It also assumes an average transit speed of $10km/h$. This results in a $60km/day$ mileage.

$$s_{T1} = 10km/h \times 6h \tag{4.21}$$

$$s_{T1} = 60km \tag{4.22}$$

To include a larger spectrum showing different mileage and make the results more comprehensive, double and triple the obtained mileage were also evaluated in the case analysis (see Table-4.11).

Table 4.11: Case study - Overview range for the category $T1$

Category	Average P_T $[kW]$	Speed $[km/h]$	Operation time $[h]$	Range $[km/d]$
T1	62	10	6	60
T1	62	20	6	120
T1	62	30	6	180

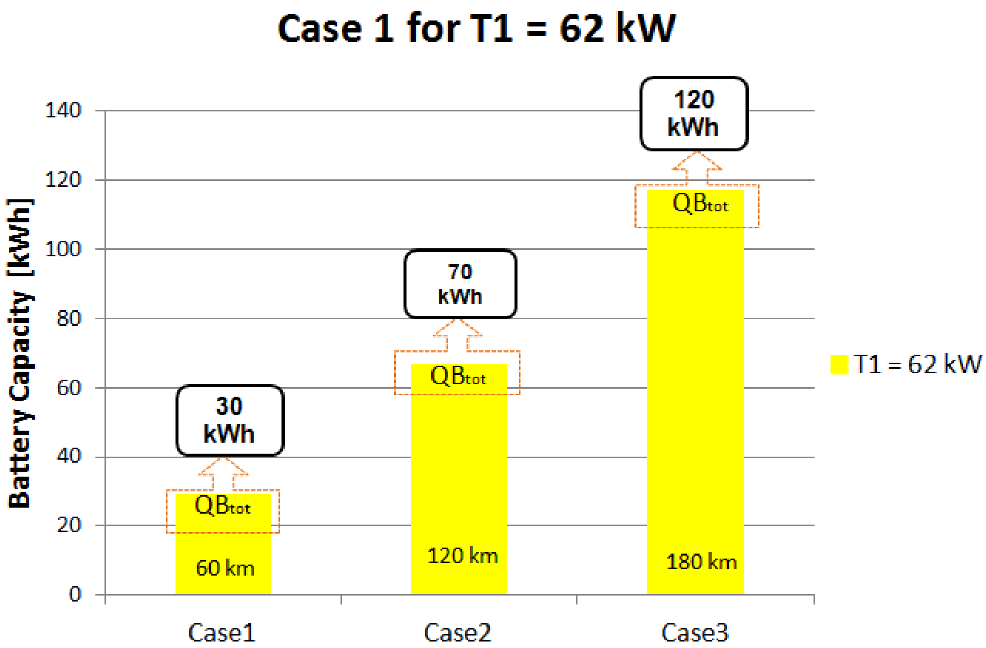

Figure 4.12: Case studies 60, 120 and 180 km for the category $T1$

The results shown in Figure-4.12 are summarized in Table-4.12.

Table 4.12: $T1$ - Recommended values QB for Case 1

	Range $[km]$	Battery Capacity QB_{T2} $[kWh]$	Total Battery Capacity QB_{tot} $[kWh]$
Case 1	60	25	30
Case 1	120	55	70
Case 1	180	100	120

- Case 2: The second case deals with category $T2$, the "medium-size" and is used to supply the city hub (e.g. supermarket). The assumption that the driver drives 5 hours effectively in an 8 hour working day at a $20km/h$ average speed results in a $100km$ mileage.

$$s_{T1} = 20km/h \times 5h \tag{4.23}$$

$$s_{T1} = 100km \tag{4.24}$$

Here we also chose to increase mileage and observe different results (see Table-4.13).

Table 4.13: Case study - Overview range for the category $T2$

Category	Average Power $[kW]$	Speed $[km/h]$	Operation time $[h]$	Range $[km/d]$
T2	142	20	5	100
T2	142	30	5	150
T2	142	50	5	250

The results of Case 2 were able to be compared with those of Case 3 and are presented below.

- Case 3: The last case presents the category T3, these are the road long haul representatives which include vehicles with more than 7 tons and a driving profile mostly on the highway. The European Commission fixed a speed limit of $80km/h$ [1] on highways and a maximum of 9 hours of daily driving.

Following the reasoning from the previous cases (Case 1 and Case 2) and the European regulations presented in article 7 [25], a maximum driving time of $4.5h$ in a $80km/h$

[1] http://ec.europa.eu/transport/road_safety/going_abroad/germany/speed_limits_en.htm

speed route is allowed resulting in a 400km mileage. The vehicle on the market with more range listed in this class is the *Eforce E8* with a lithium iron phosphate battery that provides a range of 250km. This shows that at this time, BEV have a limitation.

For the Case 3 analysis, the same mileage values as Case 2 was taken, the two categories are now in the same operation field (supply the city hub). The values for Case 3 are in the Table-4.14 listed.

Table 4.14: Case study - Overview Range for the category $T3$

Category	Average Power [kW]	Range [km/d]
T3	260	100
T3	260	150
T3	260	250

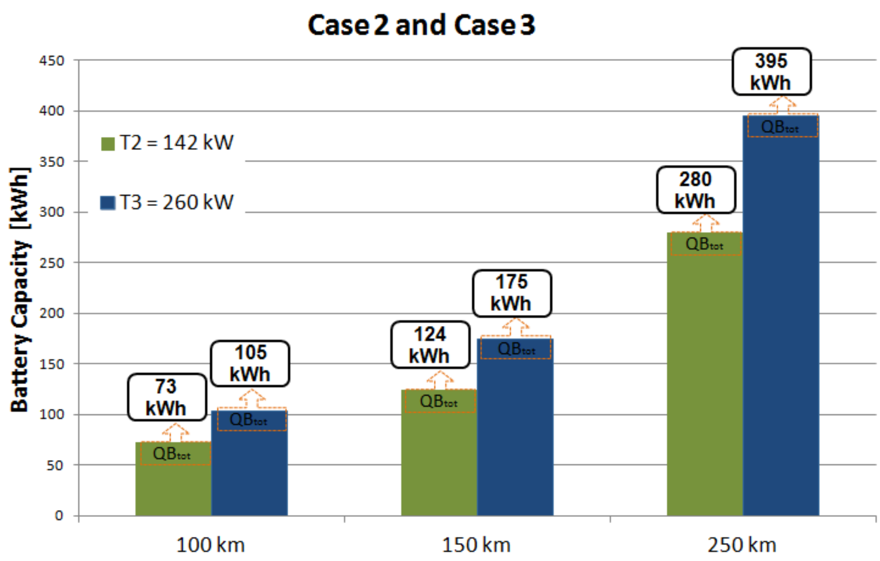

Figure 4.13: Case 2 and Case 3 studies for the categories $T2$ and $T3$

The results shown in Figure-4.13 are summarized in Table-4.15 and Table-4.16.

Table 4.15: $T2$ - Recommended values QB for Case 2

	Range $[km]$	Battery Capacity QB_{T2} $[kWh]$	Total Battery Capacity QB_{tot} $[kWh]$
Case 2	100	60	73
Case 2	150	103	124
Case 2	250	233	280

The obtained results again show the expected trend, that larger vehicles with higher engine power and higher payload capacity require more battery for a specified mileage (e.g. $s_T = 250km \Rightarrow QB_{totT3} > QB_{totT2}$).

Table 4.16: $T3$ - Recommended values QB for Case 3

	Range $[km]$	Battery Capacity QB_{T3} $[kWh]$	Total Battery Capacity QB_{tot} $[kWh]$
Case 3	100	86	105
Case 3	150	145	175
Case 3	250	330	395

5 Discussion of results

This work presents how to determinate the minimum battery capacity for different battery electric vehicle (passenger cars, buses and freight trucks). The analysis assumes that by establishing a minimum value in the batteries capacities, electric vehicles could be more competitive in the market since they would save extra costs by selecting a battery adjusted to the personal needs.

In this section the results obtained from each class are summarized, discussed and interpreted.

For the passenger cars according to case study 1 (Case 1) a driver with a low daily mileage about $40 km/day$) and a distribution of 80 % of this mileage in the city and the remaining 20 % on the highway (see Table-4.1.1), should choose for a medium size car ($C2$) a total battery capacity of $10 kWh$. In the database the smallest value offered by this category is $21 kWh$ in the car model *Chevrolet Spark EV 2016*. This would be the recommended value for a mixed consumption of $90 km$ per day, more than double what is needed in this case.

For class C, the highest treated mileage (Case 4) was a mileage of $100 km/d$ in a only city driving profile (see Subsection-4.1.1). For a taxi with completely urban consumption and classified in the category $C3$ or $C4$, a total battery capacity of $25 kWh$ is recommended. This two categories $C3$ and $C4$ are listed in the database with a minimum battery capacity of $60 kWh$. This value is 3 times higher than in this case recommended value. The vehicle with the lowest battery capacity in the category $C3$ offers a range of $300 km/day$ that is 10 hours of continuous driving at an average speed of $30 km/h$, values that do not match with the normal working day or life style in Europe nor with the average speed in the city. For this Case 4 ($100 km/d - City$) and the compact car category $C1$, a match was found. A small car used for example in the distribution of pizzas or other foods would need a recommended capacity of $22 kWh$. This value capacity represents any of the models currently listed in this work (e.g. *Mitsubishi i-MiEV* or *Smart fortwo electric drive*).

All this shows that depending on the needs and user driving profile, for the Case 1 it would be possible to save between 10 and $70 kWh$ battery capacity and for the Case 4 between 40 and 75kWh. Thus, for all the treated cases a battery capacity savings would be possible. This savings would be reflected in the vehicle total purchase price.

In general for the class C, it can be recognized that the currently offered battery capacities, differ with the consumer demanded mileage.

Following the discussion for the buses something different happens. The case studies evaluated give routes that vary between 228km and 351km with battery capacities between 340 and 445kWh. These values compared with the listed values have a better range match. Batteries range from 84 to 414kWh (see Table-2.3) but no match in the number of vehicles. For the midibus category ($B1$) all listed buses reach about half of the recommended value. For the $B2$ only four of the fifteen models and for $B3$ only one of the three models.

The results in the class T (road freight truck) have more special details, the category $T1$ or last-mile, according to the case study has about 60km distances. To satisfy this mileage, the model propose a vehicle with a 30kWh battery capacity and this matches very well with those offered.

The car model *Renault Kangoo Maxi Z.E* has a battery capacity of 33kWh and the model *emovum E-Ducato* 43kWh battery (see Table-2.4) values nearly to the recommended minimal capacity.

For the second category $T2$, the in the market offered ranges for 100 and 150km have batteries of 72 and 120kWh respectively (see Table-2.4), this agrees with the values obtained in the model that would recommend 73 and 124kWh for the same ranges. For the 250km case, the model suggests a battery capacity of 280kWh (see Table-4.15). This value is seems bigger than he minimum recommended, since the 250km mileage was chosen only for evaluation purposes. For this category the case study (Case 2) reasoning to find the necessary mileage, only 100km was resulted. However, the maximum value offered in the market for $T2$ is a battery capacity of 240kWh, this approaches the suggested value for the a mileage of 250km.

In the category $T3$ (long-haul) and its evaluated case studies, we begin to see the first gaps in BEV. For category $T3$ the demanded mileage could only possibly be fulfilled with a battery charge solution in order to fractionate the necessary mileage and make it reachable. The highest sampled range in the road freight class was 250km (see Table-2.4) and according to the case study the minimum distance would be 400km (see Case 3 in Subsection-4.3.1), this requires an extrapolation and a model limitation can be seen.

However, as said in Subsection-4.3.1 for the analysis of the Case 3 the same mileage values were taken as in Case 2. The two categories are now in the same operation field and should offer the same mileage. Because of its higher engine power, the necessary battery capacities are higher than those in the category $T2$. The vehicles with the largest battery capacity in the freight trucks class are the *E-Force E18* and the *Emoss EMS* both of them with $240kWh$ battery capacity, offering ranges of 300 and 230 km respectively and $400kg$ payload difference.

The analysis performed in category $B1$ shows that the battery capacity is smaller than the recommended values for the derived route in the case study. For the category $B2$ and $B3$ are more concordance in the offered batteries capacities than for the passenger car C_i or freight trucks T_i. The passenger cars class could be because the range offered part of marketing strategies or a differential factor between brands. For the freight truck class in the category $T3$ this discordance is about the higher amount of mileage needed and in this case the higher diesel specific energy density compared to the lithium metal batteries [1].

[1]Specific energy [MJ/kg]: Diesel = 48 vs Li-Po = 1.8[26]

6 Conclusion

The thesis presents a methodology how to find a minimal battery capacity for battery electric vehicles for different user types. The method used to minimize battery capacity provides some solutions to overcome some barriers faced by BEV and also facilitates a evaluation of their use in different transportation mode.

Based on a average driving profile, it can be concluded that for the passenger car class in general, the batteries shows certain bigger values than in model recommended. Most models offer, according to the cases studies, values for high demands on mileage. For the luxury car sector, the batteries are not designed to have a minimum capacity and save acquisition cost but to offer more comforts to users.

For the buses, it can be concluded that for a minimum use of infrastructure some models offer adequate battery capacities. According to the reasoning of the respective case study midibuses have the highest mileage demand but they have installed smaller batteries than those recommended. The possibility to load at the end of routes or at stations, can support the capacity of the batteries and giving any bus the ability to satisfy different mileage needs.

From the different truck categories presented, it is deduced that the use of BEV for long-haul transport is not used by the manufactures due to limitations in the technology (battery volume, energy density and the lack of infrastructure). That explains why these vehicles have similar range to those of short-haul category.

Based on these results it is recommended to customise the battery size with respect to the driving behaviour of the mileage demand. This could make the BEVs more friendly with the available resources, reduce the acquisition price and make it more attractive for different driver. Therefore, vehicle manufacturers should develop a more modular design for their battery capacity. Adapting the storage capacity like some trucks manufacturers or the *Tesla Model S and X* (e.g. 60, 75, 85, 90 kWh) could make the vehicle more economical.

In addition, this thesis shows the challenges that this technology will face and the results invite future work on the possibility of fast charging or to implement more charging points than on the enhancement of the battery capacity. Through this improvements it would be possible to fraction the demanded mileage and allowing much longer distances with short stops and smaller batteries.

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Hiermit erkläre ich, dass die vorliegende Arbeit gemäß dem Code of Conduct Regeln zur Sicherung guter wissenschaftlicher Praxis (in der aktuellen Fassung des jeweiligen Mitteilungsblattes der TU Wien), insbesondere ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel, angefertigt wurde. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet.

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Wien, am 04.10.2018

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