POLITECNICO DI TORINO
Master's Degree in ICT for Smart Societies

Master's Degree Thesis

Electric vehicles and performance indicators: sustainability analysis for the city of Turin

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Abstract:

Climate sustainability is becoming an increasingly important issue for the global world and has prompted the European Union (EU) to replace the New European Driving Cycle (NEDC) with the Worldwide Harmonized Light Duty Testing Procedure (WLTP) for a more accurate estimates of vehicle emissions. This action has forced the car manufacturers to move towards a transition of the electric vehicles (EV), resulting in reduced emissions.

In this context, a case study has been carried out on the EVs in the city of Turin to investigate the real effectiveness for sustainability of the electric transition by classifying the transport into private and public EVs. The probe is made possible with availability of datasets regarding the EVs, driving cycles, demography, costs and vehicle usage patterns. The energy consumption of the vehicles is estimated by implementing a mathematical model that uses the World Harmonized Light-duty Vehicle Test Cycle (WLTC) data as well as the data of various other forces that act on vehicles.

As estimates are reached on the actual values of electricity consumption of EVs, they are analysed with the reported numbers worldwide. Additionally, the electricity consumption forecasts and comparative analysis on different performance indicators of the EVs are also performed. The comparative analysis is specifically focused on the energy demand, kilometrical costs and transport capacity of the EVs. Conclusions are reached on the general usefulness of the EVs both in general and concerning public EVs, specifically when they are compared to private EVs.

The case study is concluded by evaluating the realistic suitability of electric transition of vehicles for achieving sustainability goals.

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Acronyms:

EU European Union

NEDC New European Driving Cycle

WLTP World Wide Harmonized Light Duty Testing Procedure

EV Electric Vehicle

WLTC World Harmonized Light-duty Vehicle Test Cycle

BEV Battery Electric Vehicle

PHEV Plug-In Hybrid Electric Vehicle

HEV Hybrid Electric Vehicle

FCEV Fuel Cell Electric Vehicle

ITS Intelligent Transportation System

ICT Information Communication Technologies

CAM Connected and Automated Mobility

GHG Greenhouse Gas

IPCC Intergovernmental Panel on Climate Change

UNFC United Nation Framework Convention on Climate Change

EC European Commission

OEM Original Equipment Manufacturers

ULCV Ultra-Low Carbon Vehicle

ZLEV Zero and Low Emission Vehicle

MVEG Motor Vehicle Emissions Group

UDC Urban Driving Cycle

EUDC Extra Urban Driving Cycle

CVS Constant Volume Sampling

PMR Power-to-Mass Ratio

ATCT Ambient Temperature Correction Test

FRF Family Correction Factor

TML Test Mass Low

TMH Test Mass High

RDE Real Driving Emissions

PEMS Portable Emissions Measurement System

ICE Internal Combustion Engine

ESS Energy Storage System

EMS Energy Management Strategy

KPI Key Performance Indicator

EEA European Environment Agency

QGIS Quantum Geographic Information System

GTT Gruppo Torinese Trasporti

ELN Electronic Lab Notebook

ERS Electric Road System

Chapter 1. Introduction

Mobility has become a compulsory part of the people's lives as their social, economic or cultural activities require them moving between different places. People also are sometime faced with making some difficult choices when travelling over longer distances and paying higher costs. The key stakeholders have contributed in solving such issues through the policy making and providing more public transport but these actions have come at a cost. As transport planners have built more roads and designed areas with focusing on automobiles, this resulted in limiting pedestrian zones or other infrastructures (e.g. bike paths).

In last few decades, the various pollutants and CO_2 emissions have been identified as the biggest threat to the sustainability. Also, an increased traffic has not only impacted with more travel time but it has contributed significantly to environmental degradation as well. In addition, an increased usage of private vehicles has created several problems, causing more road congestion, accidents, reducing the use of public transport and increasing carbon emissions. (Figure 1.1)

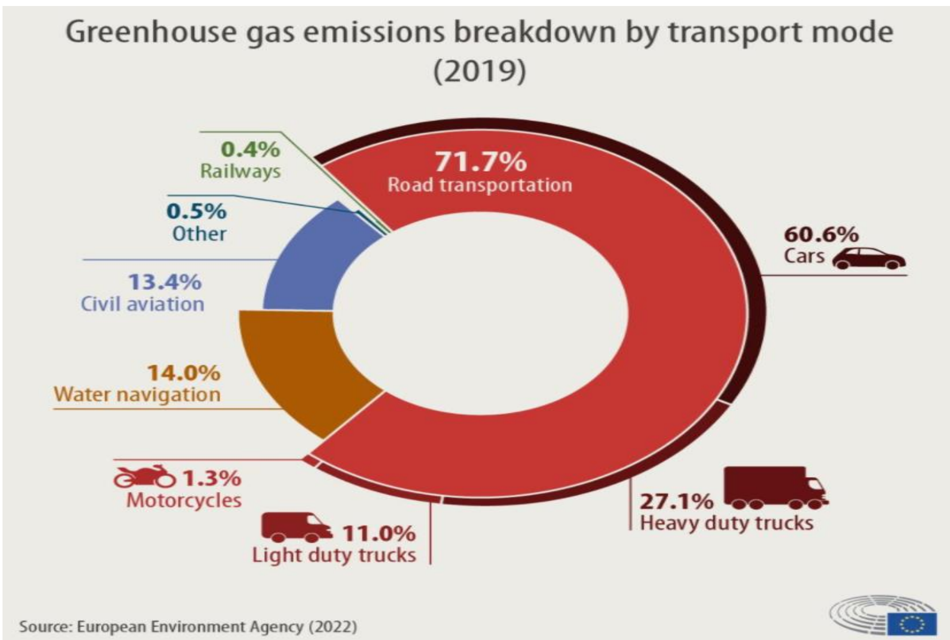

Figure 1.1: Each transport mode's contribution for greenhouse gas emissions in the EU.

With the significant implications of pollutants and emissions for the future growth, the relevant actors have started to focus significantly towards a sustainable mobility progression. Many countries are designing policies and plans that promote the use of public transport and other climate friendly modes. Several solutions for private transport have also been introduced, which include the promotion of ride-sharing, ride-hailing and carpooling services. Investments in connected and automated mobility have been encouraged, thinking they have more potential to reduce energy consumption and carbon emissions, increasing safety and accessibility. Several regulations have also been introduced, focusing on the energy transition of vehicles to electric sources to reduce emissions further.

Also, the mobility being a basic need of human beings, sustainability is covering an increasingly important role. In the last few years, there exists a rapid shift by many countries towards changing their investments, infrastructures and policies towards this specific goal of sustainability. Apart from ensuring a sustainable environment and development for everyone, sustainable mobility also contributes towards social and economic progress for everyone in the society. With the world progressing towards a green mobility, there are also growing number of hypotheses that suggest counter narratives towards the steps taken for achieving it. There exist no doubts regarding the benefits of sustainable mobility but at the same time it is important that the right steps are taken for it, otherwise it also hinders the achievement of the greater objective of environmental protection of planet.

A recent study has demonstrated that with the evolution of clean transports in last few years, the cities are also witnessing a dramatic increase in related infrastructures [1]. There has been a growing number of charging infrastructures, electric grids and different vehicle technologies. Due to an increased transition of energy sources for vehicles to electricity, there has been an increased charging load as well. This has been one of the causes for an increase in infrastructures. Hence it is important to analyze the actual impact of the charging load on these future constructions and to evaluate the realistic energy consumptions of public and private EVs.

There exists a number of different types of electric vehicles like Battery Electric Vehicles (BEVs), Plug-In Hybrid Electric Vehicles (PHEVs), Hybrid Electric Vehicles (HEVs) and Fuel Cell Electric Vehicles (FCEVs). Each of these types represent a varying transition of electricity as their energy sources, so they all have different characteristics. Their charging load consumptions, recharging durations, driving ranges and maintenance needs are contrasting from one another. This further represents the need to focus on a categorical specific evaluation of EVs instead of computing the emissions and consumption at a general scale. This is critical towards achieving a long-term sustainable transport growth. A recent study has demonstrated that when a specific methodology address a need like scheduling of charge considering each EV type, costs can be reduced by 15.93% [2]. Therefore, the EV classification-based evaluations are crucial.

Electric vehicles also have wide-ranging impacts on societal costs, noise pollution, batteries, energy use and economy of a city [3]. It is critical to take into account these other subject matters also when evaluating the realistic future benefits of EVs. Another essential consideration for EVs is the public electric buses that have a lot more stop phases, interior lights, contrasting speeds and usages of heating or cooling than the private electric cars. Thus, with the growing trend around the world of electric buses usage, it is critical to also take into account these varying characteristics as they can cause high energy consumptions and have an impact on electrical grid. Also, it is important to probe if all the transport demand in a specific area can be fulfilled with just the usage of public electric buses instead of having more electric cars. The conclusion to this query can address a future concern of increased pressure on energy resources due to higher usage of private electric vehicles.

In this thesis, the various aspects of sustainable mobility that include energy consumptions, behavioral forecasts and comparative costs have been analysed. For these subject matters, a case study for the city of Turin has been done. The focus has been on the EVs categorized as public EV and private EV. For public EVs, the emphasis has been on three different models of EV that operate on different routes in the city. With private EVs, the vehicles and trips of two different private EV rental companies have been analysed. Different datasets regarding trip durations, trip behaviors, vehicle structures, costs and infrastructures have been used for the problem evaluations.

In our analysis, a big difference between how public and private EVs operate can be observed as well as a varying capacity, driving behavior, frequency, charging requirements, emissions and energy consumptions of both these kinds of EVs. With the consideration of all diverse features of both public and private EVs, the research deals with estimating the actual usefulness of the transition of vehicle energy source to electric. By taking into account the parametric values of each type of vehicle, characteristics of city and forces acting on a vehicle while it is running, the realistic energy consumption estimates are evaluated. Additionally as part of the problem and to provide further evidence to analysis, the future trends of these estimates are also forecasted. Another task of the problem involved focusing on a specific area within the city of Turin to evaluate actual cost analytics of transforming all non-electric public transport buses to electric. In addition, as part of these cost estimations, an analysis is performed on the effects and possibility of serving all the transport demand requirements through only public EVs instead of more private EVs. As part of the conclusion for the problem, the results of these different tasks contribute to addressing various key sustainable mobility indicators.

Chapter 2. State of the Art

In this section, a review on the previous literature regarding sustainable mobility will be given. State-of-the-art will also provide a more in-depth analysis on the topics governing the sustainable mobility with having a specific focus of Europe. It will also provide a mobility background and the regulations that have been a focus for transport systems. The role of technology in shaping the mobility in recent years will also be explored.

Since the last few decades, sustainability has become a major concern for the world. The vast economic impacts of sustainability have also helped it to take the center stage. A growing awareness among communities has pushed countries around the world to take concrete steps in tackling it. Along with the different mobility’s direct costs, it also has various indirect costs that impact a society’s behavior, environment and lifestyle.

Recently, the mobility has been becoming an integral part of solutions for achieving sustainable development. The major objective of these solutions being to ensure the people’s mobility with minimal environmental impact. Also, the World Business Council for Sustainable Development has stated the sustainable mobility as a society’s capacity to satisfy the movement of its peoples without giving up any fundamental human or ecological values [4]. The United Nations in its documentation has mentioned the social equity, viable economy and environment as the fundamentals to be achieved for a sustainable development objective [5]. These three segments form the basic pillars for a sustainable development growth. A sustainable mobility contributes significantly in a better accessibility, economic integration and less pollutant environment. Hence, mobility play a critical part in sustainable development. This also emphasizes the importance for a sustainable mobility solution to have the consideration of these areas while being designed. Figure 2.1 depicts these areas and their interlinkages.

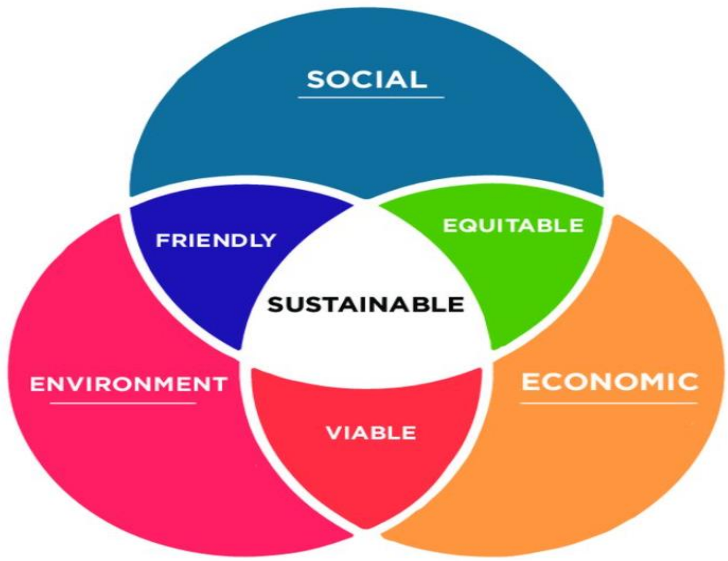

Figure 2.1: Critical areas effecting sustainable mobility.

For sustainable mobility, some of the most relevant indicators include commuting time, accessibility, emissions, costs, convenience and energy consumptions. These indicators have been a focus of various countries and organizations around the world for ensuring a more sustainable future growth.

Litman and Burwell [6] set up the link between sustainability and transport and acknowledging that for a sustainable development, mobility must consider the factors like energy conservation, economic stability and social welfare. The mobility impacts were categorized into three areas (economic, social and environmental) and it also stressed on the importance of finding solutions for achieving main objectives by a higher transport system efficiency. A study by Miller et al. [7] focused on role played by public transport in sustainability. Several case studies underlined its wide-ranging impacts. An accessible and economical system were found as key in achieving a sustainable mobility.

Having a much greater focus on sustainability issue in last few years, a more active role is still required in tackling it. Banister [8] has also emphasized on the importance of an increased role and efforts of stakeholders in ensuring transport sustainability. It was concluded that a proactive role of actors is more productive than conventional methods for future sustainability goals. Then, apart from just setting some regulations, a more coordinated effort by stakeholders for an effective implementation of policies is required.

2.1 Mobility, Big Data & ICT

Mobility is critical to European economy covering the 5% of GDP and employing over 10 million people across Europe. Despite of mobility being vital for European businesses, it also contributes significantly towards the greenhouse gas and pollutant emissions. Energy and transport are ranked as the first and fourth respectively in the biggest CO_2 emitters category of EU. Recently with transport sector contributing 17% of global gas emissions, the increase in CO_2 emissions worldwide has also been unprecedented. With the goal set by EU to have a minimum of 30 million zero-emission vehicles in an operational state by 2030, the mobility can play a big role in achieving sustainability goals. Apart from reducing the emissions, these goals can also help in enhancing the energy security for Europe. Furthermore, with the objective to convert the vehicle's fuel source to electric energy, the transport will have a much greater effect on the global carbon emission figures. For this reason, the EU has also set another objective of installing more than 3 million public charging points by 2030 to further boost the usage of zero-emission vehicles. EU also plans to change the public's behaviour towards sustainable transport with the introduction of different cost and technical incentives to have a more carbon-neutral utilization of vehicles. These incentives are vital as studies have shown them to be the key factors in people's decision making for EVs [9].

Considering another technology that is in the European mainstream, the connected and automated vehicles, it is considered that it will allow a better route estimation and efficient road occupancy, significant in achieving a reduction in fuel consumption and emission. In addition, these vehicles are considered beneficial in reducing social costs related to accidents. Considering these several benefits related to sustainability for mobility of driverless vehicles, EU allowed their practical use in 2020 and focused on devising a common automated vehicles policy that covers all transport modes and also ensures interoperability of these vehicles across borders. Due to increased usage of data in these vehicles, EU has also shown its intention to further strengthening its data protection and ethics rules in near future. Therefore, all these policies will further help in ensuring a safe, efficient and climate friendly automated mobility for everyone.

As the EU started to focus more towards a connected and automated mobility (CAM), it also made various policies to support the adaptability of autonomous transport. The aim of these policies is to bring more safety, efficiency, user-friendly and sustainable solutions in automated vehicles. Another focus of these policies is to further enhance the recent trend of connected and automated features being employed in EVs. Apart from policy making, EU has also been active in establishing standards, legislation and funding several research projects that can support growth of CAM across Europe. A study on fuel consumption and greenhouse gas (GHG) emissions for an automated mobility district shows prospects of reduction in total fuel utilization and emissions [10].

Large number of existing mobility solutions are a combination of environmental, geographical, technological and human behavioural factors. These mobility solutions are only made possible with the analysis involving a combination of diverse and large number of datasets. Even after these solutions are implemented, the running mobility keeps generating data. This generated mobility data has potential to affect other fields of a society like businesses, real estates, investments and emergency response works. These mobility characteristics makes a strong case for making use of big data in having a more effective mobility solution. Also, recent studies demonstrate the large scale and effective usage of big data algorithms and applications in Intelligent Transport Systems (ITS) [11]. Some of its most prominent applications are in traffic management, traffic route planning, ticket management systems, passengers and vehicle safety mechanisms. Hence, the usage of data is important in achieving a more digitalized and user-friendly mobility. In transport analysis, the common data solution approaches include data averaging, data visualization and data aggregation methods. These methods act as a base for achieving significant ITS solutions.

Recently, the information communication technologies (ICT) have also become increasingly important for the advancements of transport systems. ICT has been crucial in providing the critical communication capabilities required for different applications of ITS [12]. ICT manage the access to travel data, transport designing tools, multi-modal travel systems, ticket payment operations and transport tracking tools. In past decade, EU has funded some of the biggest projects that involved ICT and transport. The projects include the REDUCTION [13], the PEACOX [14] and the eCOMPASS [15]; these projects addressed the usage of ICT methodologies for travel behaviour optimization, multi-modal travel and logistical transport fleet. ICT has also been instrumental in providing solutions that can be critical for sustainable mobility. With countering emissions being a top priority for the world, ICT contribution towards mobility will only be increasing in future mobility solutions. The EU funded the ICT-EMISSIONS project that shows the importance of ICT [16]; this project included the estimates of CO_2 emissions at a regional level by vehicle fleets monitoring. Apart from sustainability, ICT has also been essential in achieving cost-effective, secured and connected transport networks.

The big data and ICT together can make a huge impact for a smart mobility future. They can be critical in effecting user travel behaviours, transport demands and multimodal travel patterns. Also, the research work conducted in thesis made use of the ICT and data analytics concepts for estimating vehicle energy consumption, EVs usage patterns, transport demands, costs and their effects on sustainability.

2.2 Development of Regulation Framework

In EU the debate on climate policy started in 1990 with the introduction of the Intergovernmental Panel on Climate Change (IPCC) report. The first ever debates were held to prepare for the negotiations on the United Nation Framework Convention on Climate Change (UNFCC) happening in the same year. It was for the first time that real debate was held among EU leaders on setting the emission reduction level targets. Also a discussion was held on having a common and coordinated policies and measures (PAMs). All the discussions and policies were centered on objectives of reduction in GHGs, increasing renewable energy sources and enhancing energy efficiency.

Transport emissions in Europe have always been mandated through various Euro emission standards and regulations since 1992 [17]. The main aim of these regulations being to target the reduction of the pollutants such as carbon monoxide (CO), unburned hydrocarbons (HC), PM and the particle number (PN). In this manner the EU has always tried to regulate and push the automotive industry to develop various strategies and methods that can help them in passing the type-approval process for their vehicles. This approval process was initially based on the NEDC but then in 2017 was replaced with the more efficient process WLTP. In 1998, the ACEA (European Automobile Manufacturers Association) introduced proposal for the reduction of carbon emission numbers for new cars to 140 g/km by 2008. Various other automobile associations around the world also introduced measures to reduce the emission numbers. Also in January 2007, a regulation was introduced the European commission as well to mandate the carbon emission to 120 g/km by 2012 for all the new cars sold. Starting from 2009, the commission also introduced a new set of standards for a more effective regulation of the carbon emissions. As a result of these standards, the carbon emissions declined steeply as shown in figure 2.2. A second set of standards was introduced in 2014 that set the target for carbon emissions to 95 g/km by 2021. Initially this target was set to be achieved by 2020 but it was later postponed by a year due to concerns raised by the German automotive industry. In subsequent years, the commission plans to introduce more set of standards regulating emissions. Additionally, in recent years the commission slightly relaxed these carbon emission numbers to various different levels in exchange for more investments, usage of renewable resources and promotion of climate friendly strategies adopted by vehicle manufacturers.

In 2015, a commitment was reached by some major countries of the world about ensuring to limit the global temperature increase 1,5°C, with 2°C set as a maximum limit, at the conference of Parties to the United Nations Framework Convention on Climate Change (COP21). Since transport is one of the major contributors towards the carbon emissions, so the series of regulatory standards introduced by EU for limiting emission levels will have critical role in achieving the agreed global temperature limit. Hence, these ambitious temperature sustainability goals will also push a transition towards zero-emission transport system.

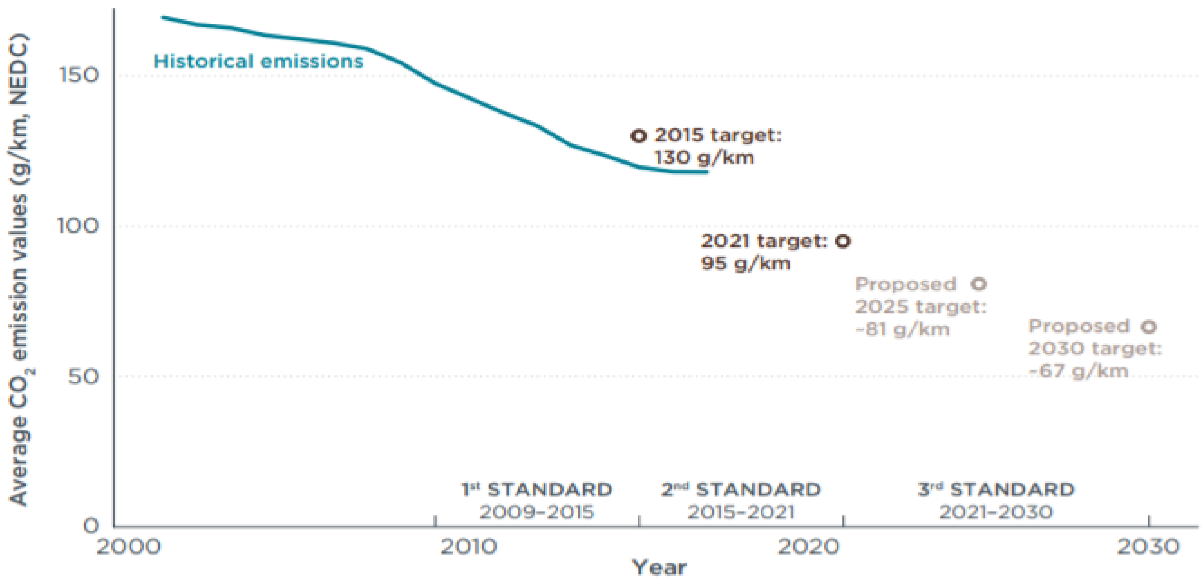

Figure 2.2: Implemented and proposed CO_2 standards in the EU for new vehicles.

According to all the European standards implemented and proposed, the average emissions for the new vehicles manufactured are assessed on the basis of their mass. This parameter is used because there exists a liner correlation between mass of the vehicle and emission levels allowed. A much heavier vehicle fleet means a higher carbon emission target, and vice versa. This parameter was implemented into the CO_2 standards for the purpose of ensuring a more diverse vehicle market and also to account for contrasting consumer needs. Apart from this parameter, with the initiation of the first CO_2 standard, the European Commission (EC) has also assessed the prospect of using another parameter like vehicle footprint. Vehicle footprint corresponds to the actual size of a vehicle and it is a standard parameter used for assessing the GHG emissions in the United States. As part of the implemented EU CO_2 standards in 2014, a consideration of change towards the vehicle footprint parameter was suggested for future regulations.

With mass as a major utility parameter used for evaluating the vehicle emissions, the permitted emissions use the following formulas [18], [19]:

For the time period of 2012 to 2015, the formula for carbon emissions is reported in eq. (2.1):

$$130 + (M - M0\ ) \tag{2.1}$$

Where: M = Mass of the vehicle $[Kg]$;
$M0$ = 1372 $[Kg]$;
a = 0.0457.

For the year 2016, the carbon emission formula remained the same with the only change now being the considerations for the $M0$ value. Now it was evaluated as the average mass of new vehicle by taking into account the last three years.

From the year 2020, formula for carbon emissions:

$$95 + (M - M0) \tag{2.2}$$

where: M = mass of the vehicle $[Kg]$;
$M0$ = the average mass of new vehicles by taking into account the average mass of vehicles sold in EU during the last three years. 1380 $[Kg]$ is the average mass value for the time period of 2019 to 2021. This value will be regulated annually.
a = 0.0333.

Despite of the using both the mass parameter and setting the carbon emission values for the regulating purposes, a little difference was still witnessed in the actual usage of these regulations within EU. The German automotive manufacturers continued with selling heavier vehicles having a bit high carbon emission value, while the French and Italian companies manufactured much lighter vehicles that had lower carbon emission values. This little difference was also interpreted as a political compromise to protect European automotive industry. Figure 2.3 shows that at the average vehicle mass values of various automotive companies, the carbon emission targets can differ by a value of 11 g/km in 2021.

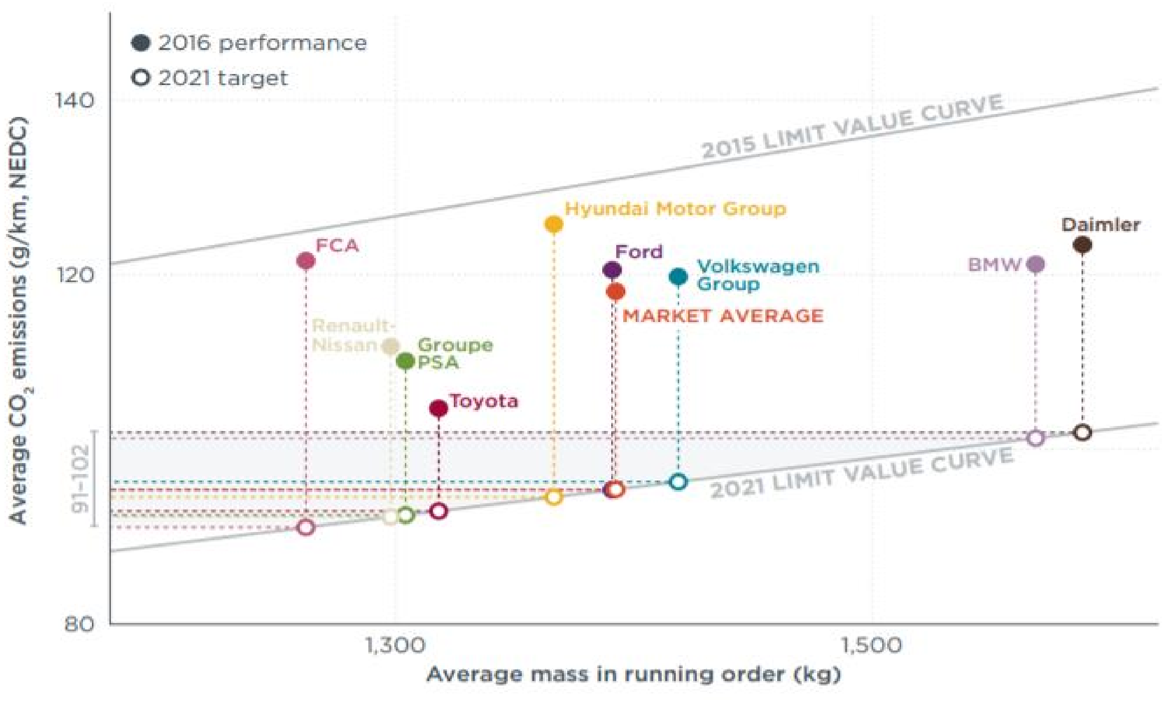

Figure 2.3: Average vehicle mass and carbon emission values of several automotive manufacturers.

A major disadvantage of this current shift in EU carbon emission target system towards mass-based limit value curve is that it discourages the vehicle mass reduction and offers small incentive. Since now the carbon emission targets also get lowered for an automotive manufacturer that produces vehicles with a lower mass value. This reduces the advantage for a manufacturer as now the current system will require it to do more efforts for achieving a much lower g/km target as compared to other manufacturers having a heavier vehicle fleet. Hence the current carbon emission target system disincentives the light-weighting in vehicles and it also increases costs regarding the regulatory compliances.

The regulations also introduced fines for automotive manufacturers in case of violations for specified carbon emission limits. Starting from the year 2012, the fine was evaluated depending on the amount of exceeded average carbon emission value as compared to the stated specified targets.

For the time period of 2012 to 2018, fine evaluations used following formulas:

Where:

N = $number\ of\ new\ passenger\ cars$

Case where automotive manufacturers breach the target by over 3 g/km limit:

$$\text{Fine} = ((excees\ emission - 3\ g/km)(\text{N})((95€)/\ (gCO_2/km)) + (1\ gCO_2/km)(\text{N})((25€)/\ (gCO_2/km)) + (1\ gCO_2/km)(\text{N})((15€)/\ (gCO_2/km)) + (1\ gCO_2/km)(\text{N})((5€)/\ (gCO_2/km))) \quad (2.3)$$

Case where automotive manufacturers breach the target by over 2 g/km but under the 3 g/km limit:

$$\text{Fine} = ((excees\ emission - 2\ g/km)(\text{N})((25€)/\ (gCO_2/km)) + (1\ gCO_2/km)(\text{N})((15€)/\ (gCO_2/km)) + (1\ gCO_2/km)(\text{N})((5€)/\ (gCO_2/km))) \quad (2.4)$$

Case where automotive manufacturers breach the target by over 1 g/km but under the 2 g/km limit:

$$\text{Fine} = ((excees\ emission - 1\ g/km)(\text{N})((15€)/\ (gCO_2/km)) + (1\ gCO_2/km)(\text{N})((5€)/\ (gCO_2/km))) \quad (2.5)$$

Case where automotive manufacturers breach the target by not more than 1 g/km:

$$\text{Fine} = ((excees\ emissions)\ (\text{N})((5€)/\ (gCO_2/km))) \quad (2.6)$$

From the year 2019, fine evaluations use the following formula:

$$\text{Fine} = ((excees\ emissions)\ (\text{N})((95€)/\ (gCO_2/km))) \quad (2.7)$$

The different economical, production and technological profile of automotive manufacturers are also taken into consideration while evaluating the penalties for breaching the emission limits. Specific kind of relaxations in following these emission limits are also granted by the EU based on the profiles of automotive companies. Some easing in the penalty regulations are also granted for the cases where manufacturers spend huge investments in eco-friendly technologies and policies. All the penalty evaluations and relaxations that are part of the regulation framework of EU also have the ultimate objective to keep pushing automakers to achieve carbon emission targets.

2.3 Progression of Regulatory Framework

The increased scrutiny worldwide over the harmful pollutants, GHG and other environment threatening elements has pushed transport industries towards a more fast-track development of elements like engines, motors and energy storage systems. With the hope of keeping up with the regulations, the transport companies are also introducing them in the markets with no delays of any kind. But all these changes are also interrelated with the consumer demands as well, which are seemed to have also evolved a lot in recent past. So, a lot of changes have also been brought with the consideration of factors like low fuel consumption, improved vehicle drivability and passenger safety. Hence, all these developments for the road transport in the form of advanced electromechanical technologies and new powertrain technologies represent a big evolution for the automotive industry. Thus, for the purpose of evaluating the carbon emission target values, in addition to the set standards of regulations in place, there is also a need for these vehicles to be properly tested in real-world conditions laboratory and get certified before being used on the roads. As this can provide a more accurate detail of standings of manufacturers for emission targets.

In the past couple of decades as the climate issue really started to take center stage in the world problems, this prompted countries worldwide to accept the need to reduce the emissions for vehicle fleets sold and to have stringent testing procedures for emission evaluations. The EU had NEDC as the testing procedure until 2017. The vehicle fleet sold in EU in 2015 emitted on average 119.6 g CO_2/km (based on the NEDC), it was 10 g CO_2/km below the 2015 target. The vehicle fleet emission standards and laboratory testing procedures have proven to be efficient in test-cycle emission reduction of vehicles.

With the WLTP, it was found that it provides a more efficient, effective and realistic values for emissions then the NEDC. There was found to be a gap between the values measured with the NEDC and what was the actual emission values on the road [20]. There were also cases of discrepancies and manipulation by some entities in the lenient procedures of NEDC. All these factors played a role in the replacement of NEDC with WLTP. There was a concern that this shift in type-approval procedure may cause an issue because the CO_2 emission targets are based on the previous testing procedure. Hence, there was a need for the new CO_2 emission values evaluated in the WLTP to still be interpreted to the NEDC equivalent emission target values. Since 2017, although a number of pollutants like NOx, CO and PM/PN are measured using the more realistic testing procedure but for CO_2 targets through the correlation procedure a more realistic evaluation will also be available. After 2020, the CO_2 targets are expressed in WLTP values and also completely tested using the new WLTP type-approval procedure. At the time of NEDC replacement with WLTP, the interpretation of CO_2 target values using specific methods prompted the EU to develop a simulated model for this purpose known as CO_2MPAS (CO_2 model for passenger and commercial vehicles simulation). Another purpose of this more stringent model was to remove any possibility for the OEM (Original Equipment Manufacturers) to take benefit from the loop holes present in the previous testing procedures and make the whole process more transparent.

CO_2MPAS is a conventionalist CO_2 emission and fuel consumption tool that is used as a simulator for the light-duty M1 and N1 vehicles (cars and vans). This tool allows the evaluation of CO_2 emission values over the NEDC type-approval test and this evaluation is being based upon the emission results of a WLTP testing procedure. Now for the WLTC, two kinds of WLTP tests can be carried out. WLTP-H (High) and WLTP-L (Low) being the two tests where the former requiring the high cycle energy demand and the later needing the low cycle energy demand. Some of the critical design characteristics of this tool are as follows:

- ability to estimate the effectiveness of any technology that ensures a reduction of energy consumption, when it is applied in a vehicle with an accuracy of 2-3% in comparison to measurements;
- capacity to demonstrate a more accurate simulation behavior of a vehicle's CO_2 emission values under varying conditions that involve usage of physical models and statistical factors being limited;
- ability to also consider the vehicle type approval process and bring ease by limiting the inputs to the vehicle characteristics that have already been present in the previous approval process.

Now with the evaluation being done by CO_2MPAS, if the NEDC equivalent emission values are found to be over 4% then previously declared value by automotive manufacturer then manufacturer has two options. The options are to either accept the new evaluation or to go through the procedure of retesting the vehicle three times over the chassis dynamometer. For the last option, if the CO_2 emission value is still found to be breaching the previously manufacturer's declared value then this last estimated value will be considered.

The European Commission's Joint Research Center became part of an analysis conducted to evaluate the real impact created as a result of the regulatory usage of the new type-approval test WLTP. For this analysis, the procedure adopted involved the evaluations of the light duty vehicle carbon emissions in addition to performing simulations of individual vehicles and with vehicle fleet composition data used. This analysis is carried out in addition to the deployment of CO_2MPAS tool. Based on the powertrain technologies and the NEDC carbon emission values, the final estimates demonstrate that the average WLTP to NEDC emission ratio usually vary between a range of 1.1 to 1.4. Other than the plug-in hybrid electric vehicles (PHEVs), the value of ratio is usually much more for the vehicles that have lower NEDC carbon emissions for all the powertrains. For the scenarios involving vehicles like PHEV, the value of the emissions ratio decreases rapidly and the value can decline to even below 1 because there occurs an increase in the electric range of the vehicle.

Starting from the year 2021, the European Commission adopted a proposal that stated that any emission target value for automotive manufacturer will be evaluated through the following formula:

$$\text{WLTP}_{2021,\ \text{target, reference}} = (\text{WLTP}_{2020} / \text{NEDC}_{2020}) * \text{NEDC}_{2020,\ \text{target}} \tag{2.8}$$

Where:
$WLTP_{2020}$ = average CO_2 emissions for year 2020
$NEDC_{2020}$ = average CO_2 emissions for year 2020

The variables present in the eq. (1.8) with a label of 'target' represent the NEDC target for that specific year. It is computed as a result from the automotive manufacturer stated average vehicle mass and the target WLTP value to be reached for the year 2021.

After the year 2020, the target WLTP value for each year will be evaluated using the following formula:

$$WLTP_{202X,\ target} = WLTP_{2021,\ target,\ reference} + a * [(M_{OEM,\ 202X} - M_{all,\ 202X}) - (M_{OEM,\ 2020} - M_{all,\ 2020})] \quad (2.9)$$

Where:
a = constant
M_{OEM} = average masses of specific vehicle fleet
M_{all} = average masses of all new vehicle registrations in the specific year

2.4 Legislation and Target Levels

After a series of first-ever emissions regulating legislations that include (EC) 443/2009 (cars) and (EU) 510/2011 (vans) were released by EU over a decade ago. On 1st January 2020, the EU introduced its most recent regulation that is Regulation (EU) 2019/631. This most recent EU's legislations have stressed on curbing the emissions with a special focus for the cases involving the transport cars and vans. It is estimated that passenger cars and vans solely represent a total of over 12% and 2.5% of the total CO_2 emissions within the EU. After a year of the introduction of this legislation, a number proposals for amendments are currently tabled at the EU parliament. These proposals are setting more ambitious targets for the emission reductions and the methods that can help the EU to reach its climate objectives according to the European Green Deal. The proposals also recommend that EU amends some of the legislative terms mentioned in previously adopted EU climate legislation.

Since the inception of Regulation (EU) 2019/631 in EU, the average usage of the electric vehicles is now tripled. Also the average CO_2 emissions of new vehicles are evaluated to have decreased by 12% when compared to past years. Some of the key aims of this legislation are as follows:

- to help achieve the commitments made by EU under the Paris Agreement in 2015;
- to play a role in reducing the costs associated with the energy consumption for the consumers;
- to contribute in further strengthening the competitiveness of EU transport industry and also help in employment growth.

The Regulation (EU) 2019/631 reiterate the previously set vehicle fleet CO_2 emissions limitations in the EU. It once again confirms the Regulations (EC) No 443/2009 and (EU) No 510/2011 and the emission targets for the time period of 2020-2024 as:

- Cars: 95 g CO_2/km
- Vans: 147 g CO_2/km.

As previously stated as well, for the year 2020 these limitation levels will be based on the NEDC type-approval test. Starting from 2021, the WLTP will replace as the new testing procedure for all the automotive manufacturers.

For the time period of 2025-2030, the EU in its legislation has set out much stringent measures and targets for the CO_2 emission targets. It interpreted the targets as a percentage reduction with having the 2021 as the reference period. The emission targets for this time period stated in the Regulation (EU) 2019/631 are as follows:

- Cars: staring from the year 2025 they must have 15% reduction and a 37.5% reduction from the year 2035
- Vans: staring from the year 2025 they must have 15% reduction and a 31% reduction from the year 2035

Also taking consideration of the average mass of the newly registered automotive vehicles, the manufacturer's yearly emission limitations will be evaluated on the basis of above-mentioned fleet-wide targets.

2.5 Incentives and Penalties

As part of encouragements, a set of incentives launched by EU included a super-credits system. For the time period of 2020 to 2022, this system was introduced to push the vehicle manufacturers towards a more ultra-low carbon vehicles (ULCV). It is applicable for the vehicles that have emissions of under 50 g CO_2/km (NEDC). The manufacturer counts each UCLV as more than one vehicle by multiplying the sales of these vehicles. This is done for the purpose of evaluating the manufacturer specific average emissions and it is done as follows:

- for the year 2020, as 2 vehicles;
- for the year 2021, as 1.67 vehicles;
- for the year 2022, as 1.33 vehicles.

For the super-credits, a 7.5 g/km per car manufacturer cap is set for a period of over three years. This credit system only applies for cars and not for vans. Starting from 2025, a zero and low emission vehicle (ZLEV) crediting system will come into force. This crediting system will be applicable for both the car and van manufacturers. This system is designed as an incentive mechanism for the automotive makers to produce more zero-and low-emission vehicles. Therefore, it sets a low emission reduction limitation for a manufacturer with a high EV sales. A leniency in emission targets for a manufacturer is granted if the sales of new ZLEVs during a specific year exceed the following targets:

- Cars: A target of 15% ZLEV for the period of 2025-2029 and a target of 35% ZLEV from 2030 onwards.
- Vans: A target of 15% ZLEV for the period of 2025-2029 and a target of 30% ZLEV from 2030 onwards.

A one percent increment in the manufacturer's CO_2 emission target will be done if the ZLEV targets are exceeded by one percentage point. A leniency in the limitation is set at 5%, so that the manufacturers can make use of the whole bonus with the sales of minimum 20% ZLEV from 2025 onwards and a sale of 40% from 2030 onwards. An accounting rule is used for the estimation purposes of ZLEV part present in manufacturer's vehicle fleet. This also ensures a much higher weight being given to the ZLEVs with a low CO_2 emission value.

As part of the incentives, the EU also allows some strategies like pooling for manufacturers to meet their limitations for emissions. Pooling can allow various automakers to jointly adhere the emission targets. To respect the competitiveness of the automotive industry, the manufacturers have to follow various rules like a pooling won't be possible between the car and van manufacturers.

Any violation of an emission target in a specific year by the manufacturer will make it liable for a penalty fine. During that year for every newly registered automotive, the manufacturer will be obligated to pay a fine of an excess emissions premium of €95 per g/km for the target breach. The EU allows the low-volume vehicle manufacturers the possibility to be exempted from the testing procedures for the emission violations. The low-volume manufacturing amounts to less than 1000 cars or 1000 vans being produced within a year in EU. However, the manufacturers can still voluntarily commit themselves to the derogation target testing. A vehicle manufacturer producing under 10,000 cars or 22,000 vans in year can set its own derogation limitation values but they have to respect the rules mentioned in the Regulation. Till the year 2028, a niche automaker producing cars in the range of 10,000 to 300,000 in a year can also voluntarily apply for the derogation target testing.

2.6 Eco-innovations

The EU in 2010 introduced an eco-innovations initiative. The main objective for this initiative being to provide an opportunity to the automakers for proving the emission reductions with vehicles practically in use on roads. This objective will also encourage manufacturers to invest more on climate friendly innovations and technologies.

The manufacturer is solely responsible for carrying out the whole testing procedure while the EU commission is only responsible for the verification process. The manufacturer needs to ensure the transparency for the whole process and make sure that the results can be verified independently through comparable data and scenarios. The automakers need to adhere to certain mentioned regulatory methods by the EU commission. The technologies also need to have specific attributes before they are allowed to be used as eco-innovation technologies. The manufacturers also receive emission credits for the eco-innovations but the cap set for each automaker on maximum credits is 7 g CO_2 /km per year. Some of the key eco-innovation technologies approved by the EU include LED lighting, engine encapsulation and method for controlling the state of charge in the Lithium-ion battery.

2.7 NEDC

NEDC is an emission assessment test based in artificial laboratories and it is performed under strict conditions and supervised by a government-appointed approval agency. It is specifically used for emission evaluations of the vehicle engines and fuel in an automotive. NEDC driving cycles is also known as MVEG-B test cycle (Motor Vehicle Emissions Group). It was introduced in 1992 and was last updated in 1997. Also, since 2000 the cold-start process has also been modified and now there exists no idle period with engine starting at 0 s and sampling of emissions also starting at the same time. It is formed on the basis of a theoretical driving profile and it consists of two different sub-cycles:

- An urban driving cycle (UDC) that is also used to demonstrate the realistic driving scenarios in a city. Attributes associated with it include low speed, low load factor and low temperatures. The maximum speed of UDC cycle is 50 km/h.
- The extra urban driving cycle (EUDC) is used for simulating a much more aggressive and high velocity driving conditions. The maximum speed a EUDC cycle can account for is 120 km/h.

A constant volume sampling (CVS) technique is used to generate emission samples of various pollutants. The speed profile of NEDC consisting of an extra-urban and four urban modes is shown in figure 2.4. Also, the major characteristics of ECE 15, EDUC and NEDC test cycles are shown in table 2.1.

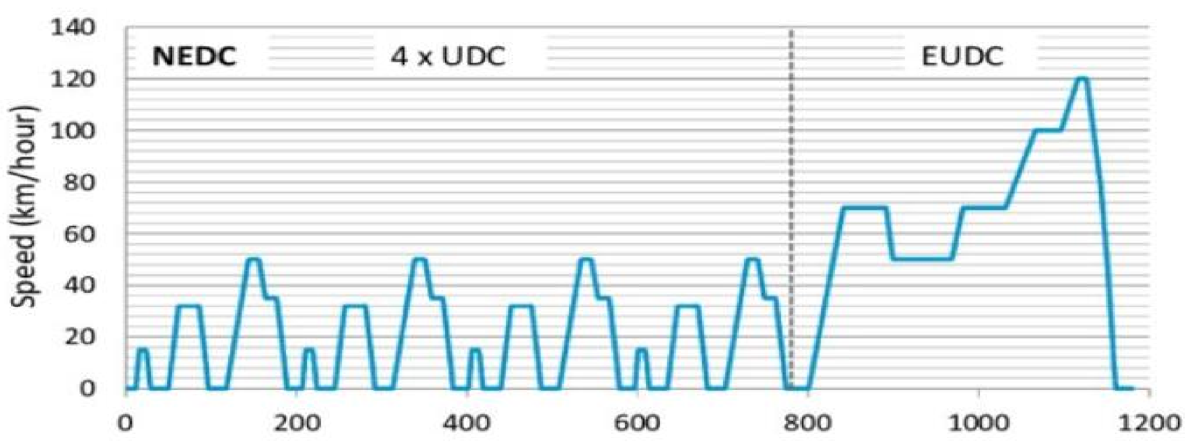

Figure 2.4: Speed profile of NEDC.

Since the introduction of NEDC in 1992, the transport industry and driving itself has undergone some huge changes. The vehicles, roads and passenger behavior has been in a continuous evolution since then. Also the consumption and emission results produced by the NEDC are not much realistic because instead of demonstrating the daily usage patterns and it compares different vehicles and their characteristics [21]. Hence, the real on-road emission numbers are far from the numbers obtained in lab results. Some other major reasons are as follows:

- the difference in theoretical and real user driving profiles;
- not sufficient acceleration variations being tested;
- no procedures involving high speeds and this makes the average speed in the testing very low. Also there exists a lot more stop phases then required;
- usage of a low vehicle load in laboratories than vehicles on-road;
- optional equipment impact on emissions of pollutants and CO_2 consumptions are not taken into considerations during assessments;
- a cycle distance of only 11 km is considered;
- according to the transmission type, a pre-determined gear shift is used.

Table 2.1: Summary of characteristics for ECE 15, EUDC and NEDC test cycles.

Characteristics	Unit	ECE 15	EUDC	NEDC†
Distance	km	0.9941	6.9549	10.9314
Total time	s	195	400	1180
Idle (standing) time	s	57	39	267
Average speed (incl. stops)	km/h	18.35	62.59	33.35
Average driving speed (excl. stops)	km/h	25.93	69.36	43.10
Maximum speed	km/h	50	120	120
Average acceleration[1]	m/s^2	0.599	0.354	0.506
Maximum acceleration[1]	m/s^2	1.042	0.833	1.042

† Four repetitions of ECE 15 followed by one EUDC
[1] Calculated using central difference method

2.8 WLTP

WLTP testing standard initiated in 1998. In that year, it was adopted by an Inland Transport Committee of the United Nations Economic Commission for Europe (UNECE). The testing procedure has acceptability worldwide. Since 2017, the EU also adopted it for the emissions testing, verification and certification purposes [22]. Few exceptions regarding a continued NEDC usage were made for the end-of-series vehicles until 2020. So, the WLTP standard has completely replaced the old testing procedure since 2020.

It is a global standard for the impact evaluations of various pollutants, CO_2 emissions and fuel utilizations of conventional and electric vehicles both. The WLTP test also usually amounts to high CO_2 emissions and fuel consumption values [23]. But these results demonstrated by it are one of the most realistic on-road vehicle values. Hence, these credible results can help in determining a more improved CO_2 emission targets as well. It also makes the possibility for the OEMs to showcase their products around the world with having them certified with one type-approval procedure, this will also be economically beneficial to them. The kind of vehicle, equipment and other varying aspects are taken into consideration by this standard. This leads to having various contrasting values even for vehicles of the same model, this was not possible with the old NEDC standard.

For the emission and consumption evaluations, the WLTP test procedures are laboratory based and are formed on the basis of real driving profiles. It consists of four varying average speeds that are low, medium, high and extra high speeds. A contrasting value of acceleration, braking and stopping phases are also considered to have more accurate daily driving simulation results. These characteristics that support the evidence of a greater accuracy in results of WLTP really pushed the EC to adopt it fully as the testing procedure and to remove exploitation of any flexibilities in the previous standard test. With the WLTP when compared to previous standard, some of the other major changes in testing procedures are as follows:

- the cycles distance is now doubled from 11 km to 23 km;
- the varying driving profile considerations of each vehicle results in a higher engine load consideration;
- procedures involve high speeds which also makes the average speed in the testing higher. In addition, the stop phases are shorter;
- usage of a realistic road vehicle load in lab testing to ensure more accuracy in results. The new system of testing also causes a higher vehicle test mass;
- the testing temperature range is also decreased now to 14 °C-23 °C. It was previously set at 20 °C-30 °C for the NEDC.

All the procedural requirements mentioned for WLTP are not much different from the NEDC with the only exception being that they further build on the regulatory requirements in more depth.

The chassis dynamometer tests part of WLTC have been formed under the supervision of UN ECE GRPE (Working party on Pollution and Energy) group. These tests are used for the evaluation of emissions and energy consumptions from light-duty vehicles. The WLTP have WLTC test cycles as part of other evaluations methods for testing vehicles for certification purposes. Based on the power-to-mass ratio (PMR) parameter value of different vehicles, several WLTC test cycles are categorized as part of the WLTP tests. The PMR parameter is the ratio between the specific power (W) and curb mass (kg). It is the actual performance measurement of an engine in vehicle. For the curb mass, the EU regulations take the “mass in running order” into consideration instead of the actual curb mass. The mass in running order does also includes the driver’s mass. The maximum speed of a vehicle also contributes in the cycle’s categorization. Some exceptions in the adjustment for cycle categories are allowed in the cases where vehicles have borderline PMR values or with maximum speed permitted values being less than required by a cycle. For the WLTP, the test mass value is greater than in NEDC. The three cycle categories based on the PMR values are shown in table 2.2.

Table 2.2: WLTC test cycles.

Category	PMR, W/kg	v_max, km/h	Speed Phase Sequence
Class 3b	PMR > 34	v_max ≥ 120	Low 3 + Medium 3-2 + High 3-2 + Extra High 3
Class 3a		v_max < 120	Low 3 + Medium 3-1 + High 3-1 + Extra High 3
Class 2	34 ≥ PMR > 22	-	Low 2 + Medium 2 + High 2 + Extra High 2
Class 1	PMR ≤ 22	-	Low 1 + Medium 1 + Low 1

For the test cycles in table 2, the Class 1 mainly refers to low power vehicles and Class 3 refers to high power vehicles. The vehicles for the Class 3 are further divided into subclasses based on their values of maximum speed. The majority number of vehicles in the world belong to Class 3. The various features of WLTP type-approval procedures allow the testing of different categories of hybrid-electric and electric vehicles. Different electric vehicles that include hybrid electric vehicles (HEV) and pure electric vehicles (PEV) are all featured in Class 3 vehicles. The emissions, energy consumptions and other parameters of EVs are evaluated with Class 3 cycle, in both the charge-depleting and charge-sustaining modes.

For WLTP, the lab regulates a specific temperature of 23 ± 5°C for Type 1 test. Then in order to ensure that the CO_2 values obtained are reflective of our daily life temperature conditions, an additional Ambient Temperature Correction Test (ATCT) is also conducted. The CO_2 emission evaluations are reached with the assistance of a Family Correction Factor (FRF) which is computed as follows:

$$FRF = CO_{2\,\mathrm{RC}} \,/\, CO_{2\,\mathrm{Type\text{-}1}} \tag{2.10}$$

Where:

$CO_{2\,\mathrm{RC}}$ = CO_2 emission value at regional conditions (14°C).

While the CO_2 estimation is done as follows:

$$CO_{2\,\mathrm{ATCT}} = CO_{2\,\mathrm{Type\text{-}1}} * FRF \tag{2.11}$$

Since the ATCT represents a group of vehicles that have similar features, so the emission value estimated will be valid for the whole group. Despite of providing a more realistic picture of emissions than NEDC, it is still estimated that there exists a gap in the range of about 10-15% between estimated and real-world estimations. When compared to NEDC, the WLTP usually employs a higher road load values and also uses two different test mass values known as Test Mass High (TMH) and Test Mass Low (TML). For an emission certification, during CO_2 emission testing procedure the TMH will be part of a worst-case scenario while TML will be part of a best case scenario. Depending on the driving cycle of WLTP, the simulations are executed. The WLTP's driving cycle is shown in figure 2.5 and it is divided into four different stages which are WL-L, WL-M, WL-H and WL-E. In addition, for different WLTC stages, their various features are shown in table 2.3.

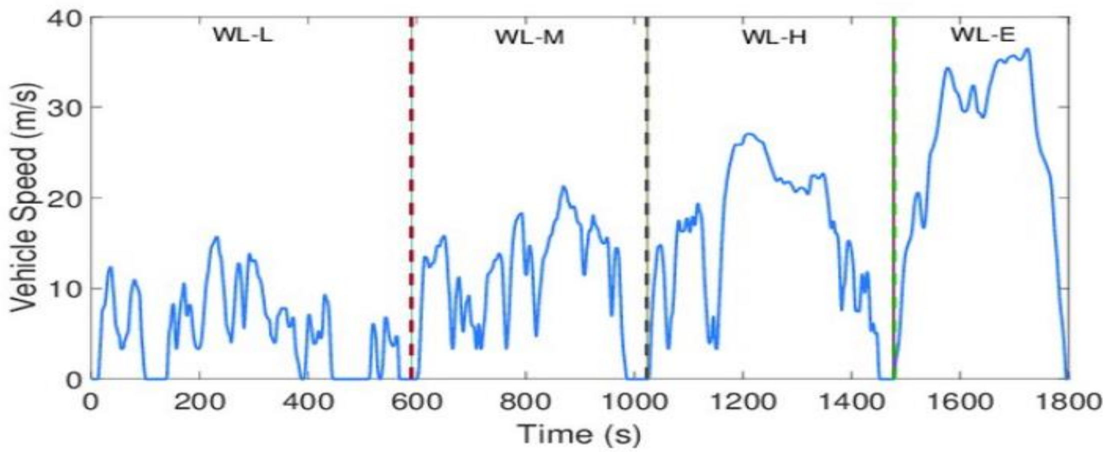

Figure 2.5: Speed profile of WLTP with its different stages.

Table 2.3: Summary of characteristics for WLTC stages.

	Low	Medium	High	Extra High	Total
Duration [s]	589	433	455	323	1800
Stop duration [s]	150	49	31	8	235
Distance [m]	3095	4756	7162	8254	23266
% of stops	26,5%	11,1%	6,8%	2,2%	13,4%
Maximum speed [km/h]	56,5	76,6	97,4	131,3	
Average speed [km/h]	18,9	39,4	56,5	91,7	46,5
Minimum acceleration [m/s^2]	-1,5	-1,5	-1,5	-1,44	
Maximum acceleration [m/s^2]	1,61	1,61	1,67	1,06	

2.9 Real Driving Emissions

Since the replacement of NEDC with WLTP, the EU regulations have further enhanced its emission testing by complementing it with another test known as Real Driving Emissions (RDE) test [24]. Unlike the WLTP testing which is takes place within a laboratory, the RDE testing involves the emissions evaluation with vehicle in driving condition and on road. This testing procedure has made Europe the only existing region in the world to have the most in-depth emission testing process for vehicles. An equipment known as Portable Emissions Measurement System (PEMS) is attached to the vehicle and is responsible for the emission estimation when vehicle is in motion on road. RDE ensures that differences in real world parameters of temperature, driving behavior and road conditions are also considered as no lab test can exactly reflect these parameter values. Additionally, the RDE also accounts for unusual scenarios like driving through a mountain with high speed, heavier load and in low temperatures. RDE was introduced in September 2017 and its implementation has been followed in two steps which are as follows:

- Step One (RDE1): This step permits the vehicle to emit 2.1 times the amount of pollutant during testing. It is applied to all new vehicle registrations since September 2019.
- Step Two (RDE2): This step permits the vehicle to emit 1.5 times the amount of pollutant during testing. It is applied to all new vehicle registrations since January 2021.

According to this new emission standard, the vehicles also would have to comply with the limitations of Euro 6d standards. Their stated emission estimations will be tested under a stricter testing conditions. Each type of vehicle is also evaluated with the kind of equipment which are both high energy intensive and economical also. With the combination of WLTP and RDE testing, a high emission and consumption figures will be obtained but now they will be much closer to the actual consumption and CO_2 values.

2.10 Electric Vehicles

The global vision for a cleaner, greener and better environment caused revolutionary changes to the conventional vehicles. It prompted the introduction of hybrid and fully-electric vehicles on world stage. With the possibility of no harmful gas release, lower consumption and emissions, the usage of these vehicles is expected to grow more in future.

This sub-section will further provide detailed description of various electric vehicles as our case study is focused on the usage of EVs in cities.

2.10.1 Hybrid & Full Electric Vehicles

In hybrid vehicles, propulsion is provided through multiple sources of power. These multiple sources can include fuel having chemical energy present in it and the other source can come from range of technologies. Hybrid systems are now increasingly used in trucks, buses, pickups and other heavy vehicles. Energy consumption savings and lower battery costs are some of the reasons that are making it more viable for automotive stakeholders.

A HEV makes use of a combination of internal combustion engine (ICE) system and electric propulsion system. For the powertrain system, these vehicles consists of a combination of conventional powertrain components, ICE and transmission with electric motor, power electronics and energy storage component like battery. HEVs mostly consists of the following key components:

- **ICE:** A conventional engine acts as the main source of power for an HEV. Therefore, the propulsion of vehicle heavily depends on this component. It is usually smaller in size and generates lower emissions.
- **Electric motor:** It is usually used as the secondary power source. The engine’s role in initial acceleration is assisted by it. For its working, it depends on the electrical energy stored in batter pack.
- **Generator:** It makes use of the power from IC engine for providing the power to electric motor and charge a battery pack.
- **Battery pack:** It is a source of power for electric motor. It also stores electrical energy and so it acts as a fuel storage for battery.
- **Fuel tank:** It is used to store the fuel. But in contrast to a conventional car, the fuel consumption for HEVs are comparatively less due to the involvement of electric powertrain.
- **Transmission:** The fundamental working principle of transmission in HEV remains the same as the conventional vehicles. It is an essential component used for propelling the vehicle. It transfers the power from IC engine to drive shaft.

Recent advancements in HEVs have ensured an achievement of a higher mileage and low tailpipe emissions when compared to the conventional vehicles. The existence of an on-board generator for charging the energy storage system (ESS) and the capability of regaining energy via regenerative braking are the factors that contribute towards a superior mileage. Depending on the energy management strategy (EMS), the ICE can be turned ON or OFF and so it remains operating within its limitations during most of its working.

Depending on design characteristics and power delivery, the HEVs are classified into three categories:

- **Series hybrid:** In this configuration, the only component attached with the wheels is electrical machine. The ICE provides power to electric generator, this then assists the electric motor and also charges batteries. Since there does not exist any mechanical connection between ICE and transmission, therefore the engine performs at its maximum efficiency point. The working of a series configuration is shown in figure 2.6.

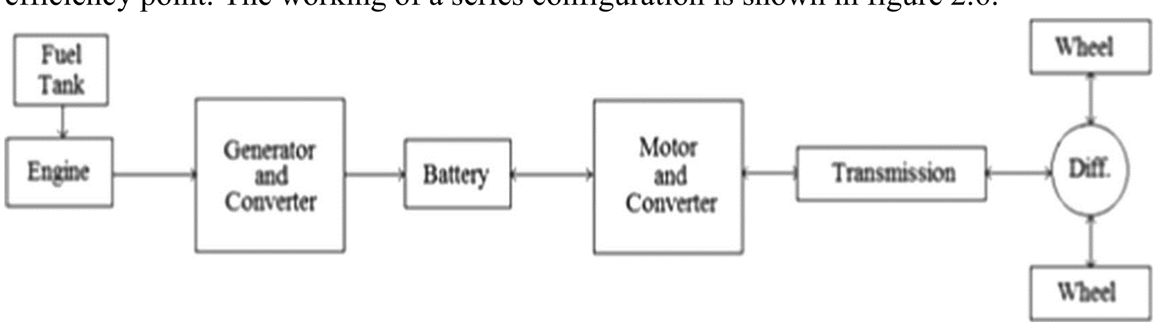

Figure 2.6: Series hybrid configuration.

- **Parallel hybrid:** As shown in figure 2.7, the vehicle is powered by having the ICE and electric motor to operate in parallel. They both ensure an optimum amount of power for the effective working of vehicle. Moreover, regenerative braking is used for charging a battery-pack.

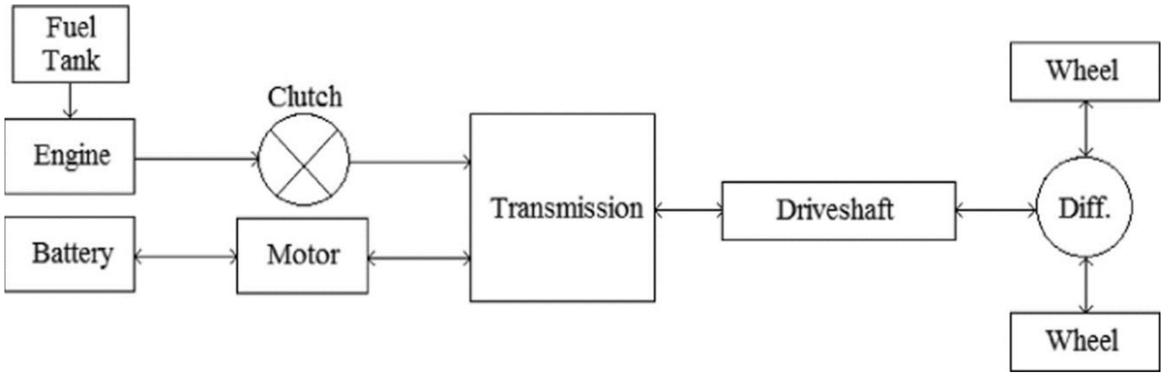

Figure 2.7: Parallel hybrid configuration.

- **Series-parallel hybrid:** This is a flexible configuration system that allows the ICE and electric motor to operate separately or together. Due to the combined configuration, the problems like sizing of ESS for series HEVs and the unfavourable stop/go driving states for parallel HEVs are now resolved. This is made possible by the power-split device which allows the usage of features from both the series and parallel configurations. Figure 2.8 shows this power-split based series-parallel configuration.

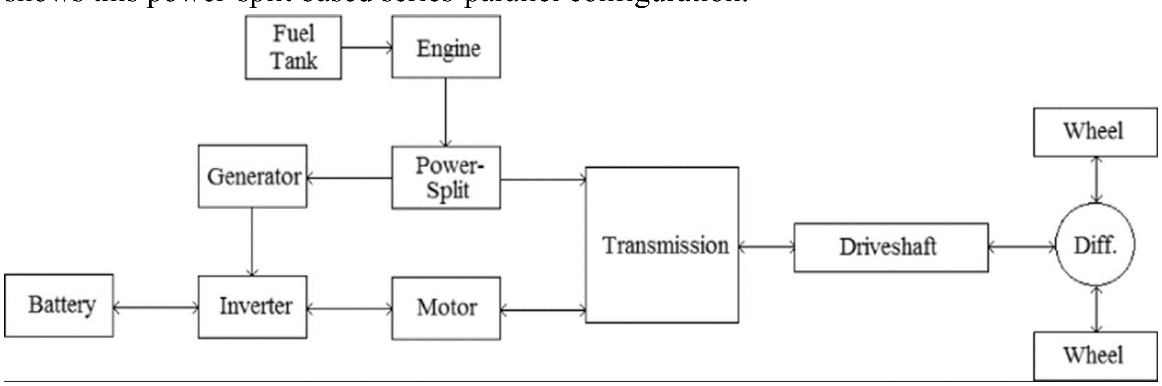

Figure 2.8: Series-parallel hybrid configuration.

The parallel and combined hybrids can be further classified based on the degree of hybridization. The degree of hybridization further relies on the power provided by the ICE and electric motor. For many vehicles, it is necessary that the electric motor is working while for some they are turned on only when there is requirement for a boost. Also in many vehicles, the load is equally shared by the ICE and electric motor. The degree of hybridization can be defined as the ratio of power being produced by the electric motor to the total vehicle's power consumption. As shown in table 2.4, it varies for different types of hybrid vehicles. It can be evaluated as follows:

$$\text{Degree of hybridization } = \frac{\text{Motor Power}}{\text{Motor Power + Engine Power}} * 100 \qquad (2.12)$$

Table 2.4: Degree of hybridization.

Type Of hybrid	Degree of hybridization
Micro	<5%
Mild	Up to 10%
Full Hybrid: Parallel Series	 10% to 50% 50% to 75%
Electric vehicle	100%

For micro hybrid vehicles, the electric motor assists in operating the system by automatically turning off engine during idling phase. The motor also don't have the capacity of delivering enough torque to the vehicle. It provides a power of 2.5 kW at 12 volts. Energy savings can reach only in the range of 5 to 10%.

In mild hybrid vehicles, the integration of electric motor generator enables a supply of 10% of engine's maximum power. The emissions are reduced with the usage of a battery-powered electric motor which assists the conventional fuel engine. The electric motor provides a 10 to 20 kW power at 100-200 volts. Energy savings can reach up to 20 to 30%.

For full hybrid vehicles, the electric motor shares almost 40% of total engine power in the form of additional torque. A full hybrid system makes use of both the ICE and electric motor for propelling the vehicle. These systems had a significant impact on reducing energy consumptions and emissions. The electric motor provides a power of 50 kW at 200-300 volts. Energy savings can reach up to 30 to 50%.

The PHEVs makes use of both the ICE and electric motor. They are also equipped with a large rechargeable battery. In contrast to the conventional vehicles, these can be driven to large distances in electric mode with the capability of plug-in charging from an outlet [25]. Also in case of a battery depletion, the vehicle turns to a non-plug-in hybrid mode as now the conventional engine starts operating. Chevrolet Volt and Mitsubishi Outlander P-HEV are some of the examples of available PHEVs.

The BEVs are fully electric vehicles that are equipped with rechargeable batteries. Electric motor is used for the propulsion of vehicles. The battery pack is solely responsible for fulfilling the energy demands required to run a vehicle. These vehicles ensure no generation of hazardous tailpipe emissions or any harmful pollutants. They are completely free from dependence on crude oils. These vehicles also have a high energy efficiency as they use four-fifths of the electricity for movements while in conventional vehicles a large part of the energy in their tank gets lost. In comparison to the conventional vehicles, the BEVs have a shorter distance range because of a lower energy density of battery. With regard to the batteries, there's an availability of various types of technologies. Among these availabilities, Li ion battery is estimated to have the best performance due to a high power and low cost attributes then other technologies [26]. The most common battery technologies and their powers are shown in figure 2.9.

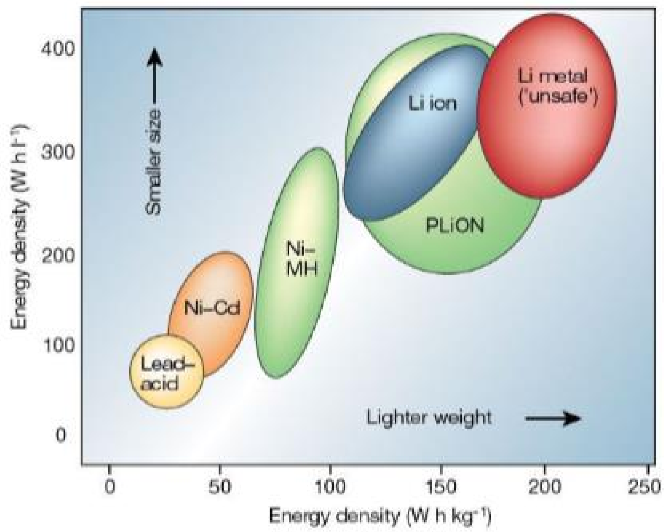

Figure 2.9: Different battery types and their specific powers.

The FCEVs are the vehicles that employ fuel cells as main source for powering their electric motors. They also use battery or an ultra-capacitor for increasing this power density. The generation of electricity by these fuel cells is done using the compressed hydrogen and air. In comparison to the BEVs who make use of batteries, the fuel cells in FCEVs are much lighter, smaller and have the ability to generate electricity for longer periods that depends on fuel supply only. These factors enhance the FCEVs suitability for long range distances. In addition, these vehicles ensure zero emission or ultra-low emissions. The Hyundai Tucson and the Toyota Mirai are some of the examples of available FCEVs. The different types of hybrid vehicles and their main characteristics are summarized in table 2.5.

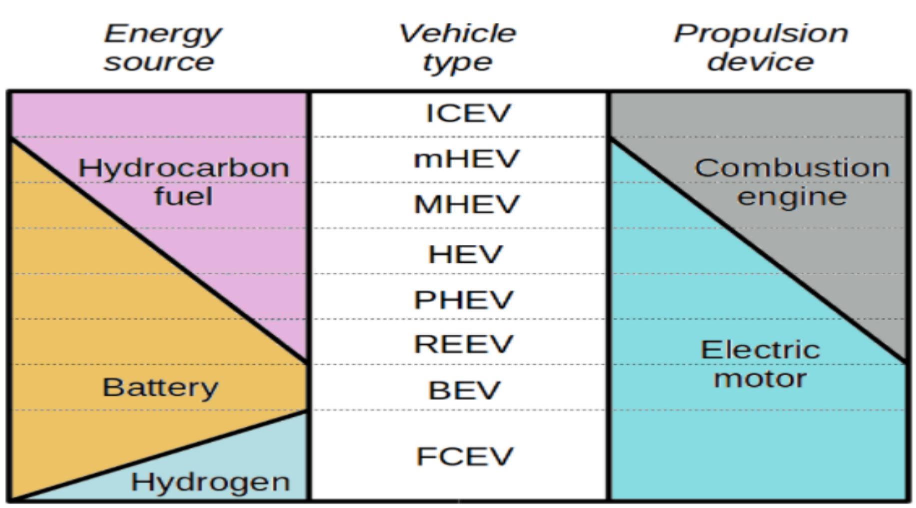

Table 2.5: Different energy source and propulsion device functions for hybrid vehicles.

Despite of having increased usage of EVs in private vehicles as an environment friendly alternative to the conventional vehicles, a more effective solution can only be possible with the this same transition for public transportation systems as well. As buses make up over 80% of the total public transport worldwide [27], so addressing the reduction of emissions from conventional buses will have significant impact on sustainability. Hence, in last decade there has been a great focus on bus electrification globally. In addition, low operational costs of bus fleets make up for the high investment costs of electric drivetrain and so the electric bus transition is becoming more economically viable as compared to conventional diesel buses.

The electric buses solely rely on electricity as their fuel source rather than diesel fuel or gasoline. Battery pack stores the electricity and it can be recharged when required. Moreover, for propelling the vehicle, the required power is supplied by battery to the electric motor. With the electric engine having less components than ICE, so the maintenance costs are also low. Due to the high numbers of passenger electric buses induction into the public transport system, the 9-14 m length is expected to prevail more in the electric bus segment. The increasing incentives for electric buses, accessibility of electric components and more charging infrastructures are expected to significantly contribute in boosting the future growth of electric buses worldwide.

Chapter 3. Objectives and Methodology

With the electric vehicles and sustainability as the central focus of this research, the objectives are as follows:

- to investigate the necessary parameters having any direct or indirect influence on the energy consumptions of an EV;
- to evaluate the realistic energy consumptions of private EVs and public electric buses in the city of Turin;
- to estimate the average energy consumption per trip of an EV;
- to probe the possibility of using only public electric transport instead of private EVs for a specific focus area in Turin;
- to analyse the varying impact of public and private transport systems in on the sustainability;
- to analyse the long-term impacts of the electric transition of mobility for battery recycling, GHG emissions, societal and economic costs;

For achieving these aims of the research, a methodology has been articulated in two major steps:

- the first step involves a model simulation for the energy evaluations of EVs.
- the second step focuses on a probe of complete transformation to electric buses and this step is achieved through following sub-steps:
    - implementing a forecasting model known as ‘Prophet’ to evaluate the future usage patterns of EVs;

- conducting a comparative analysis of different attributes regarding electric buses and vehicles;

In recent years, the electric mobility and sustainability gained immense attention around the world, lots of research, data and impact analysis of such topics are still missing. By making use of the limited literature and available data, this research can support stakeholders in achieving sustainability goals.

The two major steps of methodology are interlinked as the results for energy estimations of vehicles will be used in performing the time series forecasting of EV trips. The next section will explain the methodological steps.

3.1 Energy Evaluation

The first step estimates the realistic energy consumptions of EVs. The more realistic significance of the evaluation will be due to the consideration of factors like auxiliary components and all the direct or indirect forces acting on an electric vehicle once it is driving mode. Also due to different types of terrains around the world, the energy consumptions can never be the same everywhere. Hence, this case study is focused on the city of Turin and its specificities. A scheme for the total energy consumption evaluation is shown in figure 3.1. For energy evaluation of any particular EV, this scheme serves as a guideline for the whole process. A combination of datasets and different parameters are implemented in the simulation of model for energy estimations.

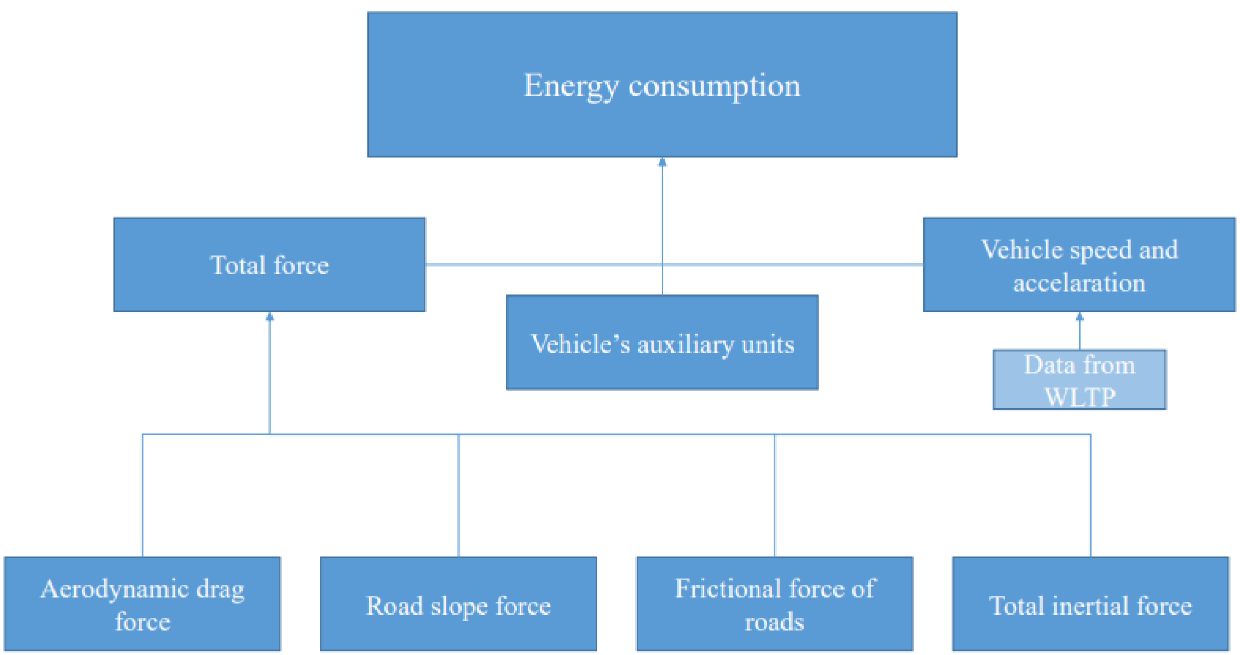

Figure 3.1: Energy consumption flowchart.

For estimating energy consumption of an EV, the specific data for its speed and acceleration attributes can be based on either NEDC or WLTP procedures. As indicated in the section 2.8 and section 2.9 that WLTP represents the more realistic results, hence for this research the WLTP data will be used. Also the average energy consumption will depend on the homologation cycle.

The WLTP dataset selection for the particular vehicle will depend on two factors:

- Power-to-weight ratio parameter;
- WLTP driving cycle;

Every vehicle will have its own power-to-weight ratio as it depends on a vehicle's engine power and kerb weight. This parameter is evaluated as follows:

$$\mathrm{PW}_r = \frac{\mathrm{P}_{max}}{\mathrm{m}_v} \tag{3.1}$$

Where: PW_r [kW/Tonne] = Power-to-weight ratio.

This parameter will determine the WLTP driving cycle. The driving cycles are categorized as follows:

- **Class 1:** It contains low power vehicles that have $PW_r \leq 22$;
- **Class 2:** It includes vehicles that are in the range of $22 < PW_r \leq 34$;
- **Class 3:** It contains high power vehicles that have $PW_r > 34$;

After each vehicle's specific class is determined based on the PW_r value, the dataset for that particular driving cycle is selected for energy estimation process. This dataset will be divided into low, medium, high and extra high average speed segments. It will also address parameters like distance, duration, stops, and acceleration.

Apart from WLTP dataset, energy estimation also requires the specifics of various force parameters that impact a vehicle on-road. These specifics will be focused on the road-load force. It is the force that acts on a vehicle which is at a constant speed in drive-mode on flat surface. The source of this force is a combination of tire rolling resistance, driveline losses and aerodynamic drag. The road-load is calculated as follows:

$$F_{\mathrm{tot}} = F_i + F_s + F_r + F_a \tag{3.2}$$

where: F_{tot} [N] = Total road load
F_i [N] = Force from inertia
F_s [N] = Force due to road slope
F_r [N] = Force due to friction
F_a [N] = Aerodynamic force.

Estimating total road load for vehicle's energy would require finding the sum of inertial force, road slope force, frictional force and the aerodynamic drag force. The inertial force for a vehicle acts as any resistance to its diversion from its speed or direction of movement. For estimating the inertial force in eq. (3.2), the following equation (3.3) is used:

$$F_i = m_v * a_v \tag{3.3}$$

Where: m_v [kg] = Total vehicle mass

a_v [m/s^2] = Vehicle acceleration.

The vehicle acceleration in eq. (3.3) is calculated as follows:

$$a_v = \Delta_v / \Delta_t \qquad (3.4)$$

where: Δ_v [m/s] = Vehicle's speed difference
Δ_t [s] = Vehicle's time difference.

The road slope force in eq. (3.2) addresses the vehicle's movement on an uneven terrain. It is the force that acts on a vehicle when it has an on-road movement with a specific elevation. This force is estimated as follows:

$$F_s = m_v * g * \sin(\alpha_s) \qquad (3.5)$$

Where: g [m/s^2] = Gravitational acceleration
α_s [rad] = road slope angle.

The road load's friction force is the resistance that acts on wheels of a vehicle during its forward motion. The force also involves a road rolling resistance coefficient which takes into account the rolling drag as well. From eq. (3.2), the road load force is calculated as follows:

$$F_r = m_v * g * C_{rr} * \cos(\alpha_s) \qquad (3.6)$$

Where: C_{rr} = road rolling resistance coefficient.

The aerodynamic drag force mentioned in the eq. (3.2) represents the resistance that air applies on a forward velocity of the vehicle. It impacts its speed and performance. This force is estimated in eq. (3.7):

$$F_a = (1/2) * \rho * C_d * A * (v_v)^2 \qquad (3.7)$$

Where: ρ [kg/m^3] = Air density at 20 °C
C_d = Air drag coefficient
A [m^2] = Vehicle frontal area
v_v [m/s] = Vehicle speed.

After the usage of WLTP data and evaluating the total external forces from the eq. (3.2), the final step for energy consumption estimation involves power estimations. This parameter is determined from the total forces acting on a vehicle and its velocity. It is computed according to eq. (3.8):

$$P_{tot} = F_{tot} * v_v \qquad (3.8)$$

Where: P_{tot} [W] = Total power.

Finally, the total energy consumption of an EV is calculated using the total power from eq. (3.8). Equation (3.9) is used for its evaluation:

$$E_{tot} = \int P_{tot} * dt \qquad (3.9)$$

Where: E_{tot} [J] = Total energy consumption.

The source of the data used for this step of methodology is open-source WLTP data, regional transport authority and private vehicle rental authorities. The data obtained from these sources is majorly in raw form. For the energy model simulation, the data will be cleaned and processed to extract the relevant data and values of different parameters.

The whole energy consumption estimations are implemented using the Scilab software. It is an open-source software used for implementing different algorithms and numerical computations. In our case study, the WLTP data and values of several parameters are set using this software. Afterwards, a Scilab tool known as Xcos is used for further computation process. Xcos is employed for the purpose of creating model and simulation of both continuous and discrete systems. Also, the explicit and implicit equations relating to any system can be simulated using this tool. This tool contains a palette browser and an Xcos workspace. Palette browser contains the available palettes and blocks for each palette. Blocks like product, gain and clock are used for implementing algorithmeic operations and simulating different systems. In this methodology, the Xcos tool will be used for building the block diagram and implementing the simulation of the model which will generate energy consumption values for any kind of an EV.

3.2 Comparative Analysis

The second step of the methodology involves two different implementations and they both are interlinked. The final objective of this step is a comparative analysis on employing electric buses and vehicles. In recent years, there is a growing trend of private EVs in many parts of the world. Some issues like smaller charging infrastructure, charging time and limited driving range may cause a halt to this growing trend. The comparative analysis in this step is also focused on this hypothesis. It will analyze these factors by comparing them to electric buses as well. This will give us an indication for both the public and private EVs usefulness.

Firstly, a time-series forecasting is implemented for the private EVs. This will allow us to study the current usage trends and also analyse the forecasted patterns. The model implemented is known as Prophet forecasting. The figure 3.2 shows the scheme of this model implemented for our case study.

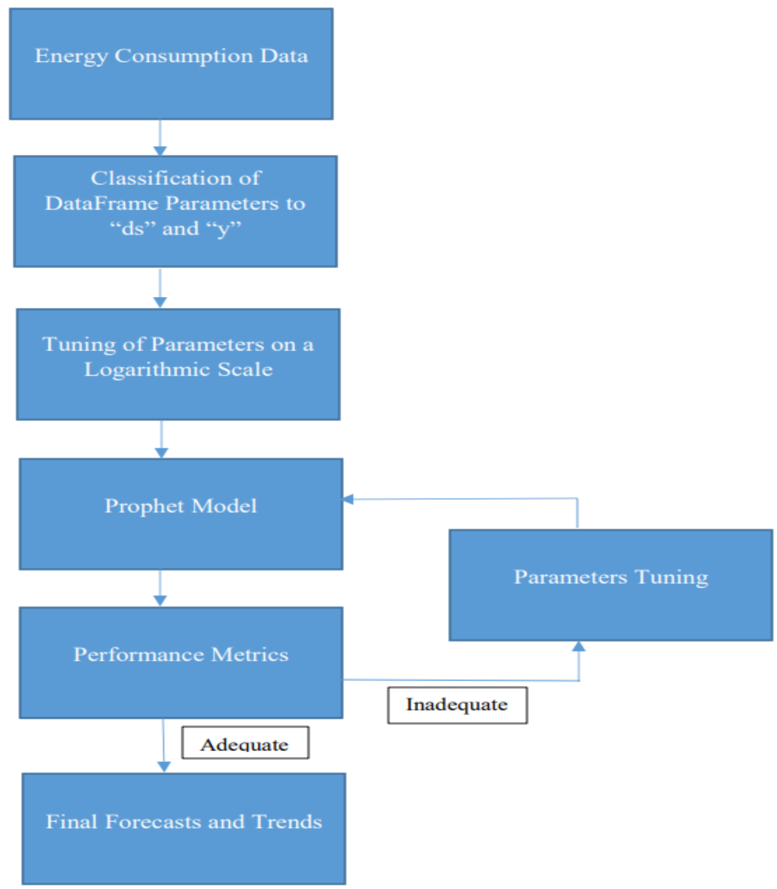

Figure 3.2: Prophet model flowchart.

This model requires setting of different hyper-parameters and the time-series data forecasting is dependent on an additive model having non-linear trends that suits the seasonality effects. It can be regarded as a non-linear regression model that takes the form reported in eq. (3.10):

$$y_t = g(t) + s(t) + h(t) + \varepsilon_t \tag{3.10}$$

where:

y_t: Additive regressive model.
$g(t)$: Trend factor.
$s(t)$: Seasonality component.
$h(t)$: Holiday component.
ε_t: White noise error term.

The key aspects of eq. (3.10) are as follows:

- the change-points for the trend factor are automatically detected by Prophet if they are not explicitly defined. Also, a logistic function can be employed for setting an upper bound limit over the trend;
- the seasonal component includes the Fourier terms of the appropriate time periods;
- the holiday component is used as a dummy variable;

- the model is evaluated by applying a Bayesian approach. This permits the selection of best parameters for the dataset.

As shown in figure 3.2, the Prophet model for our methodology requires an energy consumption specific data. The major sources of these data are the energy consumption model and a secure cloud-based communal repository known as Mendeley Data. A trip ID, initial latitude, final latitude, initial longitude and final longitude of trips taken by private EVs are part of the data obtained from Mendeley Data. The consumption evaluation of each vehicle is obtained from the energy consumption model.

The coordinates of each trip are used to assess the departure and destinations of each trip. This also helps to evaluate the distance of each trip. Based on this distance, the accurate energy consumption of the whole trip by a private EV is calculated. These trip estimations and parameters of Mendeley Data become part of the input data for the Prophet Model. The column names of dataframe that include date and energy consumption of the trip are further classified into "ds" and "y". This is a requirement of the Prophet procedure where also the "ds" parameter must contain datetime objects while the "y" parameter should be numeric and the measurement that is required to be analysed. After the formatting of input data, a logarithmic transformation is performed on the parameters of data. The purpose for this tuning of parameters is to smooth out the variations in data.

Now to use the Prophet procedure, a Prophet() object is defined. Then it is fitted on the formatted dataset by using the fit() function and passing the data. This object is used to define a 'future' dataframe for a specific time period. It is created by using a built-in helper function make_future_dataframe of the Prophet. At this point, a predict() method is used for creating the predictions and trends. Also, now the forecasted values and uncertainty intervals are assigned to a new dataframe by the Prophet. In the end, these results are visualized by making use of Prophet's built-in plot helper function. For further aiding the analysis, a describe() method is used, which provides different statistics like count, mean, standard deviation, minimum and maximum for the numerical data of the dataframe.

The prophet demonstrates robustness towards any missing data and also well manages the outliers well. In addition, the forecasts can be adjusted according to specific requirements. For our methodology, the Prophet model is implemented in the Jupyter Notebook, which is a web application used for different computations. The code, statistics and visualizations are executed on this computational platform.

The final implementation for this methodology of comparative analysis involves a focus on major key performance indicators (KPIs). The previous implementation of Prophet model will also contribute towards the results of this probe. For this analysis, the methodology has been designed to look at the comparative factors of both public electric buses and private electric vehicles. The figure 3.3 shows the scheme for this implementation.

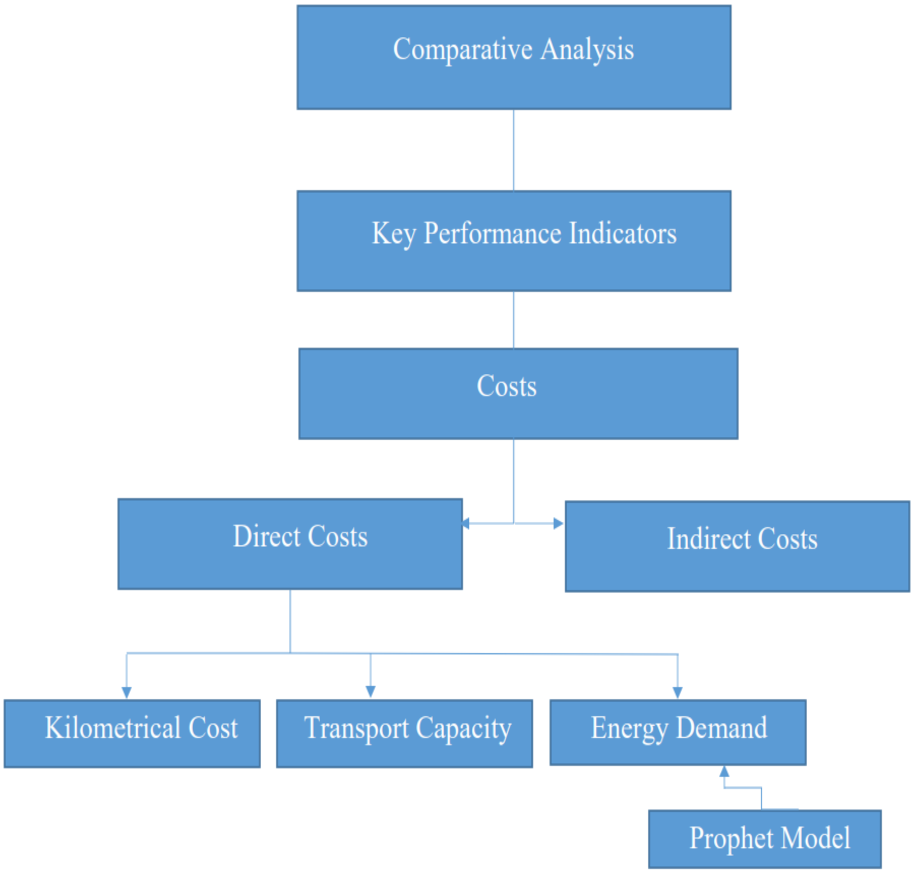

Figure 3.3: Comparative analysis flowchart.

With the consideration of costs as the main component of KPIs, the focus is on the direct and indirect cost elements. The direct costs for the transport systems are evaluated by focusing on the urban terrains. These includes the consideration of highway 2x2 lanes for the private EVs and restricted road lanes for the public buses. For our case study on Turin, these considerations are narrowed down to specific areas of the city. The selection of these areas is based on the dynamics of city and a coordinate specific dataset. According to the latitude and longitude coordinates of vehicles acquired from data, the locations of the trips by the private EVs are mapped out. Then areas with the most Private EVs trips and the bus lanes in those same locations are selected for the analysis.

For the evaluation of the transport capacity, the performance indicator considered is the 'hourly capacity' of private EVs and public electric buses to serve the passengers in a specific area. Depending on the limitations of number of vehicles that can run in the highway in a specific duration, the passenger capacity for the private EVs is evaluated as according to eq (3.11):

$$\text{Capacity} = \text{Max vehicles in unit time} * \text{average filling rate of car} \tag{3.11}$$

While for the public electric buses, the capacity of a bus station is taken into account and it is estimated according to eq. (3.12):

$$\text{CorridorCapacity}_{\text{at station}} = \text{VSize} * \text{LoadFactor} * (\text{Freq}_{\text{direct}} + \sum_{i=1}^{\text{Nsub-stops,Freqi}}) \tag{3.12}$$

where:

- $\text{CorridorCapacity}_{\text{at station}}$: total passengers a corridor can transport through a specific part of station.
- VSize: it describes the maximum capacity of a vehicle.
- LoadFactor: it is the average occupancy of vehicles at a station. It also takes into account the maximum vehicle capacity.
- $\text{Freq}_{\text{direct}}$: frequency of having a limited-stop service where the station under study is skipped.
- Freq_{i}: it represents the vehicle frequency at a sub-stop 'i' and is the total amount of vehicles that lodges at all docking bays of sub-stop i during a specific time period (typically one hour).
- $N_{\text{sub-stops}}$: total independent sub-stops in each station.

Energy demand is one of the key indicators for analyzing the transport demand in Europe; as according to the European Environment Agency (EEA), in 2017 there was a 32% increase in energy consumption by transport since 1990. In our case study for probing the energy demand, the average energy consumption per trip is considered for both the private EVs and public electric buses. For the private EVs, the statistics computed as part of the Prophet model are considered because they include the mean value of energy consumption of all private rental trips that occurred in the specified time period of a month. By considering a round trip of each bus, this stat is also estimated for the public electric buses.

For the kilometric costs evaluation of EVs, different methods has been adopted for both the private EVs and public electric buses. By employing a methodology suggested by the Automobile club of Italy, the cost per kilometer for private EVs are estimated. This has a focus on the "operating cost of a vehicle", which involves the total expenses incurred by any rider for the usage of the vehicle, with the addition of depreciated quotas of the capital in a given utilization period. Hence, the total operating cost of an EV represented in "euros per km" is obtained by the total usage expenses plus the depreciation rates. For an in-depth costs per kilometer estimations, the management costs are distributed into following two groups:

- annual costs not proportional to travel: these are the costs incurred by the driver, regardless of the degree of a vehicle usage. They include the interest rates on purchase capital, car tax and insurance costs;
- annual costs proportional to travel distance: these costs are directly or indirectly related to the degree of a vehicle usage by the driver. They include the fuel, tires, maintenance and repair costs.

Also, the model year and type of EV parameters are taken into consideration for a more realistic estimation. All these parametric values and operating cost specifications are inserted into a web-based tool provided by Automobile club of Italy. After this insertion the tool automatically generates the required cost estimations.

For estimating the kilometric costs for the public electric buses, the two major parameters considered are as follows:

- the costs related to the recharging infrastructure;
- the purchase costs of an electric bus.

By using these parameters and also employing the evaluations for transport capacity indicator, the costs per kilometer for electric bus is calculated according to eq. (3.13):

$$\text{Average cost per km} = \frac{\text{Total infrastructure costs + Purchase costs of vehicle}}{\text{Transport capacity of vehicle}} \tag{3.13}$$

As part of the KPIs, several indirect costs related to electric cars are also probed. These costs specifically pertain to the large-scale usage of electric transport. By using the limited existing literature and available open-source data, the key characteristics that contribute to the indirect costs are also analysed and include the large-scale battery recycling, increased risk of electrocution and job losses.

All the components of direct costs are investigated by focusing on a specific area of Turin, which has been selected by using a software known as 'Quantum Geographic Information System' (QGIS). It is an open-source geographic information system. For our case study, it is used to map different regions by using the spatial data. This mapping is achieved by using the data obtained from the open-source Mendeley Data repository. For comparative analysis, the transport capacity and kilometric cost evaluations are made possible by using the data obtained from Gruppo Torinese Trasporti (GTT) and vehicle specifications data acquired from transport companies.

Chapter 4. Results

In this section, the results from both the energy evaluation and comparative analysis methodologies are reported.

4.1 Energy Evaluation

The energy evaluation for the buses are focused on the electric busses used by GTT in the city of Turin. These buses are named as 2-AXLE urban BYD bus. For obtaining the evaluation through a simulation, firstly the required WLTC dataset was chosen based on the following power-to-weight ratio calculation:

$$\text{PW}_r = \frac{180 \text{ kw}}{9.020\ tonne} = 19.95 \tag{4.1}$$

Where: P_{max} = 180 kw
m_v = 9.020 tons

In the eq. (4.1), the values of the maximum power and kerb weight used are specific to BYD bus used by GTT. Since this electric bus PW_r obtained is less than 22, therefore the WLTC class 1 driving cycle dataset will be employed for energy consumption evaluation. The parameters of this class 1 cycle are shown in table 4.1, where speed, percentage of stops and acceleration variables have also been addressed

Table 4.1: Selected parameters of the WLTC class 1 cycle.

Phase	Duration	Stop Duration	Distance	p_stop	v_max	v_ave w/o stops	v_ave w/ stops	a_min	a_max
	s	s	m		km/h	km/h	km/h	m/s²	m/s²
Low 1	589	154	3330	26.1%	49.1	27.6	20.4	-1.00	0.76
Medium 1	433	48	4767	11.1%	64.4	44.6	39.6	-0.53	0.63
Low 1	589	154	3330	26.1%	49.1	27.6	20.4	-1.00	0.76
Total	1611	356	11428						

Now Scilab software is used further for implementing the model and simulation processes. The WLTC data is also imported in this software and it is stored in the variable. Also, this is used later for simulation process.

For using the imported WLTC data, a script file is implemented in an electronic lab notebook (ELN) known as SciNote. Different Scilab functions are used for opening the data file and reading the required data. The parametric values from this data are loaded allocated to a WLTP structure. Additionally, these values are validated through a data visualisation process. Figure 4.1 is obtained after running this script and it shows all the time and speed values for our data.

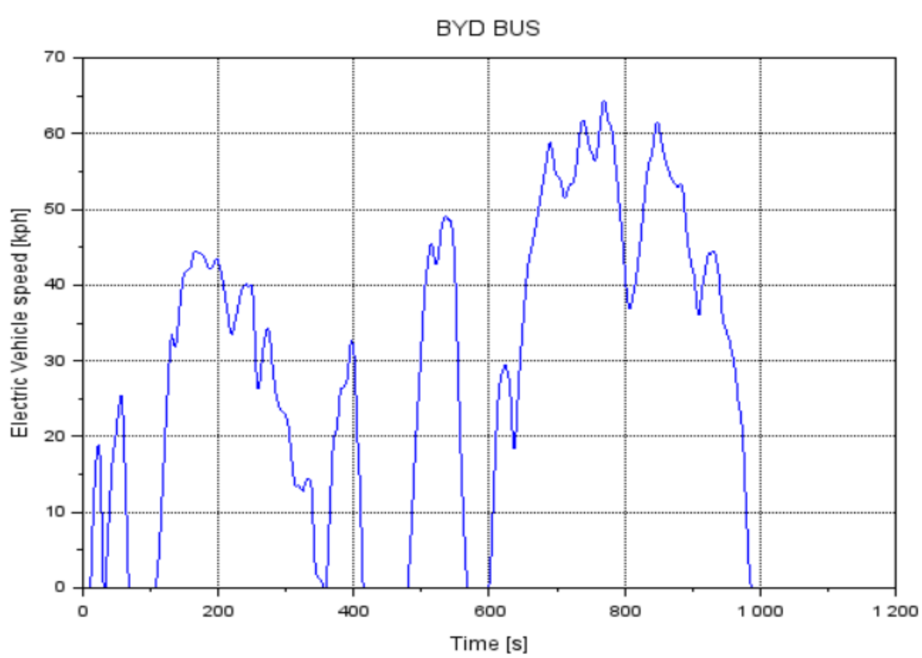

Figure 4.1: Speed and time profile.

After the WLTC data has been imported and verified, the next step include insertion of different vehicle and on-road parametric values. These will be used further in simulation modeling for different road-load forces computations. Figure 4.2 shows the parameters and their values used in the process of GTT bus energy evaluation.

ElectricityConsumption_EPTHunting.sce | EV_Consumption_Graph_EPTHunting.sce | *VehicleParameters

```
//Kerb weight of the vehicle
ElecVehMassKerb = 9020 ; // [kg]
//Weight of the driver
ElecVehMassDriver = 80; // [kg]
//Mass factor
ElecVehMassfm = 1.05;
//Total mass of the vehicle
ElecVehMass = ElecVehMassKerb * ElecVehMassfm + ElecVehMassDriver; // [kg]
//Acceleration due to gravity
ElecVehg = 9.81; // [m/s^2^]
//Drag coefficient
ElecVehcd = 0.311;
//Vehicle's frontal area
ElecVehfa = 7.13; // [m^2^]
//Air density at 20°C
ElecVehro = 1.2041; // [kg/m^3^]
//Inclination angle of road
RoadSlope = 0; // [rad]
//Road rolling resistance coefficient
RoadCrr = 0.010;
```

Figure 4.2: Parameters for simulation modeling of the GTT bus.

Now for the final step, a block diagram is built in the Xcos simulation environment. Different palettes like product, gain, switch, constant and expression are used for building the model. Figure 4.3 depicts the model built by making use of the parametric values, data and palettes. It also shows the energy consumption evaluated for the GTT bus. Before beginning the simulation process, the final integration time parameter is also manually set to 1200 seconds by browsing the setup settings of the Xcos tool. This ensures that the model runs for the entire time period of the WLTC drive cycle.

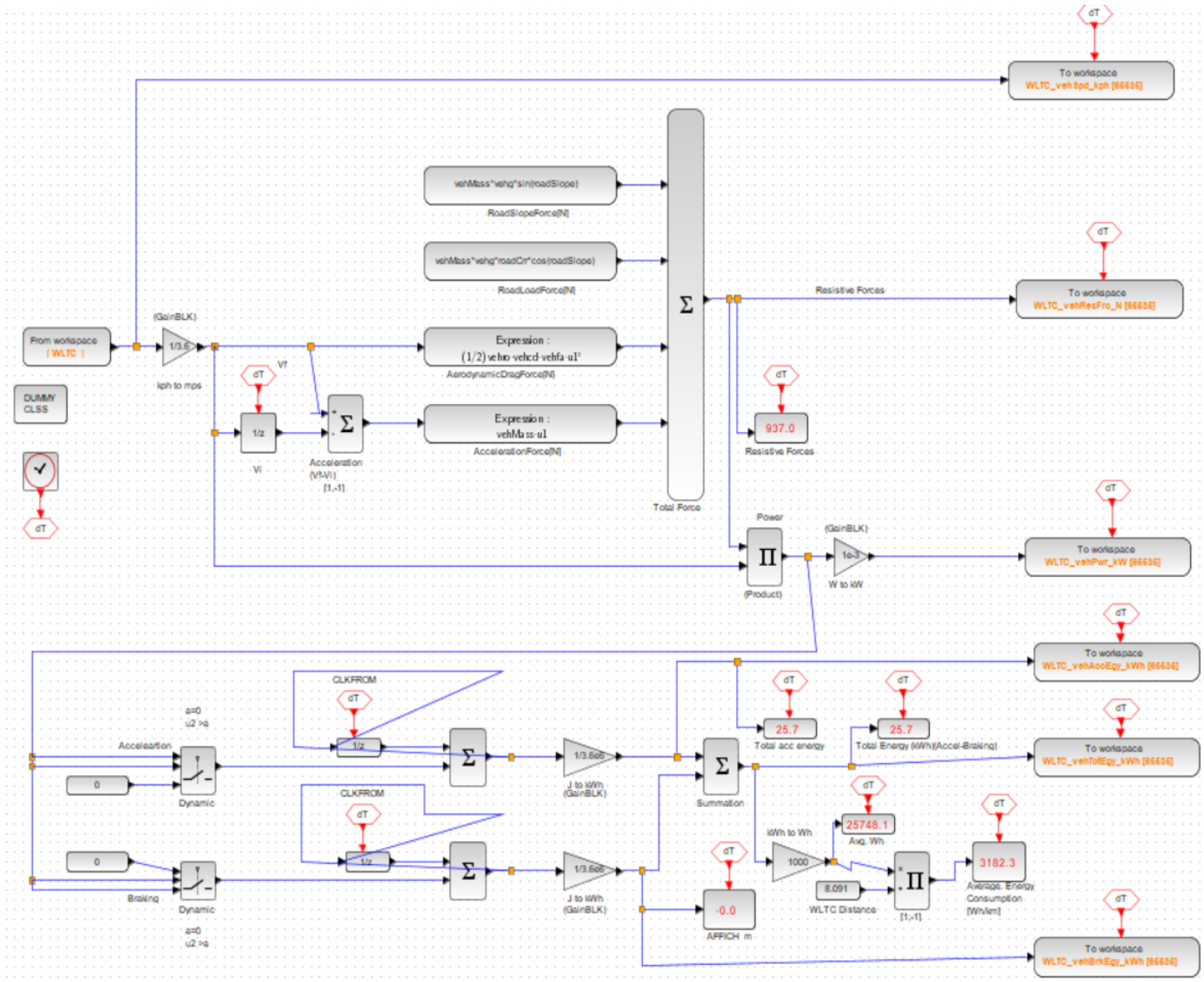

Figure 4.3: Energy consumption simulation model for the GTT bus.

For the energy consumption evaluated in figure 4.3, the consideration for rode slope is 0 rad and it does not have any impact on the consumption. Also, the acceleration and braking periods of a vehicle are identified by taking into account the total power. For this power, an integration is performed for obtaining the energy estimation. The acceleration and braking energies are computed individually and then added together for obtaining the total energy. In the end, the value of this total energy is divided by the entire length of the considered WLTC drive cycle. This gives us the average energy consumption of 3182.3 Wh/km for the GTT bus.

For the private EV, the energy evaluation is focused on the vehicle used by a rental company in the city of Turin. These vehicle are employed by the Enjoy's car sharing fleet and are named as XEV YOYO. For obtaining the evaluation through a simulation, firstly the required WLTC dataset was chosen based on the following power-to-weight ratio calculation:

$$\mathrm{PW}_r = \frac{7.5\ \mathrm{kw}}{0.85\ tonne} = 8.82 \tag{4.2}$$

Where: $\mathrm{P}_{\max} = 7.5$ kw

$m_v = 0.85$ tons.

In the eq. (4.2), the values of the maximum power and kerb weight used are specific to private EV used by Enjoy. Since this electric vehicle PW_r obtained is less than 22, therefore the WLTC class 1 driving cycle dataset will be employed for energy consumption evaluation. This dataset is similar to the one used in GTT bus estimation as well. So, the parameters of this class 1 cycle are already shown in table 4.1, where different variables like speed, percentage of stops and acceleration have also been addressed. Also, similar procedures explained earlier for importing the data and validating it through data visualisation process are followed. Figure 4.4 demonstrates the data validation process and it shows all the time and speed values for our data.

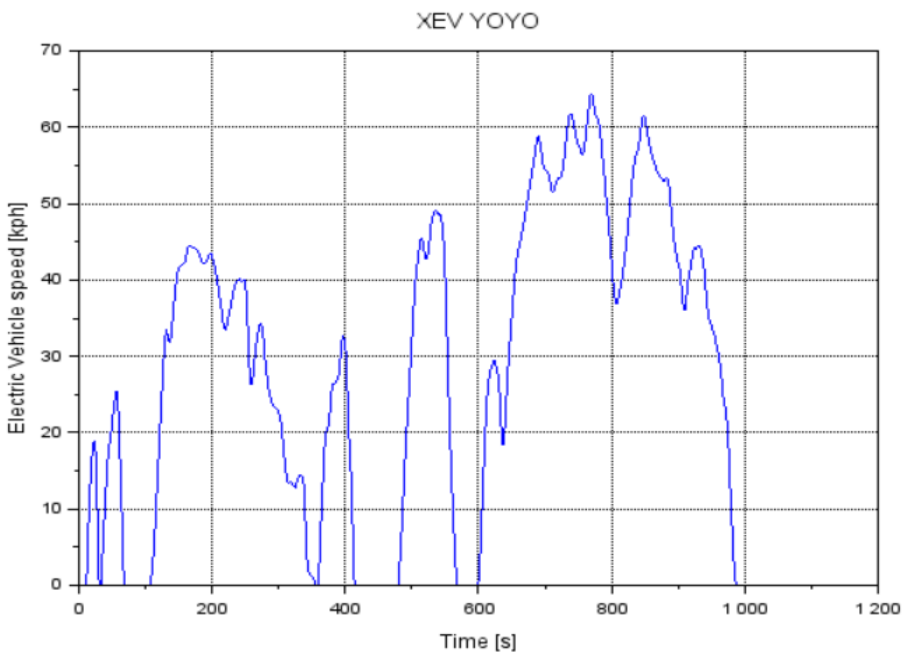

Figure 4.4: Speed and time profile.

For the next step, some vehicle and on-road parametric values will be similar to the one's used in GTT bus case but others will change due to different dynamics of the vehicle. The parameters that will have the changed values include the road rolling resistance coefficient, air drag coefficient, vehicle frontal area and kerb weight of the vehicle. All these parameters are further used in simulation modeling for different road-load forces computations. Figure 4.5 shows the parameters and their values used in the process of XEV YOYO car energy evaluation.

ElectricityConsumption_EPTHunting.sce | EV_Consumption_Graph_EPTHunting.sce | *VehicleParameters

```
//Kerb weight of the vehicle
ElecVehMassKerb = 450 ; // [kg]
//Weight of the driver
ElecVehMassDriver = 80; // [kg]
//Mass factor
ElecVehMassfm = 1.05;
//Total mass of the vehicle
ElecVehMass = ElecVehMassKerb * ElecVehMassfm + ElecVehMassDriver; // [kg]
//Acceleration due to gravity
ElecVehg = 9.81; // [m/s^2]
//Drag coefficient
ElecVehcd = 0.26;
//Vehicle's frontal area
ElecVehfa = 3.22575; // [m^2]
//Air density at 20°C
ElecVehro = 1.2041; // [kg/m^3]
//Inclination angle of road
RoadSlope = 0; // [rad]
//Road rolling resistance coefficient
RoadCrr = 0.012;
```

Figure 4.5: Parameters for simulation modeling of the XEV YOYO vehicle.

For the last step of block diagram for private EV, the palettes and procedure used are similar to the one's used in GTT bus case. Figure 4.6 shows the model built for the private EV's energy evaluation. The final integration time parameter for this model is manually set to 1200 seconds to ensure that it runs for the entire duration of the WLTC drive cycle.

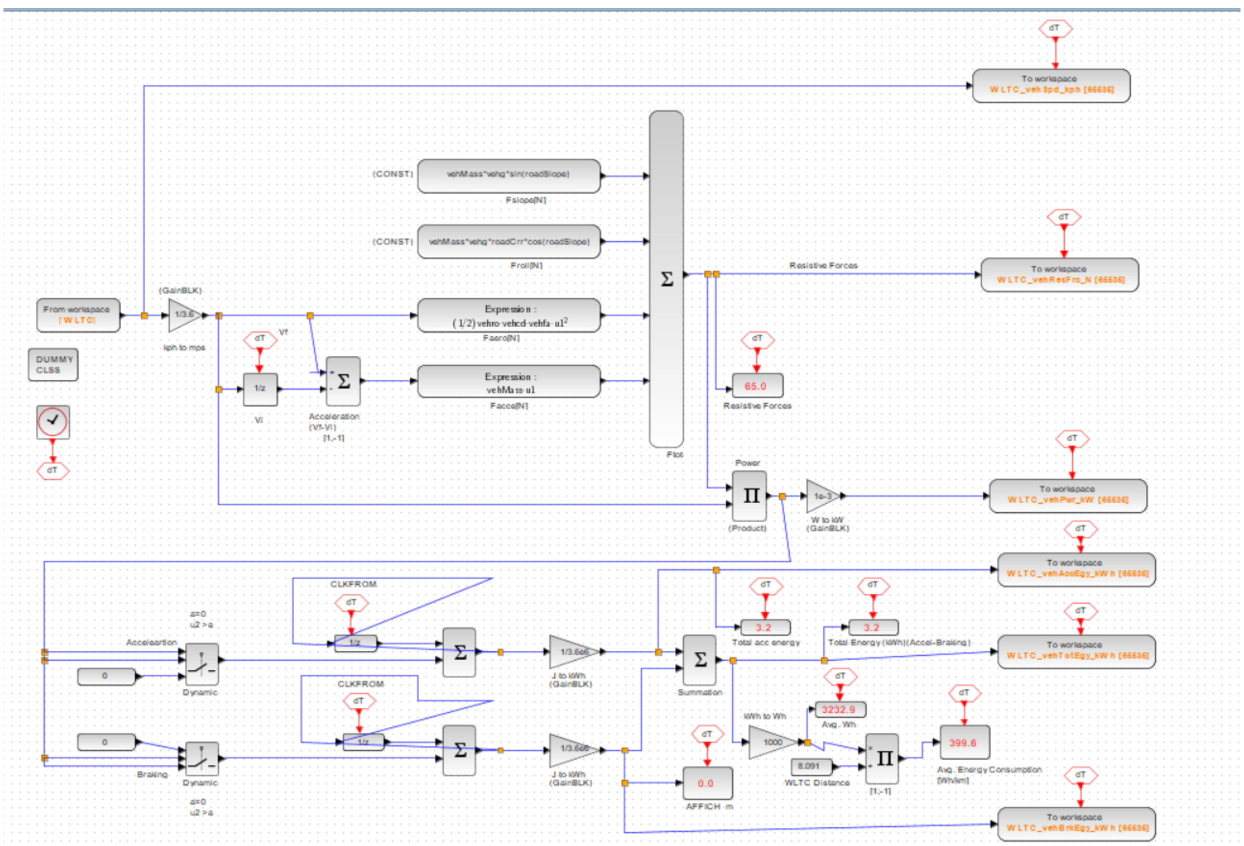

Figure 4.6: Energy consumption simulation model for the XEV YOYO vehicle.

The model depicted in figure 4.6 shows the energy evaluation of the Private EV as 399.6 Wh/km and it is equivalent to 0.39 kWh/km. This estimation can differentiate with a data that takes into account more varying weather conditions and other diverse driving behaviors.

4.2 Comparative Analysis

Before the comparative analysis process, a focus area is selected for our analysis. The Prophet model and comparative probe is centered on this area. All the eight districts of Turin are considered for its selection. Figure 4.7 is obtained by employing QGIS software and it depicts all these districts.

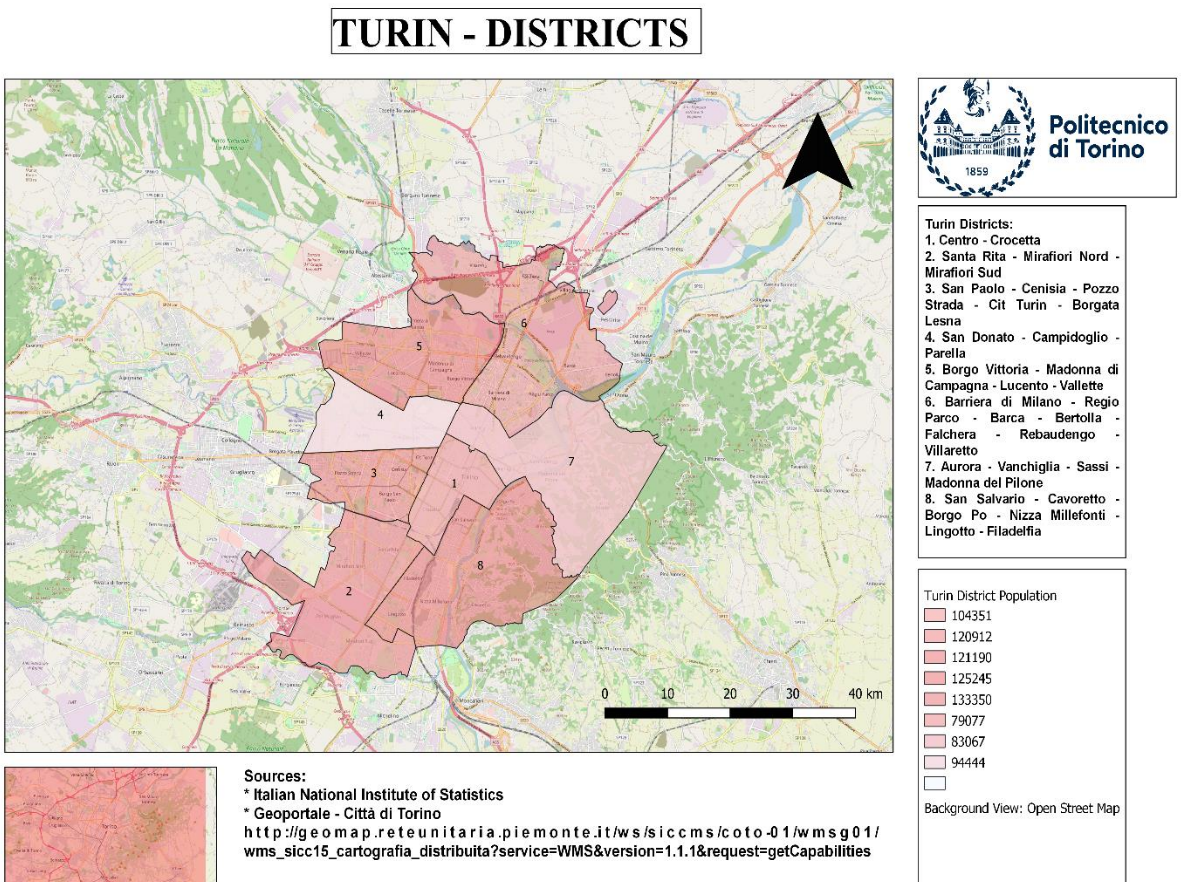

Figure 4.7: Different districts and population statistics for the city of Turin.

For finding the focus area, the coordinates of different trips obtained from the Mendeley Data are marked on the map shown in figure 4.7. Then the locations with most trips are selected for our analysis. These areas and the start-stop points are shown in Figure 4.8. These points of different trips are related to the XEV YOYO vehicle. Also, these locations include the major educational hubs, residential buildings and the city center.

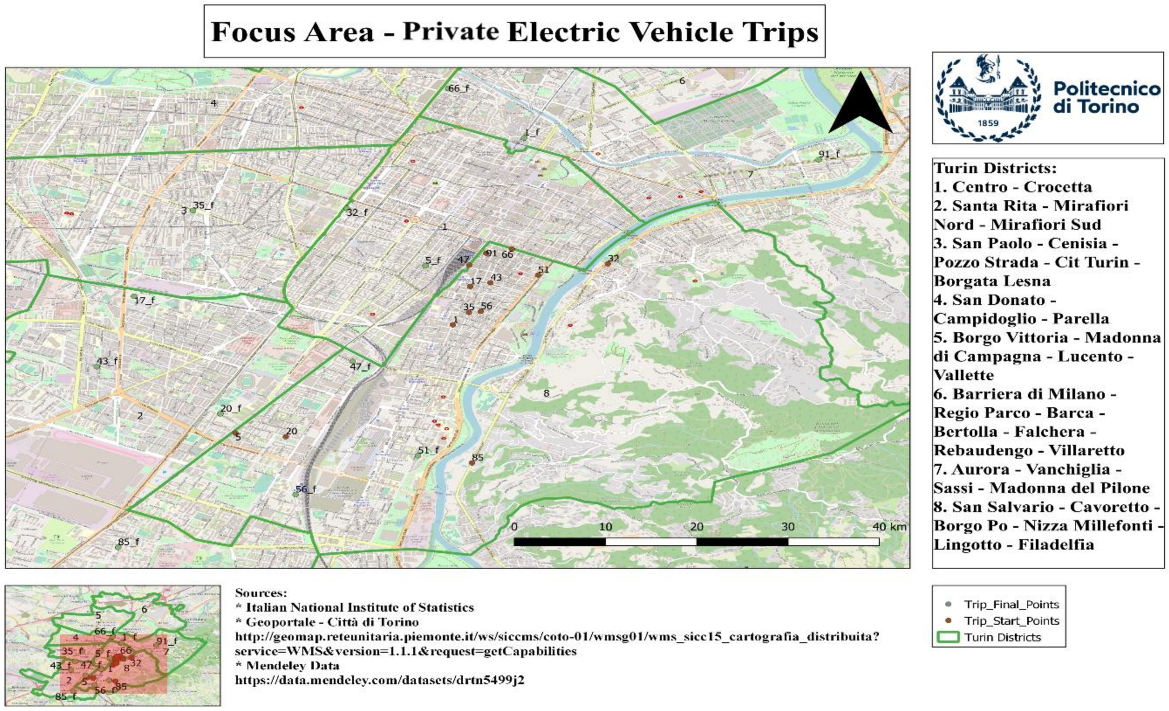

Figure 4.8: Mapped focus area and the coordinate points of trips taken by the XEV YOYO vehicle.

Since the comparative probe is based on both the GTT bus and XEV YOYO vehicle, so the routes and buses considered are of the same areas that are shown in figure 4.8. Some of the major line-routes of the GTT electric buses are shown in figure 4.9.

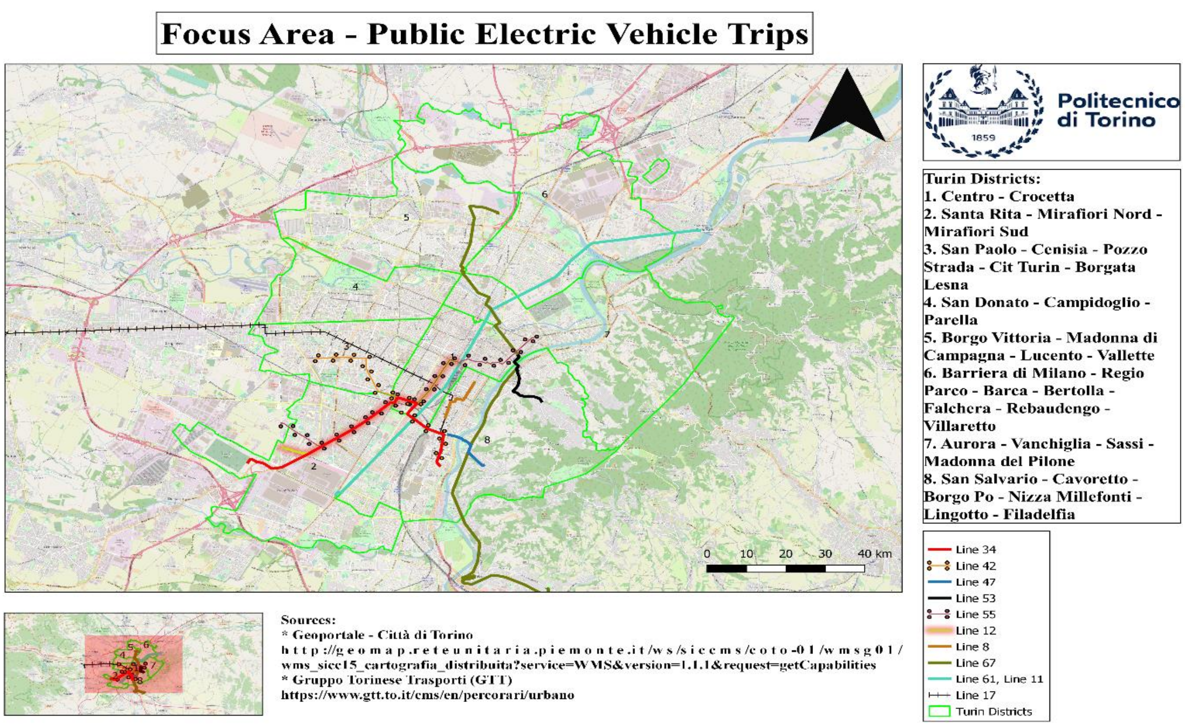

Figure 4.9: Mapped focus area and the line-routes of the GTT electric buses.

Now the Prophet model is implemented by considering the trips of the XEV YOYO vehicles for the areas shown in figure 4.8. This is executed in the Jupyter Notebook by making use of the functions and parameters described in the section 3.2. This model's visualisation is shown in figure 4.10 and it demonstrates the behavioral trend and future forecasts. It helps in analysing the following indicators for the electric vehicles:

- usual trend for the travelling distance of vehicles;
- average energy demand for a vehicle's trip.

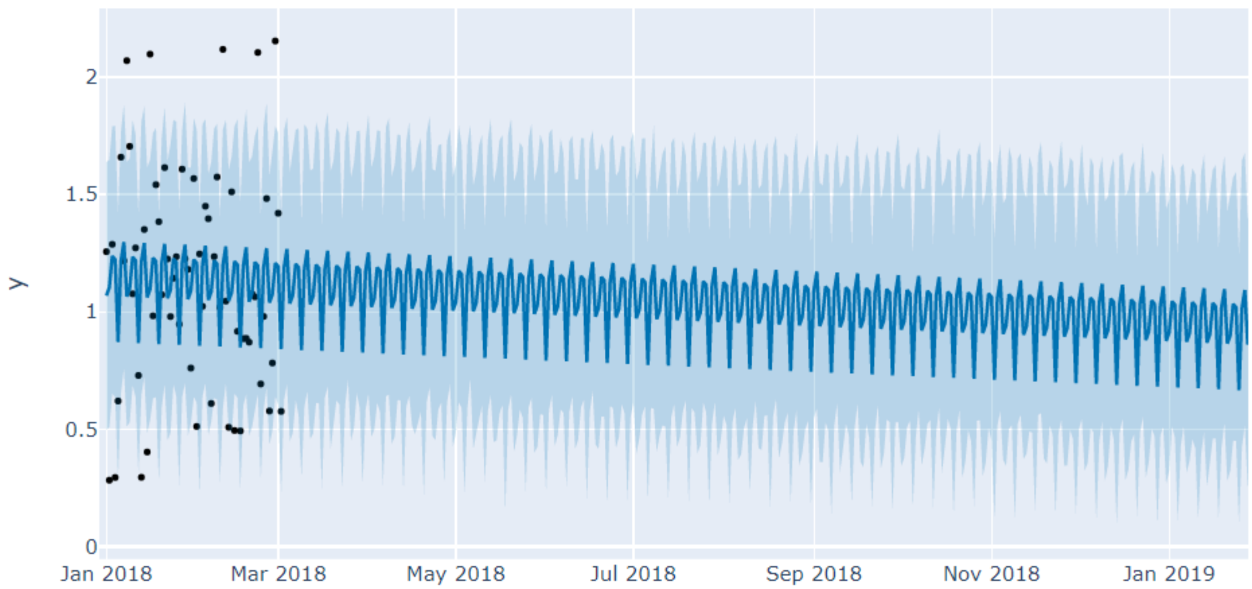

Figure 4.10: The historical trend and time series forecasting of the Prophet model.

For the visualization shown in figure 4.10, the y-axis represents the average energy consumption per trip and the x-axis shows the timeline. The major deduction that can be drawn from this result is that the average energy demand remains steady in the range of 0.6-1.2, despite of a slight downward trend towards the end of forecast. Another insight that it gives is that the private EVs are usually used only for short travel distances like 3- 4 km, as the average energy consumption of XEV YOYO vehicle computed in section 4.1 is 0.3 kWh/km. Table 4.2 shows the statistics estimated during the Prophet model implementation.

Table 4.2: Energy demand statistics.

count	426.000000
mean	1.033701
std	0.149422
min	0.647728
25%	0.946419
50%	1.058480
75%	1.146476
max	1.296566

After the Prophet model, the comparative costs analysis is focused on electric buses and vehicles. Focus area for this probe is shown in figure 4.8 and figure 4.9. Then, as also reported in the scheme shown in figure 3.3, the major concentration of this cost analysis is on the various contributors of the direct costs. These include the kilometric cost, transport capacity and energy demand.

The energy consumption estimation shown in figure 4.3 and statistics reported in table 4.2 are used for the energy demand indicator. For the transport capacity, the eq. (3.11) and eq. (3.12) are used for the calculations:

$$\text{Capacity} = 3600 * 1.32 = 4800 \text{ persons} \tag{4.3}$$

Where: Max vehicles in unit time = 3600 vehicles
average filling rate of car = 1.32.

$$\text{CorridorCapacity}_{\text{at station}} = 60.6 * 0.85 * 60 * 2 = 6181 \text{ persons} \tag{4.4}$$

Where: $\text{VSize} = 60.6$
$\text{LoadFactor} = 0.85$
$N_{\text{sub-stops}} = 2$
$\text{Freq}_i = 60$.

The result from eq. (4.3) represents the average capacity of electric vehicles for a 2x2 highway lane and the estimate of eq. (4.4) indicates the average capacity of electric buses at a specified bus station. Lastly, the kilometric cost KPI involves different implementations for the electric vehicle and the bus. As suggested in section 3.2, this KPI for the electric vehicle is acquired from a tool provided by the Automobile club of Italy. Figure 4.11 shows the results from this tool and they address the non-proportional costs, proportional costs and the total costs required for the travel.

COSTI NON PROPORZIONALI IN €	
Quota interessi	**2.041,31**
Tassa automobilistica	**0,00**
Premio ass. RCA	**732,31**
Totale	**2.773,61**

COSTI PROPORZIONALI IN €/KM	
Quota capitale	**0,1527**
Carburante	**0,0867**
Pneumatici	**0,0233**
Manutenzione e riparazione	**0,0423**
Totale	**0,3050**

COSTI COMPLESSIVI PER LE PERCORRENZE ANNUE RICHIESTE

KM	€/KM	KM	€/KM
5.000	**0,8597**	10.000	**0,5824**
15.000	**0,4899**	20.000	**0,4437**
25.000	**0,4160**	30.000	**0,3975**
35.000	**0,3843**	40.000	**0,3744**
45.000	**0,3666**	50.000	**0,3605**

Figure 4.11: Operating costs of electric vehicle.

Recently for the electric buses, a wireless charging road infrastructure known as Electric Road System (ERS) has been introduced, and it is still in the testing stages. As part of our analysis, proxy costs have been considered for this road infrastructure. Also, the fleet charging infrastructure and vehicle purchase costs data is obtained from the GTT, and the kilometric cost KPI is evaluated as in eq. (4.5):

$$\text{Average cost per km} = \frac{35{,}000\ +\ 3{,}96{,}000{+}3200000}{6{,}181}\ =\ 587.44 \tag{4.5}$$

Where: Fleet charging infrastructure costs = 35,000 €
Purchase costs of vehicle = 3,96,000 €
Electric road system costs = 3,96,000 €
Transport capacity of vehicle = 6,181.

For the electric buses, the eq. (4.5) shows the average cost per km as 587.44 and is equivalent to 0.000587 million. All the evaluated comparative analysis indicators are shown in the following table 4.3.

Table 4.3: Transport KPIs for comparative analysis.

Performance Indicators	Private Electric Vehicle – 2x2 Highway Lane	Public Electric Bus – Road Lanes
Hourly capacity	4800 pers.	6181 pers.
Construction of 1 km infrastructure in focus area (in M€)	------	3.631
Average energy consumption (kwh/km)	1.17 (Average trip consideration)	12.67 (Average trip and electric bus consideration)
Average cost per km	0.17194	0.000587

The table 4.3 describes a comparison between the usage of electric vehicles and buses. It is evident that the buses have a bigger capacity then vehicles despite of considering the whole highway lanes for them. The higher energy demand of an electric bus can also be compensated by its greater capacity. Another major takeaway from this table is the low average cost per km for employing the buses than vehicles. All these indicator assessments significantly enhance the importance of a much greater utilization, promotion and investments for the electric buses.

There are several indirect costs associated with the electric vehicles as well. Majority of them are linked to the long-term societal costs. The most critical impact of these vehicles is related to the expected large-scale battery recycling in future. A recent study indicated that in last decade the total electric vehicles circulation in only the USA and Europe have grown by 344% and 742%, respectively. It also suggested that the EVs are expected to continue this growth exponentially in future [28]. Therefore, with such big numbers of EVs anticipated to be used, the costs associated with the battery recycling will be huge. Also, the plugin charging has increased the risk 6of electrocution because the cable and connector usually provides 2-3 times more power than any standard plugs used at home [29]. Another major social cost of EVs is attributed to job loss and this has also been seen in a case study which used the bottom-up job accounting model to predict 35% job losses by 2030 if the market share of BEVs is increased to 80% [30].

Chapter 5. Conclusions

Having a major focus on electric vehicles, the sustainable mobility aims to transform the whole transport system to an eco-friendlier transport. With a peculiar concentration on EVs, the target is to reduce energy consumptions, costs and emissions.

The electro mobility (e-Mobility) requires a continuous and more robust effort from all the actors involved that include the transport operators, users, investors and governments. A better infrastructure, more renewable energy mix and cost-effective measures are needed for a long-term success of e-Mobility.

The results from the energy evaluation demonstrate that the average energy consumption of an EV varies a lot based on different impacting forces, speeds and terrains. It can also be seen that these varied factors differently impact an electric car and a bus. Therefore, it is really important that a more holistic approach be employed by the key stakeholders when evaluating the effectiveness of EVs for the sustainability.

The comparative analysis draws a clear distinction between two different modes of transport. For these modes, the evaluation of various indicators clearly demonstrates the need for a greater focus towards the public transportation. It is evident that the electric buses are a more desirable emission reduction solution then electric cars because they allow a better attainment of energy conservation and transport demand. In addition, the cost estimations evidently enhance the economic viability of electric buses and the need of a much greater investment and promotion for this mode of transport.

This research is focused on various core aspects of electric vehicles and it can play a vital role in its future wide-ranging use for sustainable environment. For the future research, more data could be very beneficial especially when evaluating the realistic energy consumptions of a vehicle. Moreover, the research can be further improved by incorporating the behavioural data based on affordability and familiarity of users towards EVs.

Bibliography:

[1] X. Zhang, Y. Zou, J. Fan, H. Guo (2019): Usage pattern analysis of Beijing private electric vehicles based on real-world data, *Energy*, **167**, 1074. https://doi.org/10.1016/j.energy.2018.11.005

[2] E. Yao, T. Liu, T. Lu, Y. Yang (2020): Optimization of electric vehicle scheduling with multiple vehicle types in public transport, *Sustainable Cities and Society*, **52**, 101862. https://doi.org/10.1016/j.scs.2019.101862

[3] S. Borén (2020): Electric buses' sustainability effects, noise, energy use, and costs, *International Journal of Sustainable Transportation*, **14**, 956-971. DOI: 10.1080/15568318.2019.1666324

[4] World Business Council for Sustainable Development (2015): Methodology and Indicator Calculation Method for Sustainable Urban Mobility, *WBCSD*, Technical Report 978-2-940521-26-5. https://www.eltis.org/sites/default/files/trainingmaterials/smp2.0_sustainable-mobility-indicators_2ndedition.pdf

[5] General Assembly of the United Nations (2015): Sustainable Development Goals. https://sdgs.un.org/

[6] T. Litman, D. Burwell (2006): Issues in sustainable transportation, *International Journal of Global Environmental Issues*, **6**, 331–347.

[7] P. Miller, A. G. D. Barros, L. Kattan, S. C. Wirasinghe (2016): Public transportation and sustainability: A review, *KSCE Journal of Civil Engineering*, **20**, 1076–1083.

[8] D. Banister (2008): The sustainable mobility paradigm, *Transport Policy*, **15**, 73–80.

[9] M. E. Biresselioglu, M. D. Kaplan, B. K. Yilmaz (2018): Electric mobility in Europe: A comprehensive review of motivators and barriers in decision making processes, *Transportation Research Part A: Policy and Practice*, **109**, 1-13. https://doi.org/10.1016/j.tra.2018.01.017

[10] Y. Chen, S. Young, X. Qi, J. Gonder (2015): Estimate of fuel consumption and GHG emission impact from an automated mobility district, *2015 International Conference on Connected Vehicles and Expo (ICCVE)*, 271-278. doi: 10.1109/ICCVE.2015.32

[11] S. Kaffash, A. T. Nguyen, J. Zhu (2021): Big data algorithms and applications in intelligent transportation system: A review and bibliometric analysis, *International Journal of Production Economics*, **231**, 107868. https://doi.org/10.1016/j.ijpe.2020.107868

[12] S. Gössling (2018): ICT and transport behavior: A conceptual review, *International Journal of Sustainable Transportation*, **12**, 153-164. DOI: 10.1080/15568318.2017.1338318

[13] EU-FP7 REDUCTION Project (2014): Reducing environmental footprint based on multi-modal fleet management system for eco-routing and driver behaviour adaptation, *Cordis*. http://cordis.europa.eu/project/rcn/100009_en.html

[14] EU-FP7 PEACOX Project (2015): Persuasive advisor for CO_2-reducing cross-modal trip planning, *Cordis*. http://cordis.europa.eu/project/rcn/100231_en.html

[15] EU-FP7 eCOMPASS Project (2014): eCO-friendly urban multi-modal route planning services for mobile users, *Cordis*. http://cordis.europa.eu/project/rcn/100714_en.html

[16] EU-FP7 ICT-EMISSIONS Project (2015): Development of a methodology and tool to evaluate the impact of ICT measures on road transport emissions, *Cordis*. http://cordis.europa.eu/project/rcn/100769_en.html

[17] TransportPolicy EU: light-duty: emissions. http://www.transportpolicy.net/index.php?Title=EU:_Light-duty:_Emissions

[18] Regulation Commission (EU) 333/2014 of 11 March 2014.

[19] Regulation Commission (EU) 2017/1153 of 2 June 2017.

[20] J. Pavlovic, A. Marotta, B. Ciuffo (2016): CO2 emissions and energy demands of vehicles tested under the NEDC and the new WLTP type approval test procedures, *Applied Energy*, **177**, 661-670. https://doi.org/10.1016/j.apenergy.2016.05.110

[21] A. Marotta, J. Pavlovic, B. Ciuffo, S. Serra, G. Fontaras (2015): Gaseous Emissions from Light-Duty Vehicles: Moving from NEDC to the New WLTP Test Procedure*, Environmental Science & Technology,* **49**, 8315-8322. DOI: 10.1021/acs.est.5b01364

[22] P. Mock, J. Kühlwein, U. Tietge, V. Franco, A. Bandivadekar, J. German (2014): The WLTP: How a new test procedure for cars will affect fuel consumption values in the EU, *ICCT*.

[23] G. DiPierro, F. Millo, C. Cubito, B. Ciuffo, G. Fontaras (2019): Analysis of the Impact of the WLTP Procedure on CO_2 Emissions of Passenger Cars, *SAE International*. https://doi.org/10.4271/2019-24-0240

[24] Consilium (2015): Real driving emissions: Council gives green light to first package. 〈 http://www.consilium.europa.eu/en/press/press-releases/2015/11/10-real-driving-emissions-council-gives-green-light/

[25] A. Mandev, P. Plötz, F. Sprei, G. Tal (2022): Empirical charging behavior of plug-in hybrid electric vehicles, *Applied Energy*, **321**, 119293. https://doi.org/10.1016/j.apenergy.2022.119293

[26] Y. Miao, P. Hynan, A. V. Jouanne, A. Yokochi (2019): Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements, *Energies*, **12***,* 1074. https://doi.org/10.3390/en12061074

[27] M. Glotz-Richter, H. Koch (2016): Electrification of Public Transport in Cities (Horizon 2020 ELIPTIC Project), *Transportation Research Procedia*, **14**, 2614-2619. https://doi.org/10.1016/j.trpro.2016.05.416

[28] L. S. Martins, L. F. Guimarães, A. B. B. Junior, J. A. S. Tenório, D. C. R. Espinosa (2021): Electric car battery: An overview on global demand, recycling and future approaches towards sustainability, *Journal of Environmental Management*, **295**, 113091. https://doi.org/10.1016/j.jenvman.2021.113091

[29] H. H. Wu, A. Gilchrist, K. Sealy, P. Israelsen, J. Muhs (2011): A review on inductive charging for electric vehicles, *2011 IEEE International Electric Machines & Drives Conference (IEMDC)*, 143-147. doi: 10.1109/IEMDC.2011.5994820

[30] A. Singh (2021): Modeling Technological improvement, Adoption and Employment effects of Electric Vehicles: A Review, *SSRN Electronic Journal*. http://dx.doi.org/10.2139/ssrn.3859496