POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA CIVILE,
AMBIENTALE E TERRITORIALE

Planning Sustainable Urban Mobility: A tool to assess the effectiveness of possible solutions

TESI DI LAUREA MAGISTRALE IN
CIVIL ENGINEERING FOR RISK MITIGATION
INGEGNERIA CIVILE PER LA MITIGAZIONE DEL RISCHIO

Author: **Nicola Capparelli**

Student ID: 977455
Advisor: Paolo Gandini
Co-advisor: Marco Ponti
Academic Year: 2021-22

Abstract

This thesis investigates the topic of sustainable mobility in the urban environment. The literature widely covers a number of different approaches to improve or innovate the transport solutions for transitioning in the direction of environmental sustainability. The main goal is the reduction of transport related greenhouse gas emissions, especially carbon dioxide, along with the emitted pollutants reduction. The literature analysis on this topic enlightens the different measures that have been historically applied or have been simulated through the use of models to understand what could fit and be more effective in a specific urban environment. The result of this analysis showed the absence of a quick model to compare the different measures effectiveness. Many research findings where showing models set to evaluate a specific set of measures. On this ground this thesis proposes a comprehensive model that, based on what was found through the literature analysis, was developed specifically to compare the different set of measures in the urban context. The main goal of the model is to assist the decision makers in the evaluation of several mobility measures oriented towards sustainability in the transport framework, considering cost-effectiveness as leading criteria for the solutions to be applied. To fulfil such a goal the model describes the actual modal split in the town, starting from aggregated, high-level data, and evaluates the current emissions. Then it simulates the effects of the different activated measures, estimating emissions reductions or increments and assessing the related costs.

Key-words: sustainable urban mobility, CO_2 emissions, modal split, micro-mobility, cost estimation

Abstract in italiano

Questo lavoro di tesi investiga il tema della mobilità sostenibile in ambito urbano. L'argomento è ampiamente coperto da un numero considerevole di diverse soluzioni, concertanti verso la transizione sostenibile, proposte per migliorare o rinnovare le soluzioni di trasporto. Lo scopo principale è la riduzione delle emissioni di gas serra, con un focus particolare riguardo le emissioni di diossido di carbonio, e la riduzione, allo stesso tempo, delle emissioni di altri inquinanti. Attraverso l'analisi della letteratura vengono messe in luce le diverse misure che sono state impiegate storicamente o simulate attraverso l'uso di modelli, con lo scopo di comprendere cosa possa essere più adatto ed efficace in uno specifico sistema di trasporti urbano. Il risultato di questa analisi mostra la mancanza di un modello che permetta di comparare l'efficacia delle diverse misure rapidamente. Molte ricerche portano come risultato modelli pensati per valutare gruppi di misure definiti. Questa tesi propone, partendo da questi presupposti, un modello comprensivo che, basandosi su quanto si evince dall'analisi della letteratura, è stato sviluppato specificatamente per confrontare i diversi tipi e gruppi di misure nel contesto urbano. Lo scopo principale del modello è quello di supportare le scelte decisionali di chi di dovere, nella valutazione delle migliori misure di mobilità da intraprendere, per muoversi verso un sistema di trasporti sostenibile, considerando come principale criterio d'adozione, il rapporto costi-benefici. Per il coronamento di un simile scopo, partendo da dati aggregati, il modello valuta il reparto modale corrente nella città e stima le emissioni attuali. Simula poi gli effetti delle diverse misure implementabili considerando emissioni ridotte o aumentate a causa delle attivazioni e i costi relativi le misure stesse.

Parole chiave: mobilità urbana sostenibile, emissioni di CO_2, reparto modale, mobilità leggera, stima costi

Executive Summary

I. Objectives, targets, and research questions

The objective of this work is the elaboration of a model intended to support decision-makers in the field of sustainable urban mobility.

The development of a similar model was considered useful after a deep analysis of up-to-date literature. Despite encountering a number of interesting models, none of them had the pursued combination of focus on urban transport and introduction of sustainable measures for all the different fields of mobility.

To analyse literature in a critical way, and to guide the further development of the work, a list of questions has been developed. The following questions are just a guideline to present the main structure of presented work.

1. How is it possible to read the current urban mobility scenario in an effective way through a descriptive, high-level model?
2. What are the measures most likely to be deployed to reduce transport related emissions?
3. After the descriptive model creation, how is it possible to assess its validity for different urban systems?

The method proposed in this thesis is open to future contributions, being directly related to other fields of study. The work focuses strongly on modal split evaluation and transport related emissions, and on the cost that should be sustained when implementing new measures.

The emissions of pollutants are, indeed, harmful also for the human life in some cases. It could be interesting to assess how beneficial would be a sustainable transition from the medical side of the matter. The number of deadly accidents in the urban environment is also a topic that would be influenced by a transition towards sustainable urban mobility. Moreover, the urban planning factor, in its connection with land use and land value, could possibly be an interesting development direction.

II. Methodology & Literature review

The first step of the process was the literature analysis focused on the state of current art analysis. The goal was firstly to understand how to develop a method that would fit into the current framework of studies in the most useful, simple, and comprehensive way. After the evaluation of current state of the art, the articles, books, and journals review had the second objective to understand what were the main and most effective measures that may be applied to move towards a sustainable mobility urban environment. The chapter dedicated to this step is Section 1, titled “State of the Art Analysis”.

Then, the method is designed, developed, and presented. The model defines a parameter, the number of passengers multiplied for the number of travelled kilometres, and its unit of measure, as a fundamental base element for further analysis. The passenger per kilometre unit is therefore useful to rely on past works results and it sets the standard base for potential future evolution of the work.

In Section 2 of the thesis, “Assessment Support Model”, it is presented how the model estimates the value of passenger per kilometre related to each mode of transport utilized by the city population in the urban area, starting from aggregated data of easy accessibility. The evaluation is conducted differently for the different modal cluster, which contain the different modes of transport assorting them in function of their common characteristic. The clusters are five, including public transport, micro-mobility, mobility as a service, private vehicles, and walking. Then it converts the estimated value into emitted quantities of carbon dioxide, ozone, and particulate matter, relying on past reference presenting this kind of process. The following step is to define the possible implementable measures and to assess the cost related to each of them. The cost evaluation is followed by an effectiveness assessment, to allow a rational comparison for a cost-benefit analysis. The model is composed by five total steps. The first one, the input phase, is followed by the descriptive phase of the model. The rest of the model develops its predictive potential. The third phase, cost evaluation, is followed by a cost-effectiveness comparison phase. In the fifth and last phase of the model the user is asked to choose what measure he would rather activate.

The Section 2.2, “Data and literature correlation”, presents the data and literature sources. The processes of evaluation are derived from academic literature sources, while the definition of the different measures and the estimation of the effects is derived by the literature analysis performed in chapter 1. The last set of data presented is the one that was adopted as reference for the process of calibration and validation of the model, to which Section 2.3, "Model calibration and validation”, is assigned.

The model was firstly calibrated on the city of Milan, chosen as a reference due to its comprehensiveness in transport offer, and its leading role for Italian sustainable mobility transition. It was then validated considering three other Italian cities. The city of Rome was elected being the largest city of the nation. The choice of the city of Florence has been dictated by the opportunity to consider a medium size city, and the city of Lecco was taken into study as a small size one. The calibration and validation process has followed an iterative path. The modification of calibration parameters was analysed in its effects on the four cities to ensure that, while getting to the most precise possible evaluation for the case study of Milan, the model would converge also in the other three reference cases.

III. Empirical findings and theoretical results

The main result of this thesis is the design of the method presented for the assessment of modal split and emissions in the urban environment, based on the management of high-level data, relatively easy to access and collect. The method was implemented into a tool that allows the possibility to modify the status quo through the activation of a list of measures, providing indications about cost and effectiveness of the possible solutions. The model itself is the practical representation of this method. While being deeply related to past literature, it makes some fundamental steps forward towards comprehensive sustainable mobility support.

A first theoretical result is the definition of the nine measures of possible implementation when investing resources to reach sustainable mobility. This list is presented in Section 2.1.3, when introducing and presenting the cost model.

A second empirical finding regards the modal split evaluation potential of the model in the different cities. This result is presented in Section 2.2.3, "Model calibration and validation", as a key step in the validation and calibration process. The modal split overall error, when estimating the share for the three main modal clusters, public transport, private combustion transport, and other means of transport, was low enough, and could be improved by further calibration and validation process considering more towns, even of other European countries. The overall error for the Milan case of study was in the last instance lower than 0.5%. The overall error was lower than 6% for the other cities, having an average error and a maximum nominal error lower than 3%.

A third empirical achievement of this work is displayed in Section 3, "Model results on the Case Study". In this section the activation of three exemplary measures, one from the public transport cluster, one from the micro-mobility cluster, and the last one from the MaaS cluster, is simulated through the model, estimating the results in terms of reduced emissions and the cost related to these activations, with reference to the city of Milan. The activation was performed firstly on its own, and then combined with the activation of a private vehicle's related measure, i.e. the reduction in number of parking slots. This process showed some results already mentioned by reviewed literature, like the convenience of working in favour of bike lanes and public transport, being private vehicle reduction and shared vehicle's introduction measures not effective enough in reducing particulate matter emissions without providing travelling population with a sustainable alternative.

However, all the activated measures effects were enhanced in a positive way when combined with the reduction of parking slots number. This measure itself is a result. In the way in which it was implemented the measure cannot be activated on its own, but only when a certain amount of passenger per kilometre is produced by the provision of new infrastructure or vehicles in the other clusters, the measure may be activated. This choice was done to enforce that, if a change in status quo is needed, it should not come from a simple reduction in what could be considered a "negative" side of the offer. This reduction is clearly possible from the government decision side, but it should come with an integration and improvement of the sustainable side of transport, to avoid excessive stress and incommodities on the user side.

IV. Main contributions to the current debate, strengths, and weaknesses

The main contribution of this work is addressed in Section 4, focusing on the methodological relevance of the presented model, and addressing the possible improvements of the method itself, starting from the reference literature highlighted. A similar improvement of work could bring to a more complete model, starting from the transport field and reaching further fields of study, providing results of interest for the economical and medical field.

Another relevant aspect is the possibility of exploitation of this elaborate in support of Government's Institutions decision making. The level of interest of this work should be the municipality one, but the performance could be interesting even on smaller portions of great towns, which may be managed as a smaller town.

The strengths of the proposed method are related to the accessibility of the data that are used as input. With a low-cost calculation process the model is able to give a high-level estimation of the costs and effects of the different implementable measures, showing clearly what would be the most efficient choice. The model can also be used just to roughly evaluate the modal split in a certain urban area, even if the full potentiality is the one just addressed. The measure implemented could be structural, such as building new infrastructure networks, or functional. Even the effect of a single stock of buses or shared cars, as an example, could be simulated.

The main weakness of the proposed method is the lack of spatial reference of the model itself. Usually a modal split evaluation could be obtained from statistical data collected by national or local agencies through a survey process, in order to produce an origin destination matrix that could be representative for the whole population. However, the cost of a similar operation may be prohibitive, and the process could produce results in a time window far from the moment when the initiative is taken. This could lead to a production of accurate results; however, a supporting model could be interesting when providing fast and reasonable results to support decisions. A geospatial reference to the model could be achieved in a further implementation, but it would be dependent on high-quality data difficult to access. The model could be extended to evaluate more precisely the effects of facilities and infrastructures outside the town area. This condition would make the model more powerful and reliable, but also less flexible and fast. Therefore, a high-level analysis, conducted starting from aggregated data and with a very low calculation cost, was still considered as useful, and therefore the work was developed in this direction.

A last weakness is related to the calibration and validation process. The process was performed on four cities, different in terms of shape, population, means of transport, and infrastructure provision. This difference was crucial when defining the upper and lower bounds of the model, and to check the validity on a higher and lower scale than the case study of Milan. However, a full and more demanding calibration and validation could have been useful, thought the application of the model itself on all the mayor Italian municipality towns or on some other European cities of interest. This extended analysis was not developed in this study, but it could be faced in further activities on the topic. A similar investigation could have improved model robustness, bringing it from the current level, that is certainly sufficient, to an optimum with higher accuracy and more particular cases. There is no section of the model that regards water nor cable transport systems, and it would be a problem for cities that strongly rely on such means.

In conclusion, the current weaknesses could be faced with further investigation and research on the topic. Nevertheless, some modifications could get rid also of some strengths as a side effect. The easy flowing model, smart and quick, could become heavy and slow if based on data of difficult production. On the one hand a similar change would certainly generate a more accurate model. On the other, the shift would come with the collateral result of making the model less useful for a quick assessment, depowering the intrinsic quality that it holds at the moment.

Contents

Introduction

Urban Mobility is responsible for 23% of all transport related emissions in the EU and about one fourth of European greenhouse gas (GHG) emissions stem from the transport sector [1].

Sustainability is an essential issue in modern societies [2]. Consequently, the Commission's proposals to cut greenhouse gas emission by at least 55% by 2030 and to become climate neutral by 2050 in all the European Union, is certainly ambitious but it is necessary to guarantee a sustainable future to our planet and a healthy life to future world inhabitants [3].

Nevertheless, being sustainability an all-round concept, addressing the complex totality of the human lifestyle. Progress needs to be achieved in all the main fields at a similar pace to get to that Net Zero by 2050 avoiding excessive stress. The goal is certainly remote. Referring to the transportation field, a 96% reduction in motor vehicle ownership and a 78% reduction in per capita vehicle kilometres travelled is estimated to be necessary to reach this goal [4].

Notwithstanding that a reduction of this magnitude may comprehensibly seem extremely challenging, the task for researchers and professionals is complex but not impossible. The complexity is driven by the different fields that need to change, comprehending economy, society, and environment. The synthesis of these topics is demanding, but necessary for further progress. In this framework of effort it would be possible to pursue the goal with a reliable and quantitative plan.

Regarding the efforts being taken in the transport field new and advanced solutions may be relied upon in the upcoming future. Tests are currently on going for Autonomous Vehicles for urban freight transport [5], for the interaction of AV with surface Public/Collective Transport [6] and population acceptance [7]. This list should also mention the studies for the effect of AV adoption on intersections Level of Service [8], for the evaluation of street land use improvement with a total adoption of private AV [9]. A further experiment was developed to create a multimodal model assessing the emissions related to a complex urban transport system. This last test depended on the percentage of trips performed on AV and on power generation process [10].

The number of reviewed articles regarding the adoption of Electric Vehicles is growing considerably. Among them, it should be mentioned a study made in Poland to assess the environmental effects of a bus fleet substitution from internal combustion buses to electric buses [11] and a scenario simulation done in Sicily, Italy to plan a small town fleet of electric bus sustained only by renewable energy [12].

The transition towards electric vehicles and the experimentation with autonomous vehicles, which could potentially lead the way towards an optimum traffic flow, in terms of efficiency [8], are only two of the several actions that could be invested on in the future.

The complete number of this measures, in development to fulfil the same objective, will be managed in the first chapter. This thesis will be devoted to the specific task of presenting and discussing the numerous different possibilities that are accessible through the more or less recent literature. Obviously, all the presented actions could be potentially beneficial to the urban system and its environment, but any measure is featured by a cost, may it be economical or social.

Hence the aim of this thesis is to design and implement a model intended to predict and assess the effects of those solutions, comparing them with regard to the correlated costs, evaluated with a certain cost model derived from the national law of the desired nation, in this case Italy [13].

In an effort to reach this prediction in a consistent way, some preliminary activities should be faced. A predictive model can only be reliable if it is capable of understanding and representing the contemporary reality through a reasonable scenario. However, the intention is to develop the process in a non-conventional way. Usually, a similar operation would rely on high quality, georeferenced data, used to describe population choice of transport. Typically origin-destination matrices are used. The purpose of this thesis is to develop a fast descriptive model to support decision making, even relying on lower quality, easily accessible, aggregated data, such as the volumes of vehicle provision in the public transport field, or the number of network kilometres. Such a model is considered to be useful, since its goal is to support decision making in a fast, high-level, comprehensive way. Only after this quick but trustworthy depiction of the real urban transport mobility system, it becomes more meaningful to manage the predictive side of the model, assessing the possible solutions that stakeholders, politicians and decisionmakers could choose to pursue, as a variation from the actual system of things.

Inauspiciously a similar model, capable to read the current transport systems of different urban environments, returning the currently mobility scenarios in a quantitative way, was not found in the European context. A similar model, namely developed to calculate the land use benefit associated to an area or a corridor of any city of the United States of America, was found [14]. Nevertheless, this model has been developed to work specifically for a limited case scenario, representing the effects of just one measure over a small area or a corridor. This would have been insufficient to achieve the aspired goal of representing the effects of different, contemporary, and reciprocally interacting measures in a city context.

To organize the work in a methodical way it is necessary to state the different subsequential questions that need to be answered to achieve the expected results, summing up what has been said up to this point:

1. How is it possible to read the current urban mobility scenario in an effective way through a descriptive, high-level model?
2. What are the measures most likely to be deployed to reduce transport related emissions?
3. After the descriptive model creation, how is it possible to assess its validity for different urban systems?

The benchmark of this dissertation will be traced answering these questions, shaping the main chapters, and the results presentation structure.

In an attempt to answer the first question, it is necessary to understand the main dimensions and units of measures of the problem, finding what the main pollutants are, in addition to equivalent carbon dioxide, the main contributor and base unit of representation of GHG. The only way to undergo this task is through a deep analysis of the past literature. Afterwards it will be necessary, starting from the acquirable transport data, to get to a reasonable unit of measures, necessary to perform the emission equivalence.

Addressing the second question, only a comprehensive state of the art analysis can be enough to have an idea of all the different possible measures, subdivided in categories of intervention. For this purpose, the first chapter of this disquisition will be dedicated to an analysis of the state of the art up to date. This will be performed on the one hand to get an overview of the discussed problem, and on the other hand to understand if some of the possible measures, which have already been applied in different cities, have underperformed and what were the conditions driving these registered results.

The third question needs to be answered after the former ones. If the first chapter will be dedicated to the state-of-the-art analysis, the second chapter will firstly present the model in its base and composition, calibrating it on a selected national city, in this case the Italian city of Milan. After the model definition and first descriptive performance, it will be evaluated on three different cities of the national territory. To assess the model flexibility and validity the cities of choice will need to be different in shape, dimension and offer of transport. After the fulfilment of this precondition, the last chapter, related to the predictive model results on the original city, will be devoted to the overview of the predictive model results. Inasmuch as the descriptive capacity of the model will be verified, it will be meaningful to carry on and examine the model predictive potential.

1 State of the Art Analysis

The majority of the articles reviewed during the thesis development belong to the journal *Sustainability*, one of the three most impacting journals of the Multidisciplinary Digital Publishing Institute.

Then a smaller share of reviews, articles and book chapters comes from the Scopus database. The rest of cited material is then related to national institutions accessible databases.

The prevalence of the first kind of articles in the total bibliography is certainly correlated with the topic of discussion. Even though the first part of the model is not strictly related to sustainability in a transitionary way, being it mainly dedicated to real scenario evaluation, the second predictive part of the model is strongly devoted towards ecological transition and, therefore, strictly correlated with the themes found in a number of articles of the *Sustainability* journal.

1.1. Classification per topic

To start with the classification divided for topic firstly it is necessary to make a list of the main topics of discussion that are present in a considerable number of articles.

Some of these articles will be of strong relevance in the third section of this chapter, where they will be discussed more into detail, but in this part the total amount of encountered considered potentially useful material, also with regards to possible future development, will be enumerated for completeness.

The main topics of discussion are presented in alphabetical order. They have not to be too specific but still can define the main field of study where the correlated work has been produced.

The topics are:

- Economical
- Environmental
- Medical
- Mode of Transport
- Urban Planning

The area of interest for our work is the urban one. An area characterized by a high degree in terms of population density and number of activities. For this reason, the presence of the field "Medical" in reasonable, despite not being the less recurrent topic.

No other words need to be spent on the other four topics, whereas they are all bond to the urban transport field by close ties.

1.1.1. Economical

Two articles related to this topic have already been mentioned, the two articles «Encouraging the Sustainable Adoption of Autonomous Vehicles for Public Transport in Belgium: Citizen Acceptance, Business Models, and Policy Aspects» [7] and «Energy Saving in Public Transport Using Renewable Energy» [12] and the Italian Ministry Law related to public transport [13].

Carrying on with our analysis it was encountered an article developed in Italy by Luca D'Acierno, which associates to each mode of transport an average emission range correlated to use phase and life cycle assessment (LCA). Than it developes toward the quantification of the associated costs, also including externalities. The goal of this project was to understand with an OD matrix the zones with the majority of trips generation/destination and to suggest a provision with the most sustainable and cheap mobility solution. Which resulted to be the e-scooter [15].

Then it follows a study from UK that may seem a bit off topic, but still has some point of interest. This article adresses the goal of Net Zero 2050 in England for the transport field. Stated that road trips generate three fourths of the total transport related emission in the island the policies developed in the past years are defined not fully efficient. The proposal of a congestion tax has been rejected by the government, being too pohibitive for car and motorbike owners. The measure that was implemented in large cities, such as London, is the road pricing. Anyway the article judges this solution as not really effective, being it sustainable for rich drivers but not for poor drivers, that sometimes may be forced to pass in a taxed road if the public transport does not serve properly that trip. The solution proposed by the article is an implementation of a tradable credit system (TCS) specific for private transport. This scheme would give each citizen a free number of car/motorbike kilometers per year. After this number the citizen would need to buy the extra kilometers from the state, paying a standardized price, or from the free market. This could also work as a social safety net, moving money from the rich population to the poor one, but it would need a reliable and accessible public transport and micromobility system in order to be actually beneficial and not to go the other way around [16].

Another article focused on Sweden urban mobility simulates the effect of implementation of five different measures aimed to reduce transport emissions and to improve the economical welfare associated to transport, reducing the overall combustible/power consumption. Out of the five solution proposed, simulating them on the majour cities of Sweden and averaging the results, two are better. One is the reduction of combustible consumption for private vehicles by tecnology improvement. The best one is the doubling of PT capacity in each city, that would lead to a reduction in terms of total consumption of three times the value related to the upper measure, the second best scenario [17]. Anyway it is necessary to comment that Sweden already has one of the best power production in terms of renewable energy, so a strong improvement in PT with mainly electric vehicles may have better benefits than in other country still strongly relying on gas consumption.

A paper of 2003 developed a comparison model for private use car and park and ride (P&R) facilities. The focus is to find an optimal location and pricing for P&R. The optimum in the model is found when highway connected to the railway by the P&R structure is not congested anymore, total travel costs are reduced and P&R facility is profitable. A strong conclusion of this work is that a clever planning in P&R facility position and features could probably help rail operators. Since also rail service quality and train cost will play an important role in the final choice equation. The paper also implies that supplementary measures like road pricing or congestion taxes, already meantioned before while talking of Pattinson [16], could have a beneficial effect on P&R facility use [18].

In conclusion, a book chapter with the title «Implementing car-free cities: Rationale, requirements, barriers and facilitators» will be shortly discussed. This chapter treats the theme of transition from a conventional city to a car-free one. The book aim is to define all the prerequisites that should be possessed before this transition, the strategies following which it would be possible and the barriers that can prevent one city to achieve this goal. Of particular interest the consideration that the main barriers towards a car-free city transition are retail interest and car industry local importance. This could mean that before it is possible to achieve a sustainable urban transport system an industry transition is needed in advance [19].

1.1.2. Environmental

Some articles belonging to this section have already been presented. To avoid repretitions they will be briefly recalled by title.

In order of citation has been presented the articles «Particulate Matter (PM10 and PM2.5) and Greenhouse Gas Emissions of UAV Delivery Systems on Metropolitan Subway Tracks» [5], «Encouraging the Sustainable Adoption of Autonomous Vehicles for Public Transport in Belgium: Citizen Acceptance, Business Models, and Policy Aspects» [7], «A Systemic View of Future Mobility Scenario Impacts on and Their Implications for City Organizational LCA: The Case of Autonomous Driving in Vienna» [10], «Environmental Effects of Electromobility in a Sustainable Urban Public Transport» [11], «Energy Saving in Public Transport Using Renewable Energy»

[12], «Adoption of Micro-Mobility Solutions for Improving Environmental Sustainability: Comparison among Transportation Systems in Urban Contexts» [15] and «Exploring the Energy Saving Potential in Private, Public and Non-Motorized Transport for Ten Swedish Cities» [17].

Some articles have been cited but not talked about properly until here. The first one that will be referred to is the study related to the concept of Sustainable Urban Mobility Planning (SUMP). This article adresses the problem of economical investment in the transport field on an european level. The investments of the Union are being directed towards sustainable mobility, but still private investors are for the majority (around 80%) investing on car infrastructures. The paper suggests that this phenomenon may be driven by the systematic underestimation of external costs associated to transport emission, and proposes an idea of awards and economical benefits for the cities that will be found leading in the low carbon emissions related to transport. The alternative would be to impose rules by law, but it has been understood by time that it would not be effective [1].

The second mentioned article is interesting from the LCA point of view. It presents the emissions depending directly on a vehicle use and the one related on its life cycle. Than both the cost of the vehicle itself, considering traction, maintenance and operation, and the cost related to it's direct emissions. The article concludes comparing the environmental wheight of vehicles with the economical cost associated to it [2].

The last already mentioned article is not directly related to transport, being it about the total concept of ecological footprint and lifestyle archetype. The first goal of the article is to compare the ecological footprint of a number of nations and to list the field governing this consumption. One of this key aspects are food consumption, buildings and transport, followed by other less impacting fields. Once a certain value in CO_2 emission is exceeded, the planet resources will be depleted faster than they could possibly regenerate. In order to obtain a sustainable resources consumption the whole society would need to change its overall lifestyle. For what concerns transport, the only way to achieve such a goal would be to reduce flight kilometers and car kilometers by nearly 80% and it would be necessary to reduce car ownership by 96% [4].

Following with the articles that have not been seen yet, there is a paper developed for the analysis of the private car fleet of Romania composition. In the country, electric cars are just starting to substitute the internal combustion vehicles. Anyway, the transition will be strongly delayed. Due to the economical situtation in the nation the cars are usually never bought brand new, but usually used, after 10 years of service. The article then proposes three different scenarios to predict the future composition of the fleet by 2035. Only a scenario that includes a ban for vehicles older than 15 years and an intake, generated by national or european economical policies, of electric/hybrid vehicles could at least preserve the current situation, without a detrimental increment of the total number of private vehicles in the country [20].

An article that adresses the effect of infrastructures investments states that it could be beneficial or negative for the environment depending on the population density of the area it would be serving. Anyhow it does an unexpected consideration in terms of economy. From a societal cost point of view the conversion from private transport to collective transport would be economically profitable in any case [21].

In the next article we see an estimation for the Barcelona city of the emissions of equivalent carbon dioxide grams over passenger per kilometers for a different set of vehicles. This vehicles are both used in private and collective transport and the main focus is on the introduction in the city of new vehicles intended for the use of micromobility. In the assessment of total emissions generated by the vehicles we have the already seen sum of use emission and LCA emission but, for the shared vehicles, we have an extra emission component that is firstly introduced: the re-balancing. After a shared vehicle is used it may be necessary to reach it in order to charge it (if it is an electric vehicle) and to move it. This is done on a daily base to have a evenly distributed number of sharing vehicles for micromobility, in order both to serve the whole urban area and to concentrate the service where the actual demand will be. This emission component generates an unexpected result, being shared electric bicicle more polluting than a bus in terms of passenger per kilometer. The emissions are evaluated in carbon dioxide and the pollution are evaluated in PM2.5 and ozone. The car is allways the worst vehicle in terms of equivalent emissions, followed by the motorbike. The less polluting vehicles would be the personal micromobility/light mobility ones, but this convenience seems to fade when adressing shared micromobility vehicles. The conclusion of this article states that, when public transport systems are not already strongly used by population, electric shared mobility could be beneficial, decreasing the total share of passenger per kilometer related to private combustion vehicles. Anyhow when the transport system is well established (like in the majour European cities) the effect of this introduction could be not benefitial, decreasing the overall usage of public transport, being this kind of trasport usually faster than public one and not way more expensive [22].

A survey has been conducted on the population of six towns of four different nations. The focus is mainly on the UK households. The population tends to define itself ecological, while not giving evidence of an actually sustainable behaviour. The ecological transition with such a precondition needs to rely on new technologies to be achieved. The 72% of trips seems to be done in car, ecological alternatives are chosen only if trips are shorter than 3 miles or longer than 50 miles [23].

It is then encountered a case of study aimed for the evaluation of energetical consumption of a Bus fleet in Avila, a small town in Spain. The method is basically to position bus stops in the best altimetric places in order to use the effect of regenerative braking system at its maximum potential. One of the conclusions of this article is that, without considering the regenerative braking system, the substitution of internal combustion buses with electrical buses would not bring a consumption reduction [24].

Another paper concentrates on emissions correlated to urban density and it notices, following a statistical evaluation, that the reduction in carbon dioxide emissions is at least 5% better in high density (urban) areas than lower density areas. This may be explained by the concept of service lifelines, that in a city will serve a substantial number of citizens per kilometre in comparison with the same ratio in a rural area. The model than uses a velocity – CO_2 emitted curve to evaluate the total value of car related emissions in Japan. It settles with a difference of 2% from the official value measured in 2010. Then it projects into the future substituting part of the vehicles with future less polluting electric vehicle and estimating that a larger share of the population will be living in urban areas. The technological impact could generate a reduction of almost 40% of total emissions by 2050, that is an optimistic result but still not enough to get to the net zero [25].

An article addressing the environmental related emission problems states that only a shift in terms of transport paradigms can bring the society to a sustainable way of moving. The author analyses the transport field literature and notices a trend, before the last ten, fifteen years to find a solution to transport related problems with a road-car oriented solution. Then a list of vehicle's emissions is presented, both internal combustion and electrical, inferring that the adoption of electrical vehicles may still not be enough to face the environmental challenge [26].

To conclude a couple of articles belonging to this topic still are to be mentioned. The first one concentrate on the possibility to implement the same measures, already adopted in western countries, also in developing countries like India [27]. The last one concentrates on the possibility to keep smart working as the main form of urban work, following the trend that was largely adopted during the last few years, and assesses what would be the environmental impact of this option [28].

1.1.3. Medical

This field of studies is not one of the most relevant one, this is the main reason, so few articles related to this topic are being presented. However, it must be addressed for a couple of reasons.

Firstly, the effects of air pollution are strongly affecting the population life expectancy, as being properly discussed in this article which analyses the main driving factors and estimates the detrimental results of mobility related polluting emissions, in terms of both pathology triggered and reduction in life expectancy [29].

Secondly, being the urban system usually a dense one in terms of population, and being urban traffic characterised by some peculiar phenomena, such as the stop and go, the crossroads and other, all caused by the coexistence on the same network of different users with different travel mode, it is not strange to consider that the majority of urban car accidents happens in an urban environment. What is strange is the number of bicycle driver victims, being themselves the 10% of the total share of street accidents victims [30].

To conclude there is also an injury risk related to the transport mode itself. Being the e-scooter introduction fast and not fully regulated by European laws, the effects of accidents on said vehicle are worrying doctors and policymakers. Though the e-scooter is one of the possible solutions in terms of sustainable vehicles so a good condition of use must be achieved. This article states that, without a personal protection regulation, a decent number of separated and protected (C1) greenways and the presence of recharging stations, the measure it is still not worthy the downsides [31].

1.1.4. Mode of Transport

Between all the topics presented this is certainly the most important one. The approach to emissions and economy can be solved by the choice concerning the actual vehicles used to travel. Then certainly there are other aspects, such as congestion or accessibility that need to be discussed, but to put it in simple words, a badly congested system of urban greenways can still be considered more environmentally friendly than a slightly crowded road system occupied by internal combustion cars.

In the environmental subsection a number of article has already been cited; [5], [10], [11], [22], [24] and [26]. The economical subsection counts a couple of meaningful references; [18], [19] while [15] and [12] are contained in both subsections.

The articles «Research on the Deployment of Joint Dedicated Lanes for CAVs and Buses» [6] and «Potential of Connected Fully Autonomous Vehicles in Reducing Congestion and Associated Carbon Emissions» [8] have instead been mentioned in the introduction, while referring to the potential of AV.

One of the first field to refer while discussing the sustainable transport transition is the Mobility as a Service (MaaS). On this topic a suggested review of 127 scientific publications was useful both as a problem overview and an effect evaluator [32].

Following this trend an article develops and proposes a model to evaluate shared mobility solutions from an operational point of view. The model, named MMQUAL was mainly developed for e-scooters and follows three main factors: mobile application functionality, vehicle characteristics and client support [33].

Another possible solution, even if not widely addressed by literature, is the ridesharing. Anyhow, from a cost effectiveness point of view, it is proposed only where a collective transport system is completely missing [34].

A survey conducted in Thessaloniki, Greece, concerning the resident's orientation towards a new metro construction revealed that in the poorest areas a strong public transport service is more desired than in the airport, for example. Because the population should be free to choose whether to rely on collective transport or on its private vehicle freely, and in the absence of the first one, the cost associated to the second one is burdening on entire more or less indigent areas [35].

Being both instruments to satisfy the same demand, MaaS and PT may be in competition. A German OD assignment model was developed to assess the modal split as a function of distance, land-use and time. The result is that the MaaS is preferable when the PT system is less frequent or reliable since they usually compete on the same distances with the exception of the metro [36].

Cars may also be seen as a competing vehicle in comparison with micro-mobility. This model tries to define the typical trip that can be transferred from car/PT to micro-mobility. The definition is a function of both distance of the trip, age, and medical condition of the users. The results are that for private vehicles, the substitution share is 10%, while it is around 50% the substitution share for public transport [37].

From a comprehensive point of view there is an interesting paper that discusses theoretically what are the preconditions for mobility transition, and what can be done in order to achieve the net zero as fast as possible. The main measures presented are MaaS, PT improvement, electric recharge infrastructure and parking places reduction [38].

Another approach is the one studying the integration between micro-mobility and PT, in particular steel transport (metro and train). The result of this study shows that the best intermodal station in terms of time of interchange is also the one better connected with the greenways infrastructure [39].

An article proposes a model to evaluate the impact of sustainable transition-oriented measures dividing the population in three income classes. The measures proposed are just 2: free public transport and road pricing. None of these two measures, alone or combined, can generate a reduction of car use more than 10%. The article justifies this result with the consideration that citizens with a higher income are not considerably impacted by the measures proposed [40].

An article proposes a point-based criteria to assign a smart mobility rating to different cities, to understand how close to smart transport they actually are. The model is quite comprehensive, but oriented in a different direction than the one this paper aims for. The measures proposed are both PT and MaaS oriented, but not in an operative way. [41].

Another article with the same goal is presented, focalized on the Zurich area. In this article anyway, the transition is clearly proposed from car oriented to alternative means of transport solutions. The factor identified by this article as the driving one in car related traffic reduction seems to be the parking slots control [42].

On the same line a last article evaluates the potential of a city to be car free in some areas, analysing GPS data related to total population walking movements. This would work well starting from the zones with maximum density in the fields of activities, decreasing both traffic congestion and increasing land use value [43].

A book titled «Car-Free Cities», published in 2000 ad, threats the whole theme of the presence of the car in the city system from a theoretical point of view. The practical focus of this discussion will be analyzed better in the following subsection focusing on an article that derived an urban planning method from this more theoretical dissertation [44].

The following set of articles will just be mentioned since they bring something to the discussion that is relevant but comprehended by what has been already presented.

Focusing on the bicycle mode of transport there are two articles, one survey conducted on university students that participated a course of street safety [45], and the other one focusing on the factors that make a urban bicycle lane effective, finding the main one in the completeness and interconnection of the cycling infrastructure [46].

For the theme of sustainable transport there is an article on autonomous zero-emission ferries in coastal cities [47] and a proposal of implementation of connection and information between freight transport vehicles to reduce both emissions and urban accidents [48].

The last article addresses the theme of street walkability, finding that there is a correlation with perceive safety and cleanliness of the road, but also with the level of instruction of the citizens interviewed [49].

1.1.5. Urban Planning

The last topic is the second one per importance. If the transition dwells in the mode of transport chosen by population, without an adequate infrastructural and transport planning, it is not granted that the population could actually be able to move towards this beneficial change in mobility.

The first article belonging to this topic already cited is «Autonomous Mobility: A Potential Opportunity to Reclaim Public Spaces for People» [9], another article proposes the use of the Analytical Hierarchical Process (AHP), a method frequently used to evaluate highways functionality level, combining it with the software PTV Vissim to evaluate a crossroad level of service of a crossroad with various conditions. Some related to the shape of the crossroad, other to the vehicle composition, considering both collective vehicles and AV [50].

Another article already seen is «A Multimodal Transport Model to Evaluate Transport Policies in the North of France» [40]. A related paper presentes the effects of COVID-19 on urban mobility, noticing that total number of travel trips reduced considerably and that the adoption of micro-mobility arised, probably just to avoid the collective transport. Anyway the effect of this period on urban air quality was strongly beneficial [51].

The next study adresses the theme of urban development of the city of Famagusta, Cyprus. The GIS based predictive model simulates urban development in two different opposite conditions: no change, and sustainable development. The problem of spontaneus development seems to be related to the increment of residential areas, characterised by a lower density and usually a lower services presence. To achieve a sustainable development the model proposes a development more focused on high/medium density areas where services are already present. If this operation is not possible due to extremely high housing need, already plans the implementation of new lifelines and services production [52].

On the bikeway provision side there is this article that tries to find the parameters driving Utilitarian Cycling, comparing the data related to 28 cities in the USA. After the statistical procedure has been carried out, the strongest correlation between cycling and the parameter was found. The first parameter for weight is the ration of bicycle lane kilometers over 10000 inhabitants. The second one is the cycling lane's related safety, that seems to be at best in the bicycle boulevard, a street where car and bicycles cohexist. The other parameters were all less impacting, apart from the cost of combustible, that was still relevant, even if less than the previusly presented parameters [53].

The topic of micromobility use and acceptance is also assessed in an article that compares population mobility preferences of a Swedish area on a map. A virtual imposition of just one mode of transport is simulated on all population, and the results are the same for each choice apart from the bicycle one. For each vehicle the population is strongly divided between entusiastic acceptance and strong opposition, only the bicycle seems to be the point of contact between different population groups [54].

A similar kind of survey was conducted in Moscow, Russia to evaluate population attitude towards sustainable mobility. The results shows that population seems to be generally in favour of temporary ban of vehicles and of polluting car exclusion policies, but are not in favour of taxis been applied to streets or parking slots [55].

The last survey seen is related to the use of PT by elder passengers. The most relevant factors boosting the decision tree for an elder citizen seems to be awning presence, punctuality of service and driver's driving habits [56].

Moving from population perception to practical urban planning the compromise point may be seen as the 15 minutes city project. One specific article focusing on the 15 minutes station, clearly adressing the mentioned project, can also drive the discussion towards the concept of intermodal change. This paper produces a model that, starting from the known characteristics of a set of train stations in northern Italy, implement a gravitational evaluation to evaluate the attractiveness of each station. The result shows that the more utilized stations are also the one with an higher attractiveness qualification. So the conclusion that the presence of services is correlated to an higher use of transportation system is reached [57].

The therm park and ride is usually used referring to the intermodal change stations where from a private vehicle (car) the user moves to a public vehicle mean of transport (train or bus). Anyway the first article met talks about the topic from a micromobility integration perspective «Spatial Integration of Non-Motorized Transport and Urban Public Transport Infrastructure: A Case of Johannesburg» [39].

The effectiveness of intermodal change is strongly related to the public transport accessibility (PTA). A paper present this concept explaining the difference with the public transport accessibility service (PTAS). The evaluation of the PTA parameter can be obtained following different paths, generally reling on a gravity model. The paper present many of these methods and combines them to find the PTA value in the city of Wuhan, China [58].

Another method of the same kind but opposite focus in evaluated in the following paper. The goal of this study is to develop a method to evaluate public recreational parks accessibility in Bejing, China. The article combines infrastructural geometry (street network and park entrace points) with the services characteristics (frequency and paths) to get the accessibility index. The end of this process is the suggestion, useful for decision-makers, to move some of the park entrances or to modify the bus line's paths in order to avoid any park exclusion. The walkable distance buffer was taken equal to 800 meters, that is a commonly found value in literature giving the upper bound limit, when refferring to elderly walkability [59].

Coming back to the original discussion point it follows an article on the P&R dynamics study. The model there presented studies the P&R facility interaction with road traffic in three different scenarios (no-traffic, regular traffic and congestion). Anyway, being the model focused on the bus public form of transport, the result is that in the area of study of Cuenca, Equador, the P&R facility is resolutely underutilized. This may be explained by the strong interaction of the mode of transport bus with the road traffic that, without external impositions, is the only driving factor for P&R facility utiliziation. This shows clearly a reciprocal effect iteratively uneffective [60].

Concluding on the intermodality sub-topic a couple of articles is remaining. One is oriented to the understanding of attractiveness and potentiality of Bus P&R system as a function of some parameters, like cost, frequency and length. The conclusion of this work is the presentation of an analysis to find the operator profit optimization through a variation on the offer side [61].

The last paper related to P&R systems presents a method that relies on GIS to map catchment areas for different P&R facilities that connect the outskierts to the city center. This article suggests that, if the P&R facility was connected to the city with a reliable and efficient transport service, better if on rail, the urban traffic could be strongly reduced. The result is a map of the areas that could be covered with each facility in the city of Cuenca, Equador [62].

From a conceptual point of view the P&R system was first introduced to provide an alternative to the congested road used for city commuting. Therefore it was an instrument to supply road traffic by improving the average travel time of both car drivers and P&R system users. The next set of cited material is, on the opposite, a series of literature reviews, models and books about the possibility to build a car-free city, partially or completely.

Of this set, the articles «Implementing Car-Free Cities: Rationale, Requirements, Barriers and Facilitators» [19], «An evaluation of the car-free city potential for the city of Munich regarding mobility data» [43], and the book by J.H. Crawford [44] have already been presented.

The first literature example of this kind of theory encountered while analysing the literature is an article from 1994. This paper treats the theme of car-free city centers in various study cases. There is the Bologna city case, that sees a limitation in parking slots number and an improvement of public transport. The cases of Lübeck and Aachen are similar, consisting in a traffic limitation on the weekends and in the provision of covered parking sites in the outskirts. The last case analysed is the one of the city of York, where city center is closed on the daily for some hour shifts [63].

In the last thirty years the number of cities to set-up a car-less city center increased consistently. An interesting article presents a more recent approach to the implementation of sustainable infrastructures in Oslo, such as bicycle lanes integrated with public transportation, modifying the street network to reduce the impact on car drivers [64].

An article discusses the result of a series of interviews conducted on residents population in four different streets that, for a limited period of time, became car-free. The factors that seemed being more influent on the approval rating of the population for this operation are the area accessibility, the architectonical value of buildings and, the most important, the potential land use value. Where profitable activities were already present the approval rating was higher, while where they were missing it was lower [65].

There is a paper which proposes a method that, starting from the geometrical network data, the average traffic data, and the touristic density data, gives an indication of what urban areas would be the most efficient to set up [66].

If a city were to build today the possibility to plan a total car-free urban environment, potentially getting to a sustainable transition faster than in older cities. It is the case of an article that proposes the plan for a city in the United Arab Emirates completely free of vehicles owned by privates [67].

The last article of this subsection is a plan to get to a car-free city and the probable effect of this transition on public health. The article presents a set of measures to be implemented to get to the car-free condition. The majority of these measures have already been discussed by other articles, like the improvement of the greenways network and the financing of a more functional public transport provision. The results would be beneficial from an environmental point of view, following the reduction in carbon dioxide, and also for the public health, decrementing the particulate matter and ozone urban production [68].

1.2. Classification per year

The written material presented before is the result of several studies of interest for this thesis. All the material has been produced during the last 30 years. The oldest article was published in 1994. The last set of material was published this last year 2022.

In the following image it is presented the number of materials of interest published per year.

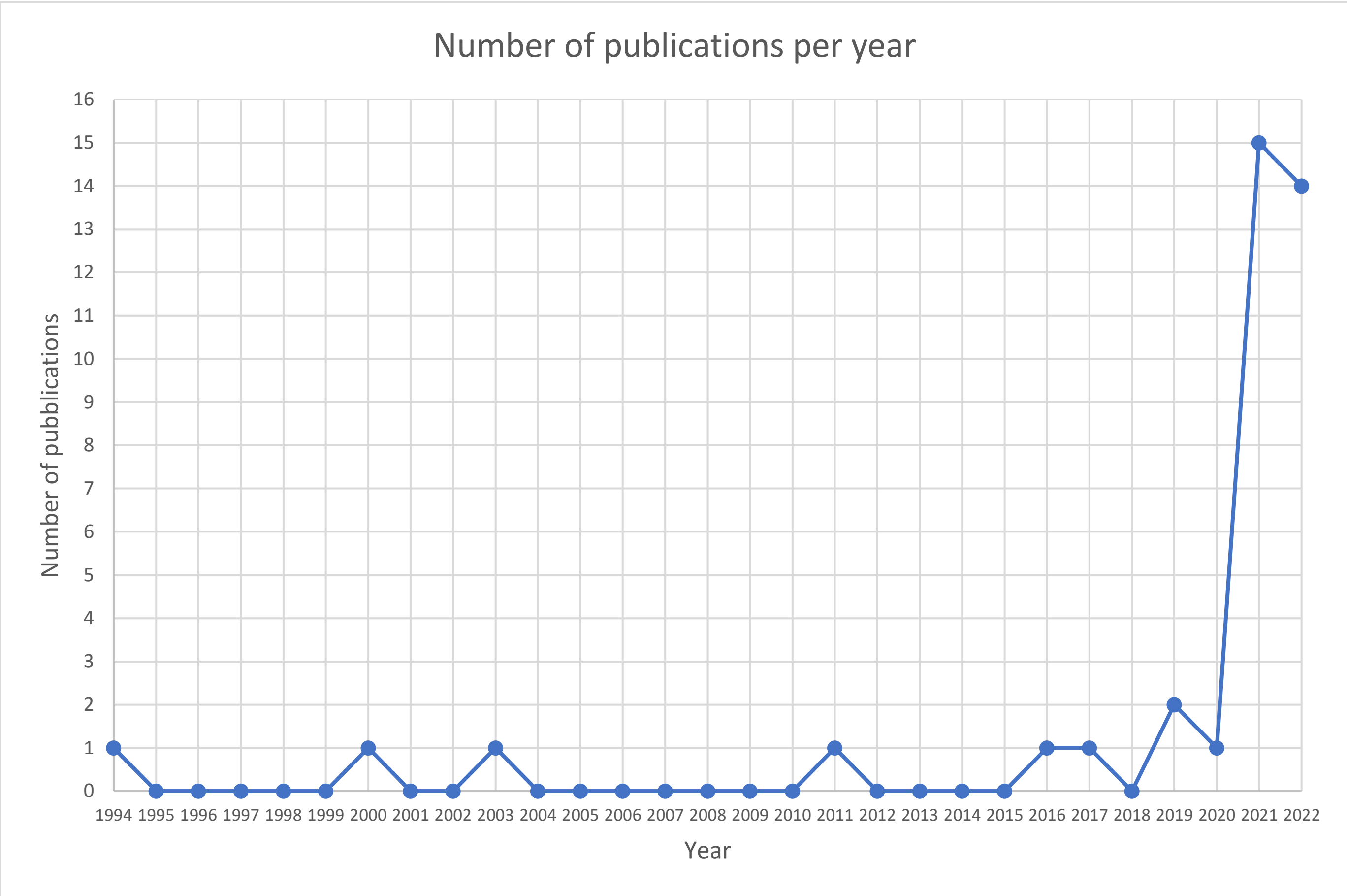

Figure 1: Publication over time trend

It can be easily observed that the number of publications has been quite low in the past years, while it suddenly arises in the year 2019, to improve consistently in both years 2021 and 2022.

The number of chosen materials in the year 2022 is lower of the number related to the year 2021, probably because this analysis has been conducted during this last year, so it is possible to infer that the number is destined to grow.

The theme of car-free city centers arises in the early nineties, with the introduction of some traffic-restricted zones in several cities [63]. Still not with an aim on sustainable mobility/transport; the first inter-ministerial decree was published in Italy just in the year 1998.

Since 1998 the law was updated with new instructions, providing some founds and benefit for the population directly contributing to sustainable mobility from 2012. The conceptual definition of a Sustainable Urban Mobility Plan (SUMP) was introduced in the Italian law just in 2017, and the activation will be seen in the close future.

Another trending factor has been the European Union policy in terms of sustainable development. The 2030 agenda, and the related 2050 net zero carbon emission long term strategy, the first one subscribed by the United Nations governments in 2015 and the second one endorsed in the beginning 2020, have set a trend in most EU countries.

The presented information can give a logical explanation on the trend observed while performing the analysis of the literature for this article. The infrastructural field is directly referred to in one of the seventeen goals of the 2030 agenda, and it is indirectly related to at least four other goals. This makes the transport study area one of the most interesting right now, being the discussion on how to perform the needed transition still in progress. This may be the driving reason for the flourishment of articles in this field. The growth in number in the last couple of years may be also explained by the normal delay that is often seen between EU laws proposal and practical application.

1.3. State of the art evaluation and possible development

As explained above this field of study is recently developing and expanding in different directions. Many of the studies seen, however, are still on the theoretical side of the matter. This is certainly not negative, but the number of mathematical models proposed by the articles is still small compared with the total number.

The first one we have encountered is the AHP Multicriteria Decision Model, used to compare economical cost associated to different vehicle types and environmental impact [2]. This model is just focused on emissions and costs as a function of engine type, but it does not provide an equivalent conversion for actual transport.

The second model encountered is the CoEXist, and improvement of the Arkins model, fit to improve the level of service of intersections simulating a different percentual presence of AV [8]. The number of models proposed focused on corridors or intersection is not wide but consistent. The model for CAV interaction with PT on a corridor [6] and an AHP model combines with the PTV Vissim software to simulate intersection functionality [50] are both of this kind. This type of models has a smaller focus than this thesis.

Transport sustainability can certainly be addressed on the micro scale, working on every crossroad and on every single corridor, anyway, the most impacting choices, and correlated measures, are the one concerning the entire system in terms of mode of transport and related laws and regulations. The special level of this kind of resolution is the urban one, so concerning an area of dimensions considerably higher than a corridor or an intersection.

On this trend the list of models related to P&R systems [18], [60], [61], [62], and the public transport accessibility models [39], [56], [57], [58], [59] despite being interesting, are not directly useful. The focus of this set of articles is quite related to urban planning, and so, still too specific for the aim of sustainability. The level of detail needed, compared with the effect of the result, is not even close to the potential of a modal transition between internal combustion vehicles and electric one. This is just an example, and it is still partially not true, but the hope is that in the next years, achieving a better power production, the electric mobility solution will actually be always convenient than the internal combustion mobility.

The scale of the problem is urban. In the analysed literature there is a collection of models on the same scale this work is intended for.

The first two encountered are concentrating on private vehicles substitution in favour of AV [9], [10]. A third one is estimating the effect of a bus fleet transition to electromobility in a small town [11]. An analogous model is doing the same thing, also trying to understand of the energy production could come from renewable, “green” sources [12].

An article that proposes 5 different measures regarding PT, car, and bicycle modes of transport [17] is of strong interest, quite similar in the aims to what this thesis aims for. However, no model is proposed in this article, the data needed are found and simply compared to different scenarios in terms of vehicle occupancy to compare the energy consumed per passenger per kilometre (pkm). In Italy, this kind of information is not ascertainable. A similar model is presented for France, but does not provide any pkm evaluation, it uses instead a cost model implemented combining MATSim and GIS maps, and then estimates the effects of different measures on each passenger depending on the income class [40]. This model is one of the most similar to our aims, but it is still quite different. Being GIS based, a modification of the input data is quite costly, even when data could be actually retrievable. Moreover, the measures are just related to access area, PT fare cost or road tax. So, this model is not fit to the prediction of effects related to more relevant measures, such as fleet modification, or shared mobility provision. In conclusion, the model does what this works aims to, on a larger area and with less transport mode complexity. Being the last factor fundamental in the urban system, the work needs to continue.

The following model analyses the replacement potential of micro-mobility in Barcelona, Spain, comparing it to a series of other means of transport, private and collective [22]. The comparison is done for pollutant's equivalent emissions over pkm. The model, as already said, is valuable, although reference data were obtained by a survey and were not part on the model, and the shared mobility, in all its different forms, is the only macro-measured analysed. A similar model uses geospatial data related to daily OD matrix to understand what the most demanding sections of a town are, to estimate a provision of e-scooters to reduce the overall carbon dioxide production [15]. The limits of this model are the same of the first one referred in this paragraph. Two other articles present two separate models to compare the maximum substitution potential of micro-mobility comparing it with public transport [36], and private cars [37]. Despite being both of interest, producing quite useful results, no other measure is proposed, and the environmental benefit of the estimated transition is not assessed in relation to any of this last models.

Two articles provide two models, not directly treating transport data, but used to assess the level of smartness [41], and sustainability [42] in the field of urban mobility. Having a quite different goal from the work presented by this thesis their utility is limited, but still consistent. Some of the themes treated, and some of the actual measures proposed by them should be treated in a comprehensive urban transport model.

Another not directly related research is the one on freight transport urban optimization related to Information and Communication technologies [48]. Being the delivery transport just a small portion of the total one this topic is secondary, nevertheless it deserves to be mentioned.

Information related to bikeways provision and related commuting comes from the previously presented article the found a correlation with the driving parameters of bicycle commuting [53]. This theme is certainly a central one, while talking of sustainable transport, and a definition of relevant measures related to is of high importance.

The car-free city model article is not adequate either, being just based on an evaluation of collective AV and rationale urban planning [67].

The last article is not presenting a model, but it is widely the most relevant citation until this point. It treats the matter of study in an extensive way, defining itself all the possible measures presented in all the previously cited articles [68]. This kind of overview of the urban system and the possibility of mobility choice connected to it is what we aim to develop in a simple and efficient model.

Summing up, the result of the progress analysis in this field showed a series of useful models addressing different kind of specific problems. The majority of them fit to evaluate the effects of sustainable mobility measures on a smaller scale compared with an urban area. Some of them could even work for larger systems but were not considering some measures that could be fundamental in an urban environment. To modify that kind of models could be possible, but certainly not simple, the way of a new model composition is viable, certainly inspired by the one seen until now, but quite different.

The modal share base unit of measures should be passenger per kilometre, being easily convertible in pollutants equivalent, being it carbon dioxide, ozone, or small particulate matter.

To be able to consider the full urban environment the model should consider at least main private vehicles (cars and motorbikes), micro-mobility private vehicles, different forms of public transport, shared mobility, and mobility as a service.

After defining the pre-existing conditions, it is possible to define the appliable measures that could improve the state of things in a urban transport contest. A list of the possible measures will follow, with the cited material that directly refers or proposes it referred directly by the citation number.

List of transport measures:

- Economical bonuses for private electric vehicles; [2], [20].
- Economical bonuses for private autonomous vehicles; [6], [8], [9], [10].
- Economical bonuses for micro-mobility; [15], [17], [22], [37], [42].
- Economic incentives for MaaS; [22], [32], [38], [41].
- Economic incentives for PT; [17], [38], [40], [42].
- Road tax; [19], [40], [42].
- Ecological tradable credit system; [16].
- Augmentation of the maximum shared vehicles number; [22], [36], [38].
- Parking slots control/reduction; [19], [38], [41], [42], [44], [68].
- Bicycle network improvement; [19], [30], [31], [39], [44], [46], [53], [68].
- Hourly/Daily car ban; [19], [38], [41], [42].
- Full PT electric fleet; [11], [12], [24], [29], [38], [41].
- Improvement in PT perceived safety; [19], [67], [44], [68].
- Improvement in PT daily cycle of service; [17], [18], [19], [44], [68].
- New PT line implementation; [17], [19], [24], [44], [67], [68].
- New PT vehicles acquisition; [11], [17], [44], [68].
- P&R facilities set up and improvement; [18], [39], [41], [57], [60], [62].

The upper list of measures can be split into 4 macro categories: Public Transport, Greenways, Private Transport, Shared Mobility. From the total selection of measures, the list of the implemented ones will be shown in the following chapter.

So, after the descriptive part of the model have run, giving its output in passenger per kilometre, converted then into equivalent pollutants through literature's derived tables, the choice between the different measures will be performed, evaluating both the cost associated and the estimated modification of passenger per kilometre share, still converted in equivalent pollutants quantities.

This model will be studied and produced in order to fill up the gap that seemingly was found at the end of this literature analysis. The main goal of this model will certainly be related to modal split and how to influence it, anyway the environmental aspect will be the other key focus.

The model could then potentially estimate the effects of this measures on human health in the urban environment. Given the estimation of reduced particulate matter, as one of the results of the measures activation, a derived effect on human life expectancy could be carried out.

Another step could be the evaluation of land use variation due to measures activation, if any. This work could be less simple than the one proposed before but could be quite useful to evaluate the effects of some measures in particular, such as the parking places limitation, or the hourly car ban.

In conclusion, if all these results could be found, an equivalent comparison on the economical side could be effective. The direct costs of transport could be derived from the service, vehicle, maintenance, and traction costs. Then the estimation of indirect costs would follow, firstly evaluating the externalities cost, associated to pollutants emitted, and then to the time spent travelling/waiting associated cost. The next step would be the evaluation of the cost associated both to measures and the economic benefits related to the direct consequences, comprehending both the kind of costs already mentioned and the one related to new infrastructure building.

The last step would be, after evaluating the beneficial effects of the measures, quantifying them from an economical aspect, the comparison with the cost of the measures. This would bring to an all-economical cost versus benefit evaluation, useful to understand from a preliminary point of view what measure would be the most cost effective.

In conclusion the model we are going to develop will be useful as a complete instrument to support decision-making by giving a fast overview of the possible alternatives to guide the urban mobility field towards a more sustainable state of things.

2 Assessment Support Model

The next chapter will be dedicated to the presentation of the process of creation and then validation of the model, divided in its two fundamental functions: descriptive and predictive.

Firstly, the model structure will be presented, focusing on inputs, process parameters and outputs description.

Secondly, a list of database and references for the before mentioned inputs and process parameters will be presented, highlighting the correlation points.

In conclusion, the process of calibration of the model on a specific urban system and then the validation on other three cities will be presented in its iterative flow.

2.1. Model description

The model presentation will be divided in five parts, following the operative structure of the main model function, from input to output. The first part will be the input one. The second part will be the one dedicated to the actual modal split evaluation and related emissions evaluation. The third part will be the cost evaluation for the different measures. The fourth part will see the measures presentation, the related change in terms of passenger kilometre variation, considering inter-modal interaction, and the estimated emissions reduction. The fifth and last part will be the final output part and the last input request, asking what measure to activate and at what level to launch the activation, and simply showing the result referring to the previous part.

In the following image, each phase has a different color distribution, related to the kind of data from which it is composed.

The green areas are corresponding to the input data. The first phase is fully an input phase, as it can be easily notices, then thare are some small inputs necessary also in phases 3, 4. Phase 5 has necessarily a larger number of inputs that the previous two phases, being it the phase where it must be decided which measures will be activated.

The light blue areas stand for the parameters that are derived directly from known data, or the calibration parameters.

The last areas in orange, are used to symbolize all the process and output parameters, comprehending also the output parameters that have been used for the calibration and validation checks for the whole model.

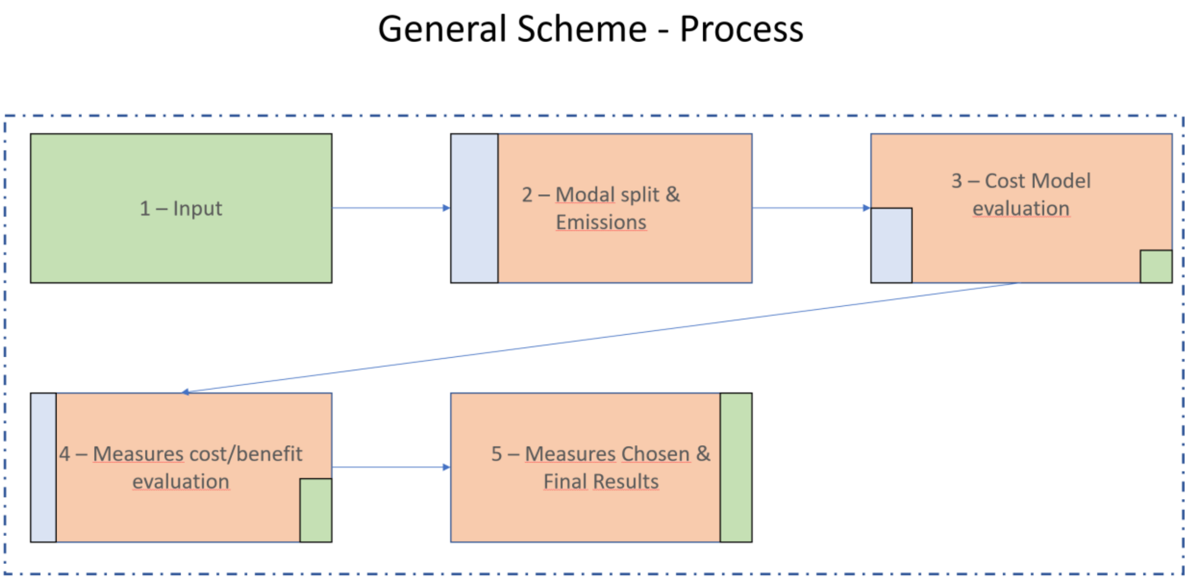

Figure 2.1: Model Overview

2.1.1. Model phase 1 – Input

This is the first phase of the model. In this phase the inputs will be defined. The total number of input parameters is 60, divided in five clusters: City characteristics, Public Transport, Greenways, MaaS, and Private Vehicles.

2.1.1.1. Phase 1: City characteristics

The number of inputs in this subsection is 6. These inputs are aiming to describe the main physical, geometrical and demographic characteristics of the city of choice.

City characteristics – input parameters:

- Total area: urban area in square kilometres.
- Total population: population of the city in integer number.
- City Spatial Distribution: qualitative description of city's shape, there are two options; Compact Circular, or Slender Linear.
- Estimated outside commuters: population entering the city daily in integer number.
- Elder population: integer number equal to the share of over 75 years old city population.
- Energy production emission equivalence: value related to the national energy production formula, representing the conversion from kilowatt hour to grams of carbon dioxide equivalent. The unit of measure is grams of CO_2 equivalent over kWh.

2.1.1.2. Phase 1: Public Transport

The number of inputs in this subsection is 46. These inputs are delineating the quantitative and qualitative description of the public transport service main characteristics of the city of choice. The inputs are the same for all the public transport mode of transport, so they will be presented just one time. The list of the different mode of transport is the following.

Public modes of transport:

- Heavy rail: this mode comprehends both heavy metro lines and urban rail lines.
- Light rail: it is the mode of transport that considers all the light metros.
- Bus: the regular bus lines will fall under this mode.
- Trolleybus with dedicated lane: the trolleybus is divided from the bus since its characteristics make it specific.
- Tram: all tram lines are considered by this mode.

It may be noticed that there could be more mode of transport, like the cableway, the cable railway used in some city of the mountain area. Also, the ferries are missing, being a mode of transport of seaside or lake cities, where their level of use is actually comparable to the one of the bus/trolleybuses. This exclusion was done to keep the model simpler as possible, but still able to define any common average city.

So, the following list of parameters will be the same for all the earlier mentioned modes of transport, with the exception of the last one.

Public transport – input parameters:

- Network length: length of the whole network, as the sum of the different line's paths in kilometres.
- Vehicles in service: quantity of vehicles that, being part of the total fleet, are actually put into service every day, in integer number.
- Vehicles: quantity of the total vehicles part of the fleet, this number also includes the vehicles that are not usually put into service, but that could be deployed if it were the case, in integer number.
- Lines: quantity of lines that are provided, in integer number.
- Average capacity of each vehicle: quantity of places offered by an average vehicle of an average line at maximum capacity, in integer number.
- Average Utilized Capacity (AUC): qualitative evaluation of the level of fullness of the vehicles during working shift. The options to choose from are 3: Full, Medium, Low.
- Daily Cycle of Service: time of service provision during the day, in hours. The options to choose from are 2: 19, 24.

- Stops: quantity of total stops associated to each mode, in integer number.
- Perceived Safety: qualitative evaluation of the level of safety perceived by the common user. The options to choose from are 3: Safe, More or Less, Unsafe.
- Electric vehicle share: share of the vehicles belonging to the bus mode that are electric or hybrid, in percentage. This parameter does not have any entry for the other modes, being them usually directly connected to the electric infrastructural system.

2.1.1.3. Phase 1: Greenways

The number of inputs of this subsection is 3. These inputs evaluate quantitatively and qualitatively the urban cycling network of the city of choice.

Greenways – input parameters:

- Network length: length of the whole network, as the sum of the different bike lanes strictly in the urban area, in kilometres.
- Ring-wise Connection: qualitative parameter, evaluating whether the bike lanes of the city connect and permit a full bike movement from origin to destination. If not, the bicycle driver will need to use car trafficked roads for a more or less long part of the drip. The options to choose from are 3: No, Partially, Yes.
- C1 bikeway proportion: qualitative parameter, used to evaluate the level of comfort guaranteed by the bike-lane's quality. A Class 1 bikeway is a lane dedicated to bikes and pedestrians, separated from other road traffic. They may be single lanes or two lanes, one per direction. The proportion number is not always available, so the evaluation is qualitative. The options to choose from are 3: Low, Medium, High.

2.1.1.4. Phase 1: Mobility as a Service

The number of inputs is 20. These inputs describe qualitatively and quantitatively the urban shared vehicles and taxis provision.

Mobility as a Service may be a concept recently introduced in the transport field, comprehending all the forms of mobility that are not properly collective nor private. The shared vehicles certainly respect this kind of classification, the taxis may also be added to the overall evaluation, similarly to the shared cars, even though having distinctive characteristics.

In an analogous manner to what have been done for the public transport, also for the subsection MaaS the inputs are the same for all the mode of transport, and the parameters will be shown once for all. The list of the different mode of transport is the following.

MaaS of transport:

- Shared Car: all cars and similar four-wheeled vehicles offered for shared use.
- Shared Bike: all mechanical bicycles offered for shared use.
- Shared electric Bike: all electric traction bicycles offered for shared use.
- Shared electric Scooter: all electric traction scooters offered for shared use.
- Shared Mopeds: all electric motorbikes and similar two-wheeled vehicles offered for shared use.
- Taxi: all taxis, or taxi licences, in use or emitted in the urban area.

MaaS – input parameters:

- Vehicles: quantity of shared vehicles present in the area, in integer number.
- Sharing operators: quantity of independent enterprises offering service for a specific shared vehicle, as integer number.
- Price: qualitative parameter to evaluate the accessibility of the price. The options to choose from are 3: Expensive, Moderate and Cheap. The price evaluation is done in relationship with the average income class citizen which usually makes use of that kind of shared vehicle.
- Electric vehicles share: the share of the vehicles belonging to the car and taxi mode that are electric or hybrid, in percentage. This parameter does not have any entry for the other modes, being them usually fully mechanical or fully electric.

2.1.1.5. Phase 1: Private Vehicles

The number of inputs is 4. These inputs describe quantitatively the number of vehicles registered strictly in the urban area.

The vehicles being part of this subsections are divided in two macro categories, cars, and motorbikes. Only one parameter is the same for both modes, while the other two apply just to the car mode of transport.

Private Vehicles – input parameters:

- Vehicles: quantity of vehicles being registered in the urban area, both for vehicles and motorbikes.
- Parking slots: quantity of parking slots present in the urban area, as a sum of public parking slots, taxed parking slots, and large private parking slots present strictly in the urban area, in integer number. This parameter, as mentioned previously, only affects the mode of transport cars.
- Electric vehicles share: share of the vehicles belonging to the car mode that are electric or hybrid, in percentage. This parameter does not have any entry for the motorbike mode, being the data not easily available.

2.1.2. Model phase 2 – Modal Split & Emissions

The second phase of the model is dedicated firstly to the evaluation of the modal repartition between the different modes of transport, and then to the associated emissions evaluated accordingly to the pollutants emitted quantities over passenger per kilometre.

The parameter presentation will be divided into the previous cluster plus three, considering the walking mode of transport, the data related to emissions, and the final outputs. Anyway, having more kind of parameters than the mere input ones, a precise analysis of them will need to follow. The diverse parameters will be presented in the following groups.

This phase does not have any input. It has a consistent number of process parameters, a total of 346, being 251 of them data related parameters, such as vehicles average speed in the urban environment and emissions conversion parameters. The remaining 95 parameters are merely used to follow the process step by step, from the input to the output. From a conceptual point of view, all the functions performed by them could be summed up in a single call, anyway this would make it impossible to follow the process, generating the unwanted result that any modification would be overly complex. On the contrary, subdividing the process in its elementary steps, despite generating a larger number of process parameters it leaves the work intelligible.

The next group of parameters is the calibration parameters. This group is composed by 20 parameters, covering all the values for which literature is missing, or not precise, usually related to the qualitative evaluations done in the input part.

After the calibration parameters, there are the outputs. The total number of outputs is 70, showing both modal split and pollution results. Only 5 of this output parameters are also used in the process of validation and calibration that will follow, the other are simply showing extra effects.

The last group of parameters is the check one. All the 31 parameters are used, in different point of the logical process, to check the work, avoiding the risk of internal error.

2.1.2.1. Phase 2: City characteristics

The number of process parameters in this phase is 7, the number of check parameters is 2. There are no calibration parameters nor data parameters.

City characteristics - Process parameters:

- Gross population density: population of the area, in integer number, divided by the area, in squared kilometre.
- Urban radius: evaluation of the equivalent urban radius with a different formulation concerning the different approximated shape of the city, in

kilometre. If the shape of the city is Compact Circular: squared root of the urban area divided by 3. If the shape of the city is Slender Linear: squared root of the urban area multiplied by five.

- Number of passengers: sum of the estimated quantity of external daily commuters and of the number of city population after the elder population subtraction, in integer number.
- Average Trip Length: the value of the average trip length is proportional to the Urban Radius. So, it is higher if the city as a Slender Linear shape/spatial distribution and it is lower for a compact circular city, in kilometre. If the entering users are more than the city population: urban radius value, divided by 2.5, multiplied by the ratio between outside commuters and city population. Otherwise: urban radius, divided by 2.5.
- Average daily trips per passenger: number of average trips for each passenger/driver in the city area. The value supposed is 3, integer number.
- Total daily passenger per kilometre: this parameter is the product of the Average Trip Length and the Number of passengers and the Average Trip Number. It is evaluated for a single day, in passenger per kilometre.
- Total daily mi pkm: this is the Total daily passenger per kilometre value in millions.

City characteristics – Check parameters:

- Total pkm check: this is the value of pkm obtained as the sum of the values of pkm produced/utilized by all mode of transport, in millions.
- Check: the final overall check is the one confronting the Total pkm check value and the Total daily mi pkm value, if the value is exactly the same, the check is passed.

2.1.2.2. Phase 2: Public Transport

The number of process parameters is 39, the number of calibration parameters is 6, the number of check parameters is 15, and the number of data parameters is 5.

In the last sub-chapter, the parameters presented were valid for all the five modes of transport. Accordingly, the process will be repeated here and later in this paper, without being mentioned again.

Public Transport – Data parameters:

- Average speed: average speed for each vehicle/transport mode contained in the Public Local Transport cluster. The value considers the stops, in kilometre over hour.

Public Transport – Process parameters:

- Kilometres over 100000 inhabitants: number of the total length of each mode network, divided by the number of the total inhabitants multiplied by a factor 10^6, in kilometres over integer number.
- Stops density: Total number of stops of each mode divided by the Urban area, in integer number divided by square kilometre.
- PT hourly pkm: this parameter is the product of the number of vehicles in service/number of lines, the average distance travelled by each user, the average capacity of each vehicle, the factor concerning average utilized capacity, the network length/the average velocity of respective vehicle and the number of lines, the line length / average distance times and an extra parameter depending on the frequency of passenger change (interchange factor). All multiplied by the number of lines, in passenger per kilometre hourly.
- PT daily accounting safety: this is the product of the previous parameter multiplied by the respective hours of daily cycle service, multiplied then for the calibrating factor related to safety, in passenger per kilometre daily.
- PT daily accounting stops density: this is the last parameter multiplied by a factor 1 or 0.85, depending on an IF cycle related to the stop's density. The thresholds proposed are the following: Heavy and Light Metro SD<0.5, Bus SD<10, Trolleybus SD<5, Tram SD<5. The value is still in passenger per kilometre daily.
- PT daily accounting overall accessibility: this parameter evaluates the effect of Bus accessibility (in the form of Station Density) on the metro modes of transport. The reduction factor is an extra 0.85, the threshold is the same as before. The unit of measure is still passenger per kilometre per day.
- PT base daily pkm: this value will be chosen, for each line, as the minimum between the last 3 upper parameters, minus the share of km that will be covered by walking while taking every mode of transport. This value is a function of stops density, and it is variable for each mode. It will be presented in the walking sub-section. PT base daily is the result in terms of passengers for kilometres for each mode of public transport, in pkm daily.
- Daily Base CO_2: value obtained as the product of pkm total on daily bases and tons of CO_2 / pkm, from the equivalence tables, in equivalent tons.
- Tot PL pkm: summation of the number of passengers per kilometre for each TPL mode, in pkm daily.
- Tot PL mi pkm: upper value in millions pkm daily.

Public Transport – Calibration parameters:

- AUC calibration parameters (α): calibration parameter function of the Average Utilized Capacity. As a base we propose Full: α1=1, Medium: α2=0,6, Low: α2=0,3. Dimensionless.
- Perceived Safety calibration parameters (ϱ): calibration parameter function of the Level of safety perceived by the common user. As a base we propose Safe: ϱ1=1, Medium: ϱ2=0,85, Low: ϱ2=0,6
- Interchange factor: factor accounting the frequency of passenger change when calculating the actual passenger per kilometre value. The values proposed are 12 for heavy metro, 4 for light metro, 2 for bus and tram, 1.5 for trolleybus.

Public Transport – Check parameters:

- Minimum hourly capacity: the minimum value related to base functionality for a transport line of a specific mode, as defined in literature, in passengers per hours per direction.
- Maximum hourly capacity: the maximum value related to full functionality for a transport line of a specific mode, as defined in literature, in passengers per hours per direction.
- Estimated capacity: this value is obtained from the PT base daily pkm, divided by the product of Daily cycle of service, the Number of lines, and the distance averagely travelled on each vehicle. The unit of measure is passenger per hour per direction. The check is considered passed if this value is comprehended between the upper two, or, if not, in proximity of the minimum one.

2.1.2.3. Phase 2: Greenways

The number of process parameters is 5, the number of calibration parameters is 6. There are nor check, nor data parameters.

Greenways – Process parameters:

- Kilometers over 10000 inhabitants: length of total kilometres of bike lanes present in the urban area divided by the total population with a multiplier factor of 10^5, in kilometre over integer number.
- Micro Base daily pkm: the maximum value for this parameter is assumed to be the 15% of the Total pkm of the whole urban area over a daytime period. This value is reduced of a share by both the calibration parameters of this cluster (Ring-wise connection and C1 proportion), in passenger per kilometer.
- Tot Micro pkm: Micro Base daily adding the product between the difference of Micro Base and Maximum value for Micro Base (0.15*Total pkm) and the number of kilometres per 10^5 inhabitants divided by 3, in passenger per kilometre.

- Daily Base CO_2: value obtained as the product of pkm total on daily bases and tons of CO2 over pkm.
- Tot Micro-mobility mi pkm: upper parameter, in passenger per kilometre.

Greenways – Calibration parameters:

- Ring-wise connection calibration parameter (R): this calibration parameter takes away a share of the total maximum micro-mobility pkm as a function of the Ring-wise Connection. The value proposed are the following Yes: R1=0.02, Partially: R2=0.06, No: R3=0.095, dimensionless.
- C1 bike lane connection calibration parameter (C): This calibration parameter takes away a share of the total maximum micro-mobility pkm as a function of the Proportion of the number of kilometres of C1 cycleways. The values proposed are High: C1=0.01, Medium: C2=0.035, C3=Low: 0.045, dimensionless.

2.1.2.4. Phase 2: Mobility as a Service

The number of process parameters is 26, the number of data parameters is 6, and the number of calibration parameters is 3. There are no check parameters.

MaaS – Data parameters:

- Average speed: average speed for each vehicle/transport mode contained in the Mobility as a Service cluster. The value considers the traffic, in kilometre over hour.

MaaS – Process parameters:

- Number of maximum passengers per day per each vehicle: the maximum number of passengers per vehicle per day is obtained by the day-time cycle in minutes divided by the average delta time between two users (15 min + 5 min reservation time) summed with the time needed per average trip (vehicle average speed in km/min divided by the average trip length), in integer number.
- MaaS Optimum estimated share pkm: product of the number of vehicles, the average distance travelled daily, a factor of value 2, and the number of vehicles, in passenger per kilometre.
- MaaS Daily Reduced pkm: upper parameter, reduced by the calibration parameter related to the price, corrected by a percentage value related to the number of operators (n/100, with maximum value of n=10), in passenger per kilometre.
- Daily Base CO_2: value obtained as the product of pkm total on daily bases and tons of CO_2 / pkm.

- Tot MaaS pkm: summation of the number of passengers per kilometre for each MaaS mode, in passenger per kilometre.
- Tot MaaS mi pkm: upper value on the left in millions of units of measure, in passenger per kilometre.

MaaS – Calibration parameters:

- MaaS price calibration parameters (M): calibration parameter representing the price of the service [Expensive, Moderate, Cheap]. The values proposed are Expensive: M1=0.25, Moderate: M2=0.35, Cheap: M3=0.5, dimensionless.

2.1.2.5. Phase 2: Private Vehicles

The number of process parameters is 12. No data parameters, check parameters or calibration parameters are use in this stage.

Private Vehicles – Process parameters:

- Parking slots density: number of car parking slots divided by the area, in integer number over the area.
- Vehicles over parking slots ratio: number of cars divided by parking slots, dimensionless.
- Car over motorbike ratio: number of cars divided by the number of motorbike and the reciprocal of that number, dimensionless.
- PV Base daily pkm: the number of pkm for the motorbike is evaluated as the number of (total pkm – PT pkm – Micro pkm – MaaS pkm – Walking pkm) multiplied by the ratio of the number of motorbikes divided by the number of cars, divided by a factor 3, given to assess the difference in term of preference (related to risk perception) between the two vehicles and the higher possession of cars. The number of pkm for the car is the residual total (total pkm – PT pkm – Micro pkm – MaaS pkm – Motorbike pkm – Walking pkm), in passenger per kilometre.
- Maximum check PV daily pkm: maximum value of pkm for each vehicle, evaluated as the product of vehicle for average distance for passengers/vehicle for number of average daily trips. This will be used as a roof when evaluating the PV share of passenger per kilometre daily, if the value of the previous is lower it will not be used, in passenger per kilometre.
- Daily Base CO_2: value obtained as the product of pkm total on daily bases and tons of CO_2 / pkm.
- Tot PV pkm: summation of the number of passengers per kilometre for each PV mode, in passenger per kilometre.

- Tot PV mi pkm: value on the left in millions of units of measure, in passenger per kilometre.

2.1.2.6. Phase 2: Walking

The number of process parameters is 6. No data parameters, check parameters or calibration parameters are use in this stage.

Walking – Process parameters:

- Modal walking distance: this value is the estimated value in kilometres of walking distance for each TPL trip. It is evaluated dividing 1 km for the value of stops/km^2 of each line. The maximum distance can be 3 km in case of metro, 1 km in case of bus and 1.5 km in case of tram. If average trip length is less than 2 kilometres than this value will be 1/2.5 multiplied for the average trip length, in kilometre.
- Walking from PV: this value is the difference between the base and the maximum value of pkm for PV vehicles, in passenger per kilometre.
- Walking from PT: this value is the product of the first parameter, the value of pkm daily of each PT mode divided by the average trip length, in passenger per kilometre.
- Daily Base CO_2: value obtained as the product of pkm total on daily bases and tons of CO_2 / pkm.

2.1.2.7. Phase 2: Emission Data

The number of data parameters is 240. No process parameters, check parameters or calibration parameters are use in this stage.

The tables are three, with 80 cells each. Each one is relative to a specific emission conversion; CO_2, NO_X, and $PM_{2.5}$. The data will be presented just one time, specifying the difference between one table and the other data per data. The data will be presented once also for all modes of transport, specifying the relative difference also here.

Emission data – Conversion tables data:

- Vehicles emissions: mode of transport emissions considering the vehicle complete life cycle equalized for pkm, in kilograms for CO_2, in grams for NO_X, and $PM_{2.5}$, over passenger per kilometer.
- Transport emissions: mode of transport emissions in the use phase, in kilograms for CO_2, in grams for NO_X, and $PM_{2.5}$, over passenger per kilometer. For all the electric modes the transport emissions are a function of the Energy production equivalence factor.

- Rebalancing emissions: mode of transport emissions in the phase of rebalancing, this phase only affects sharing MaaS modes, which need to be recharged and moved over the urban area each day, to satisfy the demand. The value is in kilograms for CO_2, in grams for NO_X, and $PM_{2.5}$, over passenger per kilometer.
- Total emissions: summation of the three previous parameters for each mode of transport, in kilograms for CO_2, in grams for NO_X, and $PM_{2.5}$, over passenger per kilometer.
- Total emissions in final unit of measure: previous parameter but, in tons for CO_2, in kilograms for NO_X, and $PM_{2.5}$, over passenger per kilometer.

2.1.2.8. Phase 2: Outputs

The number of output parameters is 75, 5 of them are specifically parameters used for validation and calibration of the model, the remaining 70 parameters are just products of the model, useful to show emissions evaluations. The number of check parameters is 9.

The output parameters are repeated three times, one for each pollutant emitted, hence they will be presented just ones, using the words emitted pollutant instead of the actual name of the external product of combustion/attrition.

All the output are presented for PT, Micro-mobility, MaaS, PV and Walking, therefore they will be presented just once for all these modal categories.

Outputs parameters:

- Total millions pkm: total millions passenger per kilometer for each mode.
- Tons or kilograms of emitted pollutant: parameter related to each mode emitted pollutant. Tons of CO_2, kilograms for NO_X, and $PM_{2.5}$, equivalent for each mode.
- Emitted pollutant share: percentage related to each mode emission share.
- Tons or kilograms of emitted pollutants in worst case scenario (100% car): the amount of emitted pollutant that would be produced if all the trips of the mode class would be conducted by car.
- Tons or kilograms of emitted pollutants reduced from worst scenario: difference between the last two results: it gives an approximated value of the already saved amount of emitted pollutant.
- Tons or kilograms of emitted pollutant sum: summation of the total emitted pollutant quantities.
- Tons or kilograms of emitted pollutants in worst case scenario (100% car) sum: summation of the total emitted pollutant quantities under the hypothesis of just car mode.

- Tons or kilograms of emitted pollutants reduced from worst scenario sum: summation of the total emitted pollutant quantities, which are potentially reduced from a worst-case scenario.

Outputs – Calibration & Validation parameters:

- Passenger per kilometer share: percentage related to each mode passenger per kilometer, it gives the modal split calculated by the model.

Outputs – Check parameters:

- Total millions pkm sum: summation of total passenger per kilometer, it must be equal to the value calculated in the city characteristics subsection
- Pkm share sum: summation of the pkm share value, the result must be 100%.
- Emitted pollutant share sum: summation of the emitted pollutant share value; the result must be 100%.

2.1.3. Model phase 3 – Cost Evaluation

The third phase of the model is dedicated to the cost evaluation of the different measures proposed.

The list of measures is the following:

- Public Transport Safety Improvement
- Public Transport Full Day Cycle
- Public Transport Full Feet Implementation
- Public Transport New Line Construction
- Public Transport Extra Vehicles Acquisition
- Greenways Improvement
- MaaS Improvement of Number of Vehicles Offered
- MaaS Improvement in the Prices Attractiveness
- Private Vehicles Decrement of the Number of Parking Slots

To sum up, there are 5 measures for public transport, 1 measure for the bikeways provision, 2 measures for shared vehicles and taxi, and 1 measure regarding private vehicles.

The parameter presentation will be split in four clusters, the same four presented in the last paragraph.

This phase has 9 inputs. The number of process parameters is 277. The number of data derived parameters is 51.

2.1.3.1. Phase 3: Public Transport

To evaluate the cost associated to the five measures related to public transport 1 input is required. Then, 45 data driven parameters that come directly from the cost model associated to DPCM 152 [13]. This derivation will be explained better in the following subchapter, dedicated to both articles that gave the concept of the various measures, and of the data provenience. The last set of parameters is the process related one, counting 228 parameters in this group.

Public Transport – Input parameters:

- Average security employee yearly gross income: This parameter is obtained as the monthly pay of a security employee multiplied for 12, in euros.

Public Transport – Data parameters:

- School days: number of school days in one year, integer number.
- Non-school, working days: number of working days that are not school days in one year, integer number.
- Free days: number of free days in one year, integer number.
- Sundays: number of Sundays in one year, integer number.
- Saturdays: number of Saturdays in one year, integer number.
- Equivalent days per year: number of equivalent days per year, obtained as the sum of School days per 1, Non-school working days per 0.85, Free days per 0.5, Sundays per 0.6, Saturdays per 0.85, in integer number.
- V_1, V_2, K_1, K_2: optional factors from DPCM related to velocity and service.
- NV: number of vehicles, in integer number.
- AMM: modernizing of rolling stock for bus kilometer of service, in rational number.
- C_e: operational cost, in euros.
- NPG: divers' number, in integer number.
- NPM: moving personnel number, in integer number.
- C_{pg}: guiding personnel cost, in euros.
- C_{pm}: other moving personnel cost, in euros.
- C_{ene}: traction energy cost, in euros.
- C_{rot}: rolling stock cost, in euros.
- NP_{ROT}: each vehicle capacity, in integer number.
- KAT: number of annual kilometers for vehicle, in kilometer per vehicle.

- AMM_{SP}: standard depreciation per place, in rational number.
- C_{man}: maintenance, cleaning, and rolling stock security and safety cost, in euros.
- C_{mif}: maintenance of fixed installations cost, in euros.
- $C_{i.inf}$: utilization of infrastructure and plants cost, in euros.
- C_{gen}: general and other costs, in euros.
- C_{cap}: depreciated cost, in euros.
- WACC: capital cost for bus, trolleybus, and tram modality, in euros.

Public Transport – Data parameters:

- Places km offered hourly: this parameter is obtained by the product of the number of vehicles in service, the number of passengers transported at maximum capacity and the average velocity of each vehicle, since the calculation is performed on one hour, in places per kilometer over hour.
- Places km offered daily: this parameter is the product of the places per kilometer offered hourly for the service hours, in places per kilometer over day.
- Places km offered daily cycle: this parameter is the product of the places per kilometer offered hourly for the maximum service hours, in places per kilometer over day.
- Places km offered by base: same parameter contained in the places per kilometer offered daily, in places per kilometer over day.
- Places km offered potential fleet: parameter evaluated as the places offered hour cycle times the service hours but, instead of the number of vehicles in service, the number of total potential vehicles is used, in places per kilometer over day.
- Places km offered daily difference max and min fleet: difference between the last two parameters, in places per kilometer over day.
- Places km offered daily by one vehicle: this value is obtained as the division of the number of places km offered from the whole fleet daily for the number of vehicles of the same fleet, places over day.
- Average Security employee daily gross income: Average security employee yearly gross income divided by workdays in a year, in euros.
- Average Security hourly daily gross income: previous parameter divided work hours in a day (8), in euros.
- Average daily € spent for vehicles/carriage: last parameter multiplied per 2, per the average number of hours of service of each mode, in euros.
- Places kilometer offered 1 day by each line: product of the value of daily places offered by one vehicle per number of average vehicles of each line, in places kilometer.
- Places: maximum capacity of each vehicle, in integer number.
- Standard cost for vehicle kilometre: standard cost for vehicle kilometre obtained by the DPCM tables, in euros.

- Operational cost for millions of places kilometre: standard cost for places kilometre obtained by DPCM tables, in euros.
- Length: standard length of each line, obtained as the length of each mode network divided by the number of lines, in kilometre.
- Average life length: average life expectancy for each vehicle, defined by law, in years.
- Kilometres per year for each vehicle: average kilometre over year per vehicle, defined by law, in kilometres.
- Rolling stock evaluated by the frequency of service: evaluation of the number of vehicles in service on the network for each line, obtained as number of vehicles divided by the number of lines, in integer number.
- Places per kilometre per year over vehicle: product of the number of places times kilometre over year per vehicle, in places per kilometre.
- Vehicle cost: nominal cost of each vehicle, in euros.
- New line cost per meter: nominal cost of construction per meter of new line, defined by law, in euros.
- Capacity Improvement without modifying the network: evaluation of the feasibility of an improvement from the offer side without a network modification. The focus will be on the features of the service, on the time offer or on the frequency. This parameter is evaluated from a Capacity of service comparison. If Capacity of the average line (evaluated starting from the value of passenger per kilometer hourly found in last section) is lower than the maximum capacity potentially associated with that kind of service than an improvement may be feasible, otherwise it could be more efficient to work on the network itself.
- Capacity Improvement modifying the network: evaluation of the efficiency of an improvement from the offer side implying a modification of the network. The focus will be on the acquisition of new vehicles, new drivers/service personnel, and the building of a whole new line. The operation is considered efficient if the difference between the actual capacity of service and the maximum one is less than 10% the value of the maximum capacity of service OR if the precedent measures have already been implemented.
- Safety improvement: this parameter is used to evaluate the feasibility in terms of perceived safety. If the perceived safety is less than "Safe" the measure aimed to the safety improvement can generate an improve in terms of offer.
- Full day cycle improvement: this parameter is used to evaluate the feasibility in terms of hours/day offer. If the offer is still a not full day cycle offer the measure is feasible.
- Fleet improvement: this parameter is used to evaluate the feasibility in terms of frequency offered, working on the number of vehicles to be possibly used

without buying new vehicles. If the number of vehicles in service is lower than the total number of vehicles the measure is feasible.

- Extra line construction: if the number of kilometers over 100000 inhabitants for each line is less than 1, than a new line may be efficient, otherwise it could cause a detrimental reduction in average occupancy.
- Extra vehicle acquisition: if the capacity of service per hour, associated with the average line of each mode, is less than the minimum expected value, than an increase in frequency may be beneficial. If overperformed also this measure could generate a decrease in vehicles average occupancy, increasing comfort but decreasing efficiency.
- Safety improvement cost: this value is evaluated as the cost of assigning one guard for one day (two turns) to each vehicle or carriage, for this reason, unlikely the other two following, in euro over vehicle or carriage.
- Full day cycle cost: this value is evaluated starting from the operational cost for passenger per kilometer offered associated to each mode of public transport, in euro over passenger per kilometer.
- Fleet improvement cost: this value is evaluated starting from the operational cost for passenger per kilometer offered associated to each mode of public transport, in euro over passenger per kilometer.
- Extra line construction cost: this is the product of the linear cost of construction of a new meter of line times 1000 meters, for each mode, in euros over kilometer.
- Extra vehicle acquisition cost: this is the nominal cost of each vehicle for each mode, in euros over kilometer.
- Safety Improvement daily cost: this parameter is the product of the Safety improvement nominal cost for each vehicle/carriage, the number of vehicles for each mode and, only for the metro lines, the number of carriages, which are considered 5 for the heavy metro and 3 for the light metro, in euro over day.
- Full day cycle daily cost: this parameter is the product of the difference in terms of places offered per kilometer between the full day cycle offer and the base offer and the nominal cost (euro/places kilometer) of service cost, in euro over day.
- Fleet improvement cost for 1 vehicle: this parameter is the product of the places per kilometer offered by 1 vehicle of each mode in and the nominal cost of service, in euro over vehicle.
- 1 Extra Line construction cost: this parameter is the sum of the nominal cost of construction of 1 line, plus the cost of the number of vehicles to be bought, plus the service cost associated to that number of vehicles over one year of time, in euro over line.

- 1 Extra Vehicles acquisition: this parameter is the sum of the nominal cost of acquisition of one vehicle plus the service cost associated to each vehicle type, in euro over vehicle per year.

2.1.3.2. Phase 3: Greenways

Evaluating the cost associated to the bicycle lanes improvement we used 14 process parameters and 1 data related parameter.

Greenways – Data parameters:

- Goal: data representing the ratio of bikeway's kilometers over 10000 inhabitants, the value 3 is taken as a goal.

Greenways – Process parameters:

- Bicycle base length: equal to the input data asked in phase 1, in kilometer.
- Base kilometers over 10000 inhabitants: equal to the input data asked in phase 1, in kilometer over integer number.
- Total kilometers needed to get this ratio to goal ratio: number of kilometers needed to get to the goal ratio. Obtained as the population number multiplied for the ratio goal and divided by 10000, in kilometer.
- Increment needed: increment of bikeways kilometers needed to get to the set goal value. Difference between the last 2 parameters, in kilometer.
- Overall improvement: evaluation of the efficiency of an improvement from the bikeways offer side as a function of the three following parameters.
- Kilometers of bikeways improvement: if the ratio kilometers of bikeways over 10000 inhabitants is less than a value of reference, in this case taken as 3, new bikeways can be built to get to this number.
- C1 lanes proportion improvement: if the C1 lane proportion is already high, an improvement in this direction could not be efficient.
- Ring-wise Connection: if the city is not already ring-wise connected, the creation of the new bike lanes should solve this problem.
- Bikeway construction nominal: cost for each kilometer of base level bikeway construction, this is the cheap solution, in euros over kilometer.
- C1 Bikeway construction nominal cost: cost for each kilometer of top-level bikeway construction, this is the expensive solution, in euros over kilometer.
- Ring-wise Connection nominal cost: cost related to the ring-wise interconnection of the bikeways. It is supposed obtained if the last measures are obtained.

- Bikeway construction total: cost for the total implementation of a low-cost greenway system, obtained as the product of the nominal cost for kilometer and the increment length, in euros.
- C1 Bikeway construction total: cost for the total implementation of a high-cost greenway system, obtained as the product of the nominal cost for kilometer and the increment length, in euros.
- Ring-wise Connection total: Cost considered to be the average between the last two parameters, doing a strong assumption that the goal could be reached setting up both types (expensive and cheap) of bikeways, in euros.

2.1.3.3. Phase 3: Mobility as a Service

The measures related to Mobility as a Service are evaluated from a cost point of view through the definition of 6 input parameters, 5 data parameters and 31 process parameters.

MaaS – Input parameters:

- Cost each minute: input cost of the service for each minute, used for all the MaaS modes apart from the taxi, which has a different way of pricing, in euros over minute.
- Cost each kilometer: input cost of the taxi service for each kilometer, in euros over kilometer.

MaaS – Data parameters:

- Average vehicle speed considering traffic: average vehicle speed considering urban traffic conditions, in kilometer per hour.

MaaS – Process parameters:

- Cost each km: cost each hour, obtained from cost each minute multiplied by 60, divided by the average vehicle speed, in euros over kilometer.
- Improvement of number of vehicles offered: evaluation of an increase in number of the vehicle of each sharing mode. If the number of vehicles multiplied for the number of average daily trips is lower than the 10% of the total travels, the measure is considered positive.
- Improvement in the price's attractiveness: if the price of the service is not cheap than it could be possible to mitigate it to promote the use of a certain sharing mode.
- Improvement of number of vehicles offered nominal cost: the cost of this measure is supposed as null, since just a repositioning or a removal of the limit regarding the shared vehicles may be necessary.

- Improvement in the price's attractiveness nominal cost: cost of each reduction of price to get to the cheaper. The price of the cheaper sharing mode is the only one to not be reduced, in euros over kilometer travelled by passenger.
- Improvement of number of vehicles offered total cost: this cost is considered null for the public system, anyway the sharing operator founds are not infinite, so a maximum 200% growth must be considered.
- Improvement in the price's attractiveness total cost: this cost is the product of the base cost for improvement in price attractiveness multiplied for the number of kilometers done by the total number of passengers by each mode, in euros over day.

2.1.3.4. Phase 3: Private Vehicles

The cost of the single measure associated to private vehicles is evaluated in a process related to 2 inputs parameters and 4 process parameters.

Private Vehicles – Input parameters:

- Average day cost / park: input data describing the average parking lot per day cost to user, in euros over day.
- Share of taxed parking slots: input data evaluating the share of the parking slots that are not free and not residential, in percentage.

Private Vehicles – Process parameters:

- Decreasing the number of parking slots: if the number of linearized kilometers of parking areas in the city is higher than the total length of bikeways, than the number of parking areas may be decreased usefully. No measure is proposed concerning directly motorbikes.
- Average cost for Decreasing the number of parking slots: average cost for each parking lot, in euros over day.
- Decreasing the number of parking slots: averaged cost for the elimination of one casual parking lot from the total number, in euros over one day.

2.1.4. Model phase 4 – Measures Evaluation

In the fourth phase of the model the effects of the different measures are estimated. The process of calculation is the same showed in the second phase, the measures are simply modifying the inputs, then the process of calculation is performed on the new input data.

Every measure is producing an unbalance in terms of passenger per kilometre from the base condition. This impact on the total modal split needs to be rebalanced subtracting the number of surplus passengers per kilometre from the other modes. How this subtraction is broken down is not fixed, and a new input is therefore asked: the interdependency matrix.

The number of input data of this phase is 201, mostly derived from the interdependency matrix, with the exception of five inputs that needed to be asked in the public transport section when deciding how many new lines to set up.

The data driven parameters are in total 293, this number includes the cells of explanation, the calibration parameters, and, by the largest share, the emission matrices.

The number of process parameters is the largest, topping the others by the value of 1344, this number is so big because, while working on Excel, the process must be repeated one measure after di other, so it is almost like phase 2 calculation process happened a new time for every measure.

Finally, the output parameters number is equal to 200.

The outputs are four for every measure, to keep the final comparing easy and effective. They are showing the cost, or the benefits (reduced emission) ratio over percentage of variation, to understand what the cost per 1% variation is related to the measure. In this way the measure's effect are compared on the same ground.

2.1.4.1. Phase 4: Public Transport

In this section, both effects and costs associated to the public transport related measures will be displayed as an output.

The number of inputs is 5, the number of data derived parameters is 26, the number of process parameters is 950, and the number of output cells is 120.

Public Transport – Input parameters:

- N of new lines: specify here the number of new to-build lines for each mode, in integer number.

Public Transport – Data parameters:

- AUC calibration parameters (α): same parameter used in phase 2.
- Perceived Safety calibration parameters (ϱ): same parameter used in phase 2.
- Average speed: same parameter used in phase 2.
- Measures Subfield: Safety Improvement
- Physical Limit: minimum number of new employees for each vehicle/carriage.
- Functional Limit: maximum useful number of new employees for each vehicle/carriage.
- Measures Subfield: Full day cycle
- Physical Limit: number of hours of service.
- Functional Limit: decrease in average vehicle occupancy risk in case of low night-shift demand.
- Measures Subfield: Fleet improvement
- Physical Limit: presence of at least 1 vehicle for supplementary/reserve service.

  - Functional Limit: overcrowding of the line risk.
- Measures Subfield: Extra Line construction
  - Physical Limit: high-cost measure, to be used as a second/third option. Only 1 extra line for less accessible field.
  - Functional Limit: if the city already has enough lines this measure could not be so beneficial.
- Measures Subfield: Extra Vehicles acquisition
  - Physical Limit: high-cost measure, risk of buying unusable vehicles if line is charged.
  - Functional Limit: to be activated only if a line is underperforming, otherwise useless.

Public Transport – Process parameters:

- Network Length: same parameter used in phase 2, modified by the Extra Line construction measure.
- Vehicles in Service: same parameter used in phase 2, modified by the Extra Line construction measure, by the Fleet improvement measure, and by the Extra Vehicles acquisition measure.
- Lines: same parameter used in phase 2, modified by the Extra Line construction measure.
- Average Capacity of each vehicle: same parameter used in phase 2.
- Average Utilized Capacity: same parameter used in phase 2.
- Daily Cycle of Service: same parameter used in phase 2, modified by the Full day cycle measure.
- Stops: same parameter used in phase 2, modified by the Extra Line construction measure.
- Perceived Safety: same parameter used in phase 2, modified by the Safety Improvement measure.
- Kilometers over 100000 inhabitants: same parameter used in phase 2.
- Stops density: same parameter used in phase 2.
- New electric vehicles share: this parameter, valid only for bus mode, calculates the new share of electric vehicle, in percentage.
- TPL hourly pkm: same parameter used in phase 2.
- TPL pkm daily accounting Safety: same parameter used in phase 2.
- TPL pkm daily accounting Stops density: same parameter used in phase 2.
- TPL pkm daily accounting multimode interaction: same parameter used in phase 2.
- TPL Base daily pkm: same parameter used in phase 2.
- Daily Base CO_2: same parameter used in phase 2.
- TOT TPL pkm: same parameter used in phase 2.
- TOT TPL mi pkm: same parameter used in phase 2.

- Daily Direct Maximum effect: difference in terms of passengers per kilometers each day between base scenario and measure applied scenario, in passenger per kilometer.
- Direct Maximum effect: percentage effect in terms of passenger per kilometer.
- Daily GW related Emissions: increase in terms of tons of CO_2 eq emitted each day between base scenario and measure applied scenario.
- Daily Reduced All mode broke down emissions: decrease in terms of tons of CO_2 eq emitted each day between base scenario and measure applied scenario, considering intermodal interaction effect.
- Reduced Equivalent GW emissions: difference between reduced and emitted new tons of CO_2 eq, divided by the total number of CO_2 eq emitted in the base scenario, in percentage.
- Daily Pollution NO_x Maximum effect: increase in terms of kilograms of NO_x eq emitted each day between base scenario and measure applied scenario.
- Daily Reduced All mode broke down NO_x emissions: decrease in terms of kilograms of NO_x eq emitted each day between base scenario and measure applied scenario, considering intermodal interaction effect.
- Reduced Equivalent Ozone emissions: difference between reduced and emitted new tons of NO_x eq, divided by the total number of NO_x eq emitted in the base scenario, in percentage.
- Daily Pollution $PM_{2.5}$ Maximum effect: difference in terms of kilograms of $PM_{2.5}$ eq emitted each day between base scenario and measure applied scenario.
- Daily Reduced All mode broke down emissions: decrease in terms of kilograms of $PM_{2.5}$ eq emitted each day between base scenario and measure applied scenario, considering intermodal interaction effect.
- Reduced Equivalent $PM_{2.5}$ emissions: difference between reduced and emitted new kilograms of $PM_{2.5}$ eq, divided by the total number of $PM_{2.5}$ eq emitted in the base scenario, in percentage.
- Accumulative Measure Packet Cost to get the following results: maximum Cost if measure is activated for all modes, in millions of euros.
- Direct Measure Maximum effect: sum of the effect in terms of percentage of passenger per kilometer difference for each mode.
- Measure Reduced Equivalent CO_2 emissions: weighted Sum of the effect in terms of percentage of CO_2 emissions for each mode.
- Measure Reduced Equivalent NO_x emissions: weighted Sum of the effect in terms of percentage of NO_x emissions for each mode.
- Measure Reduced Equivalent $PM_{2.5}$ emissions: weighted Sum of the effect in terms of percentage of $PM_{2.5}$ emissions for each mode.

- Measures Subfield: Safety Improvement

- Minimum Yearly Cost: cost in millions of euros for the safety improvement related to 1 guard for each vehicle of each line multiplied for the equivalent service days in one year.

- Maximum Useful Yearly Cost: cost in millions of euros for the safety improvement related to 2 guards for each vehicle of each line multiplied for the equivalent service days in one year.

- Measures Subfield: Full day cycle
  - Minimum Yearly Cost: cost in millions of euros for the improvement from a reduced day cycle of service to a full one.
  - Maximum Useful Yearly Cost: Cost in Millions of euros for the improvement from a reduced day cycle of service to a full one.
- Measures Subfield: Fleet improvement
  - Minimum Yearly Cost: cost in millions of euros for putting into service 1 of the reserve vehicles.
  - Maximum Useful Yearly Cost: cost in millions of euros for putting into service all the reserve vehicles.
- Measures Subfield: Extra Line construction
  - Minimum Yearly Cost: cost in millions of euros for building a new line.
  - Maximum Useful Yearly Cost: cost in millions of euros for building a new line.
- Measures Subfield: Extra Vehicles acquisition
  - Minimum Yearly Cost: cost in millions of euros for buying and putting into service 1 new vehicle.
  - Maximum Useful Yearly Cost: cost in millions of euros for buying and putting into service the maximum number of vehicles (equal to the difference between the number of line kilometers multiplied by 2).

Public Transport – Output parameters:

- M € for 1% of pkm variation (combined): cost in millions of euros divided by the percentage of new pkm produced.
- M € for 1% of CO_2 emissions variation (combined): cost in millions of euros divided by the percentage of CO_2 reduced.
- M € for 1% of NO_X emissions variation (combined): cost in millions of euros divided by the percentage of NO_X reduced.
- M € for 1% of $PM_{2.5}$ emissions variation (combined): cost in millions of euros divided by the percentage of $PM_{2.5}$ reduced.

2.1.4.2. Phase 4: Greenways

For the three possible alternatives of the same measure related to the greenways section, both effects and costs are evaluated.

There is no input in this section, the number of data derived parameters is 9, the number of process parameters is 94, and the number of output cells is 16.

Greenways – Data parameters:

- Ring-wise connection calibration parameters (R): same parameter used in phase 2.

- C1 bike lane proportion calibration parameter (C): same parameter used in phase 2.
- Measure Subfield: Increase Greenway Network
  - Physical Limit: costly measure.
  - Functional Limit: logarithmic trend effect curve. The benefit gets to an optimum and then stalls.

Greenways – Process parameters:

- Length: same parameter used in phase 2, modified by the Increase Greenway Network measure.
- Connected – Ring-wise: same parameter used in phase 2, modified by the Increase Greenway Network measure.
- C1 bikeway proportion: same parameter used in phase 2, modified by the Increase Greenway Network measure.
- Kilometers over 10000 inhabitants: same parameter used in phase 2.
- Micro Base daily pkm: same parameter used in phase 2.
- Daily Base CO_2: same parameter used in phase 2.
- TOT Micro pkm: same parameter used in phase 2.
- TOT Micro mi pkm: same parameter used in phase 2.
- Minimum Yearly Cost: Non defined parameter.
- Base bikeway
  - Maximum Yearly Cost: cost in millions of euros for building all the needed bikeways as low cost.
- Average
  - Maximum Yearly Cost: cost in millions of euros obtained averaging the upward and downward parameters.
- C1 bikeway
  - Maximum Yearly Cost: cost in millions of euros for building all the needed bikeways as high-cost ones.

The parameters that are not shown have a description that fits perfectly the one delivered in the Public Transport section.

Greenways – Output parameters:

All the outputs parameters in this section are already described and presented in the Public Transport section.

2.1.4.3. Phase 4: Mobility as a Service

The mobility as a service section evaluates costs and benefits of the possible two measures for every single mode of transport concerned.

There is no input in this section, the number of data derived parameters is 15, the number of process parameters is 266, and the number of output cells is 56.

Mobility as a Service – Data parameters:

- MaaS price calibration parameters M: same parameter used in phase 2.
- Average vehicle speed considering traffic: same parameter used in phase 2.
- Measure Subfield: Improvement of number of vehicles offered
- Physical Limit: the number of vehicles must not grow too fast, otherwise there is a risk of generating traffic.
- Functional Limit: being the sharing operator the manager of the fleet, it will try not to increase service too fast. Our supposition is that the total increment it will maximum be three times the volume of the current fleet.
- Measure Subfield: Improvement of number of vehicles offered
- Physical Limit: there is not a physical limit related to price attractiveness, apart from the service being free.
- Functional Limit: reducing the price too much could bring to a non-rewarding service, where citizens use a service that is more polluting than the public transport.

Mobility as a Service – Process parameters:

- Vehicles: same parameter used in phase 2, modified by the Improvement of number of vehicles offered measure.
- Sharing operators: same parameter used in phase 2.
- Price: same parameter used in phase 2.
- Vehicles over 1000 inhabitants: same parameter used in phase 2.
- Importance multiplier MaaS: same parameter used in phase 2.
- MaaS Optimum estimated share pkm: same parameter used in phase 2.
- MaaS Daily Reduced pkm: same parameter used in phase 2.
- Daily Base CO_2: same parameter used in phase 2.
- TOT MaaS pkm: same parameter used in phase 2.
- TOT MaaS mi pkm: same parameter used in phase 2.
- Measure Subfield: Improvement of number of vehicles offered
- Minimum Yearly Cost: cost in millions of euros for increasing the limit of sharing vehicles of 200%, there is not minimum cost estimation from the operator side.
- Maximum Useful Yearly Cost: cost in millions of euros for increasing the limit of sharing vehicles of 200%, there is no maximum cost estimation from the user side.
- Measure Subfield: Improvement in the price's attractiveness
- Minimum Yearly Cost: No minimum cost is defined for this measure.
- Maximum Useful Yearly Cost: cost in millions of euros to reduce the price of the sharing modes bring it to the cheaper.

The parameters that are not shown have a description that fits perfectly the one delivered in the Public Transport section.

Mobility as a Service – Output parameters:

All the outputs parameters in this section are already described and presented in the Public Transport section.

2.1.4.4. Phase 4: Private Vehicles

The only measure related to private vehicles is the parking slots suppression. This measure is a subtractive one, it does not produce new potential passenger per kilometer, but simply reduces the overall. This number must be covered by other measures activation, for this reason it is depending on phase five.

There is no input, the number of data explanatory cells is 3, the process parameters total number is 34 and the output number is 8.

Private Vehicles – Data parameters:

- Measure Subfield: Decreasing the number of parking slots
  - Physical Limit: the number of parking slots is finite.
  - Functional Limit: last resource lever to be activated.

Private Vehicles – Process parameters:

- Reduction [min 0, max 1]: share of removed parking places. 1 Means 100% reduction, 0 stands for 0%. Function of number of measures activated in phase 5, if no measure is activated, then the value is forced to be 0.
- Vehicles: same parameter used in phase 2.
- Parking slots: same parameter used in phase 2, modified by the Decreasing the number of parking slots measure.
- Parking slots density: same parameter used in phase 2.
- Max pkm motorbike: evaluation of the maximum pkm daily. Product of total number of motorbikes, number of average daily trips and average trip length.
- Vehicles over parking slots: same parameter used in phase 2.
- Car over Motorbike ration: same parameter used in phase 2.
- PV Base daily pkm: same parameter used in phase 2.
- Daily Base CO_2: same parameter used in phase 2.
- TOT PV pkm: same parameter used in phase 2.
- TOT PV mi pkm: same parameter used in phase 2.
- Daily Reduced All mode broke down CO_2 emissions: this parameter is evaluated similarly to the one presented in the Public Transport section, but if the pkm given to motorcycle get to the estimated maximum (related to the maximum number of motorcycles of property) the partition of pkm over the other modes gets redistributed, following the lower line.

- Measure Subfield: Decreasing the number of parking slots
  - Minimum Yearly Cost: No minimum cost is defined for this measure.
  - Maximum Useful Yearly Cost: cost in millions of euros sustained in case of reducing the share of total parking slots.

The parameters that are not shown have a description that fits perfectly the one delivered in the Public Transport section.

Private Vehicles – Output parameters:

- M € for 1% of pkm variation: cost in millions of euros divided by the percentage of old pkm reduced.

All the other outputs parameters in this section are already described and presented in the Public Transport section.

2.1.4.5. Phase 4: Interdependency Matrix & Emission Matrices

This section of the phase is only related to inputs and data. The data related to the conversion from passenger per kilometer to equivalent emissions are 240, split into 3 matrices of 80 parameters. The inputs, on the other hand, are new, and are describing the inter-modal effects of the different measure's related mode. For example, a measure producing new passenger per kilometer by bus service implementation could potentially reduce the use of car and motorbike, but also the use of micro-mobility.

Emission Matrices – Data Parameters:

All the data parameters that are in this section are equal to the one presented in the section 2 of the model.

Interdependency Matrix – Input Parameters:

- Field: PT, Competing Field: PT
- ▪ No competing effect is expected between different PT modes if the local project and urban planning was designed properly.
- Field: PT, Competing Field: Micro-mobility
- ▪ Modes like Bus, Trolleybus and Tram may be competing with Micro-mobility vehicles (bike, electric bike, electric scooter).
- Field: PT, Competing Field: MaaS
- ▪ While metros are competing mostly with Cars and Taxis, Bus, Trolleybus and Tram are competing with s-bikes, s-e-bikes, s-e-scooters, and s-mopeds.
- Field: PT, Competing Field: Car
- ▪ This value is the difference between 100% and all the others.
- Field: PT, Competing Field: Motorcycle
- ▪ Metros are not considered competing with Motorcycles, while other TPL modes are.
- Field: Micro-Mobility, Competing Field: MaaS
- ▪ A measure concerning Greenways will certainly also boost the use of shared micro-mobility, anyway the population will more likely try to buy their own vehicles.
- Field: Micro-Mobility, Competing Field: Motorcycle
- ▪ Micro-mobility is competing with motorbikes from the electric part of it.

- Field: MaaS, Competing Field: PT
  - Each shared mode's vehicle has a typical spatial range, comparing this range with TPL ranges and typical speed the competition could be slight (5%) or strong (10% or more). The faster the vehicle within the same spatial range the larger share it will take.
- Field: MaaS, Competing Field: Micro-mobility
  - The sharing modes that are respective to the micro-mobility may be in intense competition.
- Field: MaaS, Competing Field: MaaS
  - There is some intra-competition in this cluster. Mainly between shared cars and taxis, but also other modes that are comparable in terms of range and speed, such as s-e-bikes and s-e-scooters.
- Field: MaaS, Competing Field: Motorcycle
  - The competing modes are s-mopeds and s-e-scooters.
- Field: PV (Car & Motorcycle), Competing Field: All apart from Car
  - This share must be seen as an opposite effect with respect to the ones upwards. Until here the affected modes where the one that were going to lose a share of their passengers per kilometer depending on the selected measures, that would generate an extra amount of pkm in its field. Now the effect of the measure of reducing parking slots is simply reducing car-related passenger per kilometers, but the effect on the system is hardly predictable. The only sure hypothesis is that the total amount of lost pkm will need to be reassigned all over the system, starting from the competing modes, such as metro, shared cars, taxis, and motorbikes.
- Field: PV (Car & Motorcycle), Competing Field: Car
  - This value is the difference between 100% and all the others. In this case it must be 0.
- PV (Car &Motorcycle after saturation), Competing Field: All apart from Car & Motorcycle
  - The assignation of pkm to the mode of motorcycle is dependent on the number of total motorbikes type vehicles possessed by the population. Doing the hypothesis that, anyone who could buy a car, could have already bought a motorcycle, if he wanted to, then the number taken as input is not changed. So, the maximum number of pkm related to motorcycles is the same. It means that, ones reached that number, the share of pkm reassigned from car to motorcycle drops to 0 and gets redistributed between PT, micro-mobility and MaaS.
- PV (Car &Motorcycle after saturation), Competing Field: Car & Motorcycle
  - In this case, it must be 0.

2.1.5. Model phase 5 – Chosen Measures & Final Output

The fifth phase is dedicated to the activation of the measures presented in phase 4, to the evaluation of the costs related to these measures evaluated by phase 3, and finally to the modification of the modal split and the emissions previously calculated in the second phase.

Since the workflow is shifting from a modal class-oriented calculation to a more measure focused evaluation, the presentation of parameters will be performed following the parameter type.

The number of input parameters in this phase is 60, the number of process parameters is 603, and the number of output parameters is 19.

2.1.5.1. Phase 5: Inputs

Phase 5 – Input parameters:

- Activation choice: user's choice, may be "Yes" or "No", for the Greenway Network only one of the three may be active at the same time.
- Multiplier: for the Fleet improvement and the Extra Vehicles acquisition measures, the choice regards the number of reserve vehicles to deploy. For the Increase Greenway Network measure, the choice regards the number of kilometers to be built. For the Improvement of number of vehicles offered measure, the choice is about the number of new vehicles to be put into service.

2.1.5.2. Phase 5: Process

Phase 5 – Process parameters:

- Activation condition achieved: if the condition is achieved the output is “Yes” otherwise it is “No”, and the measure cannot be forced to activate. For the Safety Improvement the condition is that the safety level must be lesser than Safe. For the Full day cycle if daily service is not 24 hours. For the Fleet improvement if there are some reserve vehicles. For the Extra Line construction, the condition is achieved automatically, but it is suggested as a reserve one. For the Extra Vehicles acquisition, if the number of vehicles is lower than 2 times the line kilometers, the condition is achieved. For the Increase Greenway Network measure if the ratio km/10000 km is lower than the reference ratio the condition is achieved. For the Improvement of number of vehicles offered, the condition is achieved automatically, but it is suggested as a reserve one. For the Improvement in the price attractiveness, if the price is not classified as "Cheap" than the condition is achieved. Finally, for the Decrement in number of parking slots the condition is achieved automatically, but it is possible only if other measures are producing extra service.
- Maximum multiplier: This is the maximum value that will be accepted as relative input parameter. For the Safety Improvement the value is equal to the

reserve vehicles. For the Fleet improvement the maximum number of buyable vehicles in function of line length. For the Extra Vehicles acquisition the condition is achieved automatically, but it is suggested as a reserve one. For the Increase Greenway Network measure, it is the number of kilometers needed to get to the goal ratio. For the Improvement of number of vehicles offered, the maximum number is two times the actual number of vehicles.

- Activation verified: activation is verified if both Activation condition is achieved, and Activation choice is positive.
- Cost [M €]: cost of each measure activation.
- Δ pkm daily [pkm]: number of passengers per kilometer produced by the measure. As calculated in phase 4 calculation and multiplying the Multiplier and dividing by the Maximum multiplier.
- Δ pkm daily [%]: share of passenger per kilometer obtained by the phase 4 calculation and multiplying the Multiplier and dividing by the Maximum multiplier.
- Measures affected modes matrix [pkm]: number of passengers per kilometer subtracted by each mode. Obtained by the multiplication of Delta passenger per kilometer for the table of measure affected mode share in phase 4.
- Electric vehicle percentage: percentage of old electric vehicles summed with new.
- Car measure check: the passenger per kilometer share of car substitution must be lower than the maximum substitution, which is dependent from the other measures. Therefore, the number of passengers per kilometer reduced must be also lower than the total initial number of passengers per kilometer related to car. Depending on the difference of this last two factors, we get the maximum share of reduced parking slots that can be activated, requested by phase 4.
- Δ pkm daily DIRECT: number of passengers per kilometer produced.
- Δ pkm daily INDIRECT: number of passengers per kilometer subtracted by other modes production.
- pkm Total partial: base passengers per kilometer plus passengers per kilometer directly produced, minus passengers per kilometer indirectly reduced.
- pkm Total corrected: value on the left corrected, if it is negative, it becomes null and that passengers per kilometer value goes to walking.
- Check total pkm: check if the number of total passengers per kilometer is different from the base model "False". "True" if it is the same.
- Total Cost [M €]: sum of the cost of each measure.
- Emitted ton CO_2 eq: emitted tons of CO_2 on the daily for each mode.
- Total ton CO_2 eq: emitted tons of CO_2 on the daily for each cluster.
- CO_2 share: share of CO_2 on the daily for each cluster.
- Total kg NO_X eq: emitted kilograms of NO_X on the daily for each cluster.
- NO_X share: share of NO_X on the daily for each cluster.
- Total kg $PM_{2.5}$ eq: emitted kilograms of $PM_{2.5}$ on the daily for each cluster.

- $PM_{2.5}$ share: the share of $PM_{2.5}$ on the daily for each cluster.
- TOTAL: sum of the respective parameters to check the total value.

2.1.5.3. Phase 5: Output

Phase 5 – Output parameters:

- pkm share [%]: share percentage of passengers per kilometer.
- Total cost [M €]: total cost of each measure activated.
- Total ton CO_2 reduction yearly: total tons of CO_2 estimated reduction in one year.
- Total kg NO_X reduction yearly: total kilograms of NO_X estimated reduction in one year.
- Total kg $PM_{2.5}$ reduction yearly: total kilograms of $PM_{2.5}$ estimated reduction in one year.

2.2. Data and literature correlation

In this subchapter the different data sources will be presented, for both the inputs and the processes proposed, covering again briefly, in a more discursive way. To facilitate the data roots presentation, it will be split in the distinct phases of the model itself. In conclusion also the data provenience for the modal split of the different cities used for the calibration and validation process will be presented.

2.2.1. Phase 1 – Data sources

The input parameters data provenience is fundamental since they are driving the descriptive evaluation of the actual urban contemporary condition. Obviously, the databases of provenience will be different from one city to another, depending on the local public transport administration. All the cities the model will be calibrated and validated on will be Italian cities. The first one to be presented will be Milan, the city the model was initially calibrated on. The second city will be the capital Rome, the third one will be the medium dimension city Florence, and the last on the small city of Lecco. These three cities transportation systems will be used to validate the model previously calibrated on Milan. A more detailed and consistent validation could be performed on a higher number of cities, however, having selected a city of each reference dimension for the Italian country, and calibrating the model on one Italian city with an extensive transportation system could be enough to start the work with the correct direction.

The first city characteristics, comprehending Total Area, and City Spatial Distribution may can easily be found on any online search engine. Total Population, Estimated outside commuters, and Over-75 years old Population percentage can be retrieved relying on the national Italian statistical agency ISTAT, in particular the census data of each Italian town in the year 2011 can be found here [69], then is sufficient to insert region, province and municipality. The database was used for Milan, Rome, Florence, and Lecco. The last city characteristics parameter is actually a national one, the Energy production emission equivalence data comes from ISPRA, the national Superior Institute for Environmental Protection and Research [70].

The public transport will be discussed separately for each city.

The greenways data, like the Mobility as a service data, may be find on online search engine, with the exception of the municipality of Milan. The local Agency Mobility Environment & Territory, said AMAT, provides these data through the Milan Integrated Statistical Sistem, SISI [71]. The electric vehicles percentage may also be found through online search engine.

For the private vehicles, the number of cars and other vehicles registered for each Italian municipality may be found on a website, collecting many demographic and economic statistics, with a section dedicated to the number of cars and other vehicles, showing the data collected by Italian Car Club, ACI, from the Public Automobile Register, PRA [72].

2.2.1.1. Phase 1 – Data sources – Milan

The data for the public transport in the city of Milan, were found on the SISI website. The Network Length, Vehicles in Service, Vehicles, Lines and Stops were directly available on the same database cited before, the data were collected by AMAT [71].

Some data that were missing in the cited database, such as Average Capacity of each vehicle, Average Utilized Capacity, Daily Cycle of Service and Electric vehicle share, are available on the official urban transport operator for the municipality of Milan, ATM [73]. The last data, related to the perceived safety, is available after a brief newspaper search on the online search engines.

2.2.1.2. Phase 1 – Data sources – Rome

The data for the public transport in the city of Rome, were found on the official Mobility Report website, ROMAMOBILITA'. The Network Length, Vehicles in Service, Vehicles, Lines and Stops, Average Capacity of each vehicle, Average Utilized Capacity, Daily Cycle of Service and Electric vehicle share were directly available on the same database cited before, the data were collected by Rome municipality [74]. The last data, related to the perceived safety, is available after a brief newspaper search on the online search engines.

The Mobility Reports for the years 2020 and 2021 were not utilized, due to the reduction in terms of offer service related to the COVID-19 restrictions. Being the agency already working to recover the reduction related to this hard period of time, we took the 2019 Report as a more reliable and useful source, being, in our opinion, more exhaustive than the papers produced in the following two years.

2.2.1.3. Phase 1 – Data sources – Florence

The data for the public transport in the city of Florence, were found on the official Mobility Report website, Città di Firenze. The Network Length, Vehicles in Service, Vehicles, Lines and Stops, Average Capacity of each vehicle, Average Utilized Capacity, Daily Cycle of Service and Electric vehicle share were directly available on the same paper cited before, the data were collected by Firenze municipality [75]. The last data, related to the perceived safety, is available after a brief newspaper search on the online search engines.

2.2.1.4. Phase 1 – Data sources – Lecco

For the city of Lecco the data retrieval was quite harder than the previous case. Being the town itself under a shared service, also covering Como and Varese, being Lecco a mountain city grown beside a lake, and by far the smallest one of the three cited cities, one of these reasons might be the true answer to this lack of easy to find material.

However, some data useful data were found on the website of the urban local transport service society LineeLecco. The Network Length, Vehicles in Service, Vehicles, Lines and Stops, Average Capacity of each vehicle, Average Utilized Capacity, Daily Cycle of Service and Electric vehicle share were available on the paper of mobility for the Lecco province. the data were collected by AgenziaTPL, the public transport agency active on the area of the three cities of Como, Lecco, and Varese [76]. The last data, related to the perceived safety, is available after a brief newspaper search on the online search engines.

2.2.2. Phase 2 – Evaluation process sources

From now on, there will not be a differentiated input source for the different cities, being the requested inputs a mere choice of the model user, or valid on all the national territory.

For the second phase of the model, all the city characteristics parameters are directly obtained by the data collected before. There is not a particular source for what regards this calculation process. Being the passenger per kilometre total calculation quite basic from this side; provided by just a simple multiplication between average trip length, number of moving people, and number of average trips per day.

In contraposition, the public transport calculation process, is strongly based on literature. The calculation of passenger per kilometre, in opposition to the calculation of places per kilometre is not simple. Since, being the offer taken as a rigid side of the matter, the actual number of passengers travelling daily on public modes of transport is dependent on many factors that need to be calibrated, such as average utilization factor, perceived safety, and interchange factors. The calculation made to go from the public transport inputs to the passenger per kilometre evaluation, are derived and inspired by the scholar's literature of Transport Engineering. The capacity calculation, in particular, derives from lectures delivered at Polytechnic of Milano [77], while the passenger per kilometre evaluation was performed based on the didactic material of Naples University [78].

The micro-mobility related passenger per kilometre calculation was performed following the assumption, suggested by an article [37], that the maximum share of this kind of transport mode, cannot exceed 15% of the total trips. This maximum value is achieved only under the conditions of high C1 proportion, full ring-wise connection, and bikeway over 10000 inhabitant's ratios higher than 3. As reference values were taken the cities of Paris and Copenhagen.

For the Mobility as a Service and the private vehicles no other source was used is this phase, since the calculation are, again, quite basic.

The emission related data matrices were derived from some articles, already mentioned in literature, which aimed to the evaluation of equivalent pollutant emitted over passenger per kilometre for different vehicles in different urban conditions. In particular considering the life cycle effect and the rebalancing operation related to shared mobility. The majority of modal emissions come from the article focused on light mobility potential impact in the city of Barcelona [22]. The electric vehicles related equivalent emissions come from an article evaluating the effect of electro-mobility in Vienna [10]. The hybrid and electric car's equivalent emissions are derived from an article evaluating the potential effects of electric micro-mobility in Naples city centre [15].

2.2.3. Phase 3 – Cost model sources

The most data related section of this phase is the one of the public transports. When considering the service cost, the operational cost, maintenance cost, new vehicle acquisition cost and new infrastructure cost, all the calculation formulas and data directly come from the Italian DPCM 152 of 28/03/2018 [13]. A specific source that was of high use in this phase is the calculation model that estimates the different costs for conventional vehicles and electric vehicles, developed for the website CITYRAILWAYS with the coordination of the Italian Ministry of Infrastructures and Transports, and the organization of the Italian association for traffic and transport engineering (AUT), the transport association (ASSTRA), and the board of Italian Railways engineers (CIFI) [79]. For the average security employee income, the data may be found on online search engines.

For the greenways, the cost of bikeway construction, variable for the different bikeway's classes, derives from the now called Ministry of Infrastructures and Sustainable Mobility [80]. The goal value for the kilometres of bikeways over 10000 inhabitants, roots to the value 3, valid for the city of Copenhagen.

The Mobility as a Service inputs references, used for the prices and costs of service, each minute for all the shared modes of transport, and each kilometre for taxis, can be easily found on online search engines, being it a transparent information when utilizing a smart service.

Regarding the private vehicle's measures, the suppression of parking slots, the only two inputs are the ones related to average day cost for parking lot and the share of taxed parking slots. These values changes for each different city and can be simply found on online search engine.

2.2.4. Phase 4 – Measure's effects sources

The heavy theoretical source of this phase is the list of articles presented in the first chapter of this thesis, in particular focusing on the last sub-chapter. The models for sustainable mobility encountered were all considered and analysed to understand what measures could actually work, and to evaluate on historical basis if there were other measures that were not considered as useful as the others. No citation of that material will be done here, since we believe that the space dedicated to it in the first chapter was enough, and here it would just be a mere repetition.

The fourth phase is a combination of the two processes of phase 3 and phase 2, after a modification of the parameters of phase 1, for this reason there are less data derived parameters than in the previous three phases.

Again, we put in use the emission matrices already presented at the end of the last sub-section about phase 2. The references are the same, and the data themselves have not changed, therefore the sources are still the three cited upwards.

Also, the basic inputs for public transport are also following the user's choice, and do not need further base or explanation.

On the contrary the modal interdependency matrix, the main new process that it is introduced in this phase, needs some further explanation. As mentioned previously, the effects of a new measure, affects the supposed rigid modal split and the supposed rigid demand of travel, taken as the value of total passenger per kilometre in the city, that is constant, in a complex way.

For instance, modifying the number of micro mobility offered by the sharing service operators, on the Mobility as a Service side, the effects on the other modes of transport systems are hardly predictable. Reasonably it could affect car usage and decrease other means of transport total amount of used passengers per kilometre, but certainly also modes of public transport such as the bus, the tram and the trolleybus will be strongly affected by that kind of measures.

Even the last measure, the one aiming for a reduction in terms of parking slots, has not a simply predictable effect. From a glance it may seem that the measure is just affecting the car users but given that we supposed the demand of our system as a rigid one, we need to understand how these users that could not rely on their private car anymore, would choose to travel. We supposed that anyone that could go from using his car to using is motorbike, would move in that direction to avoid a modification of his mobility that would be too fast and uncomfortable. After this percentage of population run out, however, it will be necessary to adopt other modes of transport from the other modal clusters, may it be public transport, micro-mobility, or MaaS.

Another example that helps us in the explanation of the topic is the following. A measure such as the increment in shared electric cars offered, combined with the improvement of the price attractiveness providing the population with economical bonuses, would certainly be beneficial for the shared electric cars use point of view, increasing the number of passengers per kilometre used associated with that mode of transport. Nevertheless, a similar measure, could not be beneficial, taking that share of passenger per kilometre not from private cars and motorbikes users, as intended, but from public transportation modes users or worst, micro mobility users, shared or not shared.

In conclusion, the matrix proposed by this model is left as an input because it is not the only matrix possible, and certainly it is not perfect, anyway it is useful to understand that all the measures are useful only when compared with what they are currently replacing.

In conclusion the list of articles used as a reference for the matrix values will be delivered: [15], [22], [36], [37], [40]. All the articles have been already cited and presented in the first chapter.

2.2.5. Phase 5 – Output sources

The last phase of the model is just requiring the activation of the measures by using some inputs and after a simple calculation it is showing the results of phase 4 on both the modal split and the overall emission.

Despite being the most important phase of the whole model, from the user side, every process present in this phase is the mere repetition, with some small variations, of what has been presented in the previous four phases. Hence, no extra data source was taken into consideration for this phase.

2.2.6. Validation & Calibration – Data sources

A reference modal split matrix was derived from certified data for each city. These data were fundamental at this stage of the work.

The modal split data for the city of Milan come from the analysis of commuting for work or job, developed in the framework of 2011 Census [81]. The data used for the calibration of the city itself, in particular for the public transport modal share calibration, come from ATM. For the Metro line 5, the first light metro of the city, the municipality provided a web page [82]. For the other lines, the ATM website [73] was used to gather the data taken as a reference.

The modal split data for the city of Rome come from the 2019 Mobility Report also used to gather the inputs of phase 1 [74].

The modal repartition in the city of Florence was gathered from the Urban Plan for Sustainable Mobility (PUMS) [83].

The city of Lecco data retrieval process was harder. The data of a mobility report were found on an online informative network of Lecco province [84]. A data gathered from a similar source, would not be considered reliable. However, a report of Fondazione Cariplo, a welfare foundation active on the national level, developed by the society of transport engineering and applied mathematics, Polinomia s.r.l, was encountered [85], validating the data firstly encountered on the online newspaper.

2.3. Model calibration and validation

The validation and calibration processes are two parallel processes with the same goal. The aim is to check what is the difference of the output of the model from reality, or the most reliable approximation of it.

Our main validation parameters are the five outputs produced at the end of phase 2, that define the percentual share of passengers per kilometres of all the five different clusters of mode of transport. The reference values to be confronted with these results are the data related to each municipality used in calibration and validation.

The processes of calibration and validation cannot be performed at the same time. The first step is the calibration on the city of Milan, the most complete city in terms of provided services from the Italian pool. Then the second step is the validation of the model on the other three cities, one by one. What is follows may be a general correction of the model itself, or a more precise modification of some parameters to fit the different kind of cities, big or small, into the general model. At the end of this process another validation would be needed, followed by another calibration and so on. Being the processes fundamentally iterative, it makes more sense to join them into a single iterative process called calibration & validation of the model.

The steps and results of this process will be shown here in its main turning points, in chronological order. The images of the starting points and the ending point will be then showed to give the general idea of the ranged way.

As anticipated, the model was calibrated on the city of Milan, the calibration was, however not perfect, since the difference of the model's result from the reference data was about 4.2% in total, and 1.4% as an average for the three errors. These errors were obtained as the differences between the two public transport, private vehicles, and other means of transport modal split value. The maximum difference was for the other means of transport cluster, being equal to 2.1%. Both private vehicles and public transports modal shares were overestimated, while other means of transport was underestimated.

At this point, even though it would have been reasonable to refine the first calibration on the city of Milan, the validation process was initiated. This choice may be explained by the uncertainty related to the developed model, developed on only once city, which forced the fastness of validation process. The results of this first validation phase would have been a stopping point to evaluate whether the work done until this point, while being theoretically consistent, would give a correct, or at least reasonable result. Otherwise, the model should have been stopped in order to find eventual conceptual or practical mistakes.

The first validation results, however, were reasonable, if not acceptable. The main achievements of this phase were three. The first one was definition of a roof for the walking modal share, when deriving it from the public transport. The second one was the formulation of the operation used to obtain the urban radius, in particular for the case of Lecco that has an elongated shape when compared with the other three towns. The third one was performed adding a condition to the average trip length calculation. This condition stated that, if the entering population was higher than the actual urban population, then the average trip length formula would be multiplied by a factor obtained by the ratio of the two population parameters.

The results of this first validation phase are shown in the following image:

	Milano		Roma		Lecco		Firenze	
	Expected	Model	Expected	Model	Expected	Model	Expected	Model
TPL	37%	38.0%	21%	23%	11%	11%	16%	19%
PV	37%	38.4%	60%	61%	67%	65%	63%	62%
Other	26%	23.6%	19%	16%	22%	24%	21%	19%
Max Nominal Error	2%		3%		2%		3%	
Average	1.4%		2%		1%		2%	
Total	4.2%		6%		4%		6%	

Table 1: First validation table

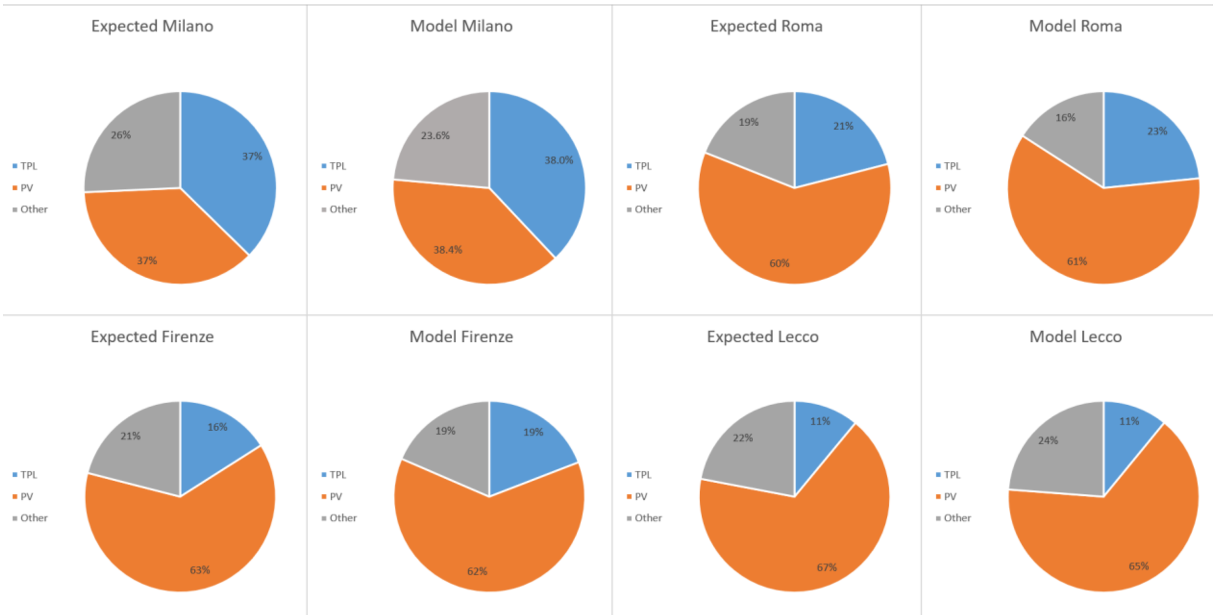

Figure 3: First validation, graphical comparison

A brief comment to this image is needed. The total errors between references and model result are similar for the cities of Rome and Florence, the same pattern is also noticeable for the average and maximum nominal error. However, none of these values worried us, being them low for the intended use of the model. Anyway, the existing difference of the errors in Florence and Rome, could infer a better accuracy of the model for larger cities when compared with smaller ones.

The results for Lecco are somehow better. But one of the three modifications derived in the performance of this validation was actually working only for Lecco, being it the only non-circular-shaped town.

The total error for the modal split in the city of Milan is comparable with the other three cases, so the focus for a better calibration should be driven by the evaluation of the error trends, if any may be noticed.

The first noticeable trend is the overestimation of the public transport modal share. This error, despite not being present in the Lecco case, is visible and comparable in the other three cities. This could mean that, for a further improvement, an overall decrement in terms of public transport shared mode, through a better calibration of the public transport in the Milan reference case, could be strongly beneficial.

Another evident trend, still not present in the Lecco case, is related to the underestimation of the other means of transport modal share. This could mean that an improvement on the side of micro-mobility, walking, or mobility as a service should be implemented for the next calibration.

For the private vehicles modal share errors there is not a clear trend. For the cities of Milan and Rome the modal share is over-estimated, while for Lecco and Florence, an underestimation is manifest.

The next calibration, still performed on the city of Milan, starts focusing on public transport, decreasing the overall value of passenger per kilometre covered by this modal cluster. The re-calibration of the parameters was performed following the data presented at the end of this subchapter, trying to bring the values of passengers transported each day by the light metro and the other public means of transport as close as possible to the value proposed by the transport agency ATM. This process was concluded with the redefinition of the values of α, the average utilized capacity parameter. The values related respectively to a Full, Medium, or Low input went from 1, 0.6, and 0.3, to 0.98, 0.59, and 0.29. This small reduction of this value solved the mistake related to the transport system over-estimation.

However, this modification alone, as a secondary result, would just increase the modal share of private vehicles. This effect, potentially beneficial for two of the cities, would be negative for the others. Therefore, another modification was chosen. The new modification was performed on the greenway's two calibration parameters. R, the ring-wise connection calibration parameter, went from the values 0.01, 0.06, and 0.095, correspondent to the entries Yes, Partially, and No, to the values 0.01, 0.07, 0.1. C, the C1 bike lane connection calibration parameter, went from 0.005, 0.02, 0.045, correspondent to the entries High, Medium, and Low, to the values 0.005, 0.02, 0.04. One the one hand, the first calibration parameter increment had an incremental result, on the other hand, the small reduction of the other parameter rebalanced it where it was needed. The overall result was a convergence for the city of Milan, of the public transport and other modal shares, and, consequently also of the private vehicles modal share.

After these modifications, the three cities of Milan, Rome and Florence were all converging, while the city of Lecco was slightly diverging, increasing its overall error by 0.1%. Only after further research towards the cause of what could be the driving problem for this inherent difference, it was possible to understand and solve the bias. The strong simplification of the model is that, starting from the number of outside commuters, e standard 50% of them will enter the city by car, while the others would choose other solutions. This is true for large cities, due to public transport provision and lack of parking slots. For small and barely internally served towns, even if the population from other large cities will choose the train as their mode of transport when entering the town area, all the surrounding population will be forced to go by car, if they own one. This is the reason, in the city of Lecco, between 60% and 70% of outside commuters are entering by car every day. Some may argue that also for Milan, Rome, and Florence, the share of entering car-drivers may not be exactly 50% of the outside commuters, but the variation is generally assimilated by the larger numbers. In Lecco this kind of difference was having a stronger impact, the input had to be modified.

Being the production of public transport insufficient, the greenway network barely existing and the sharing mobility just formally present, when the number of maximum passengers per kilometre by car was reached, the previous calibration could not have any beneficial effect. Only a modification of the maximum check for private vehicles daily pkm could solve the issue.

This result brings an interesting reflection point, the calibration and validation process, certainly mostly important for what it regard multiplied parameters used for the calibration itself, may bring to the discovering of biases or even actual mistakes that otherwise may had gone unnoticed, due to their specificity and sensibly low impact.

The last validation phase is the check of the effect of the previous calibration on the three cities.

	Milano		Roma		Lecco		Firenze	
	Expected	Model	Expected	Model	Expected	Model	Expected	Model
TPL	37.3%	37.3%	21%	23%	11%	11%	16%	19%
PV	37.0%	37.1%	60%	61%	67%	68%	63%	62%
Other	25.7%	25.6%	19%	16%	22%	21%	21%	19%
Max Nominal Error	0.1%		2.8%		1.3%		2.6%	
Average	0.1%		1.9%		0.9%		1.7%	
Total	0.2%		5.6%		2.6%		5.1%	

Table 2: Second validation table

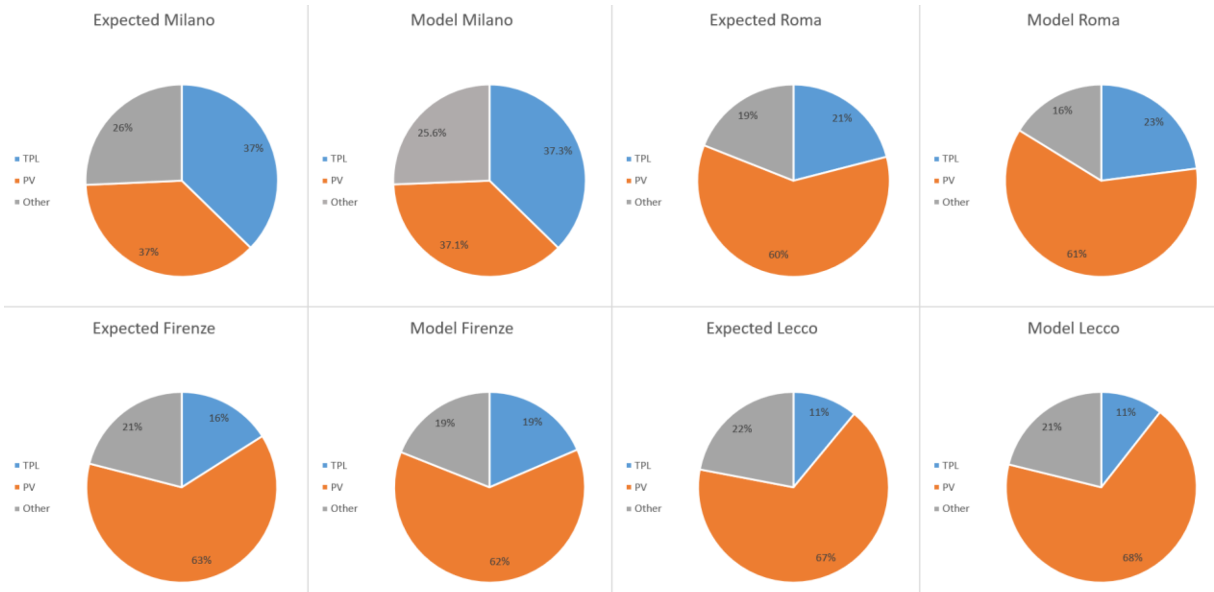

Figure 4: Second validation, graphical comparison

This is, indeed, the ending point of this subchapter. The Milano case, the one used as a reference, got to an average error almost irrelevant. For the other three cases the average error got lower than 2%, with Lecco now being lower than 1%. The total error is still far from being perfect, but in the worst case got to 5.6%, decreasing of 0.6%. In the case of Lecco the total error got to 2.6%, with an overall decrement of 1%. The nominal maximum error got decreased, getting under the 3% threshold for every city.

The last calibration process seems to have had its best effect, excluding the one seen on Milan, on the city of Florence modal split simulation. The reason may be that Florence has a better transport system compared with Rome and Lecco, therefore a modification of both the public transport and greenways calibration parameters in the correct direction resulted in the better effect.

The calibration and validation process could have been performed several other times, on other cities transport systems, but for the purposes of this work the point reached was considered enough. The goal of the model is not to describe modal split in a perfect way, but to support the choices that may be taken when addressing the topic of urban mobility.

3 Model results on the Case Study

This chapter will be dedicated to the presentation of the model outputs as a result of the activation of three different measures. The previous chapter's objective was to present the model in its detailed structure, while proving the validity and explaining the reasoning behind the calibration of the model itself. Therefore, it was more focused on the descriptive side of the matter.

Now the focus is moving towards the predictive potential of the model. Since it would be too demanding to present the effects of all the measures for all the different cities, a set of three measures will be activated separately only on the case study city of Milan. The choice of Milan is quite obvious at this point of the work because it is the city firstly used for the model calibration, consequentially being the city with less error on the modal split evaluation side.

On the other hand, the choice of the three exemplary measures is less simple. To choose them we can rely on an output table produced in the fourth phase of the model, ideated exactly for this purpose.

MEASURES FIELD	MEASURES SUBFIELD	M € for 1% of pkm variation (combined)	M € for 1% of CO_2 emissions variation (combined)	M € for 1% of NO_X emissions variation (combined)	M € for 1% of $PM_{2.5}$ emissions variation (combined)
Existing Transport Network	Safety Improvement	41	79	185	110
	Full day cycle	18	34	71	47
	Fleet improvement	35	72	348	114
Increased Transport Network	1 Extra Line construction	1278	1279	1459	1852

	Extra Vehicles acquisition	458	430	439	738
Greenway Network	Increase Greenway Network	50	90	40	42
Sharing Services	Improvement of number of vehicles offered	0	0	0	0
	Improvement in the price’s attractiveness	1	12	4	-6
Parking slots	Decreasing the number of parking slots	NA	NA	NA	NA

Table 3: Milan case study, phase 4 outputs

The first observation to do on this table is that values related to the parking slots decrement are non-defined since, as explained in chapter 2 of this thesis, all measures in phase 5 are non-active by default. The parking slots decrement is a reserve measure and may be activated only after other measures activation. To consider this factor the three measures we will assess and show, will be shown in two alternative versions: with or without the parking slots measure activation.

The three measures to be activated will be chosen from the three main clusters: the public transport, the greenway network, and the shared mobility.

For the sharing services the activation will be about the improvement in price attractiveness since the other measure has virtually zero cost.

For the greenway network the measure will be activated under the condition of average cost, so with half of the new bikeways being Class 1 and the other half being cheap bikeways.

For the public transport network, the measure chosen will be the Extra Line construction, just considering the development of a new light metro.

3.1. Improvement in MaaS price attractiveness – results

The activation of the price improvement measure for all shared mobility and taxi modes brings an interesting result.

In the first case we are considering just the measure's activation, then we will evaluate it jointed with a reduction in parking slots availability.

MEASURES FIELD	MEASURES SUBFIELD	Field directly affected	Activation condition achieved	Activation choice	Activation verified
Sharing Services	Improvement of number of vehicles offered	Shared Car	Yes	No	No
		Shared Bike	Yes	No	No
		Shared E-Bike	Yes	No	No
		Shared E-Scooter	Yes	No	No
		Shared Mopeds	Yes	No	No
		Taxi	Yes	No	No
	Improvement in the price's attractiveness	Shared Car	Yes	Yes	Yes
		Shared Bike	No	Yes	No
		Shared E-Bike	Yes	Yes	Yes
		Shared E-Scooter	Yes	Yes	Yes
		Shared Mopeds	Yes	Yes	Yes
		Taxi	Yes	Yes	Yes
Parking slots	Decreasing the number of parking slots	Car parks	Yes	No	No

Table 4: MaaS measure activation, no parking slots reduction

As anticipated the activation input is switched on "Yes" only for the measure of interest. Later, the Parking slots measure will be activated. The activation is verified for all the modes apart from the shared bike, the reason is that, in the cost model definition in phase 3, the bike price per minute was the lowest when compared to all the others. Leveling the other modes prices to the one of the bikes would not make sense to lower it too.

Also, the unactive MaaS is shown here. Having chosen a measure from each cluster, at the end of this chapter all of them will be actively shown. However, the un-active measures will be shown just once. Once assessing the measure's performance again, this time combined with the parking slots measure, only active measures will be shown.

	Total cost [M €]	Total ton CO2eq reduction yearly	Total kg NOX reduction yearly	Total kg PM2.5 reduction yearly
Results	5	-2888	22344	-15681

Table 5: MaaS measure result, no parking slots reduction

Being the cost of this measure limited, the result is interesting, despite being detrimental. If a reduction output is negative, it means that the activated measure is generating an increment in terms of emitted pollutants. MaaS is based on electromobility in Milan, therefore ozone reduction is a prominent result of these modes adoption by population, however, some modes are less sustainable than others. And the rebalancing factor is something that cannot be avoided, when considering shared vehicle emission. These considerations combined with the strong competition of shared mobility with other forms of more sustainable mobility, such as personal micro-mobility and public transport, can explain this result.

MEASURES FIELD	MEASURES SUBFIELD	Field directly affected	Activation condition achieved	Activation choice	Activation verified
Sharing Services	Improvement in the price's attractiveness	Shared Car	Yes	Yes	Yes
		Shared Bike	No	Yes	No
		Shared E-Bike	Yes	Yes	Yes
		Shared E-Scooter	Yes	Yes	Yes
		Shared Mopeds	Yes	Yes	Yes
		Taxi	Yes	Yes	Yes
Parking slots	Decreasing the number of parking slots	Car parks	Yes	Yes	Yes

Table 6: MaaS measure activation, parking slots reduction

Now we will evaluate the measure again with the activation of parking slots reduction measure. The reduction of parking slots is proportional to the measure effects. In this case, the production of passenger per kilometer removed from cars, associated only to the previous measure activation is around 2% of the total pkm. The starting share value of car related trips was 35%. When activating the parking slots limitation measure the percentage decrement will be proportional to the ration of pkm produced and total previous car pkm. In this case, because of the activation of this supplementary measure, the reduction of car modal share could be around 3%. The results in terms of emissions of this combination of measures is shown below.

	Total cost [M €]	Total ton CO2eq reduction yearly	Total kg NOX reduction yearly	Total kg PM2.5 reduction yearly
Results	54	6389	32253	-4009

Table 7: MaaS measure result, parking slots reduction

While the cost increased, the predicted effect of reduction in car's emissions is showing. Although, the particulate matter emissions are still increased from the status quo, despite the reduction in carbon dioxide and ozone emitted.

3.2. Greenway Network improvement – results

Being a ring-wise connected greenway network still not complete in Milan, the second measure we will activate is this one. However, we will activate it in the average condition, being the implementation of more than three hundred kilometres of C1 bikeways quite unrealistic.

MEASURES FIELD	MEASURES SUBFIELD	Field directly affected	Activation condition achieved	Activation choice	Multiplier (optional) [number]	Maximum multiplier [number]	Activation verified
Greenway Network	Increase Greenway Network	Base bikeway	Yes	No	1	356	No
		Ring-wise connection	Yes	Yes	365	356	Yes
		C1 bikeway	Yes	No	1	356	No
Parking slots	Decreasing the number of parking slots	Car parks	Yes	No			No

Table 8: Greenways measure activation, no parking slots reduction

The activated measure is the average one, the less costly to achieve ring-wise connection without building a too cheap bike infrastructure. The parking slots measure is not active. The optional multiplier is here present, since the measure may be activated without covering the whole number of suggested kilometers, but the result of even a small network implementation may be assessed.

	Total cost [M €]	Total ton CO2eq reduction yearly	Total kg NOX reduction yearly	Total kg PM2.5 reduction yearly
Results	360	75753	258542	91141

Table 9: Greenways measure results, no parking slots reduction

Being this measure related to three of the lower emission related modes, the private micro-mobility ones, the effects are clearly beneficial. Only the light and heavy metro could be less polluting per equivalent passenger per kilometer, but the private micro-mobility modes are competing more with other public means of transport, like bus, and with the other private modes of transport.

MEASURES FIELD	MEASURES SUBFIELD	Field directly affected	Activation condition achieved	Activation choice	Multiplier (optional) [number]	Maximum multiplier [number]	Activation verified
Greenway Network	Increase Greenway Network	Base bikeway	Yes	No	1	356	No
		Ring-wise connection	Yes	Yes	365	356	Yes
		C1 bikeway	Yes	No	1	356	No
Parking slots	Decreasing the number of parking slots	Car parks	Yes	Yes			Yes

Table 10: Greenways measure activation, parking slots reduction

	Total cost [M €]	Total ton CO2eq reduction yearly	Total kg NOX reduction yearly	Total kg PM2.5 reduction yearly
Results	475	97531	281826	118555

Table 11: Greenways measure results, parking slots reduction

In this case, being the effect of parking slots reduction quite beneficial, its influence is not as important as it was to support shared mobility actions. Certainly, the increment in reduced emissions is consistent, but it is not referring a trend or affecting the order of magnitude of the emissions. The amount of reduced passenger per kilometer share could go from 4% less to 6% less, depending on the parking slots decrement measure's activation. This value is the higher of the one we will see in this thesis. The reasons have been presented in the previous pages addressing the characteristic of light and green private transport micro-mobility modes.

3.3. New Light Metro line construction – results

The last measure we are activating to show the simulated results is the construction of a new light metro line in the city of Milan, for all it matters similar to the one already built and active, the so-called Metro 5: "Lilla". Like the previous one, also this last shown measure will be displayed alone and combined with the activation of a parking slots reduction measure.

MEASURES FIELD	MEASURES SUBFIELD	Field directly affected	Activation condition achieved	Activation choice	Activation verified
Increased Transport Network	1 Extra Line construction	Heavy Rail	Yes	No	No
		Light Rail	Yes	Yes	Yes
		Bus	Yes	No	No
		Trolleybus with dedicated lane	Yes	No	No
		Tram	Yes	No	No
	Extra Vehicles acquisition	Heavy Rail	Yes	No	No
		Light Rail	Yes	No	No
		Bus	Yes	No	No
		Trolleybus with dedicated lane	Yes	No	No
		Tram	Yes	No	No
Parking slots	Decreasing the number of parking slots	Car parks	Yes	No	No

Table 12: Public transport measure activation, no parking slots reduction

The activation of this measure could comprehend lines of other means of transport, for more than a single line. The default number is one, but the user can change it in the fourth phase of the model. However it seemed more meaningful to activate the measure for just one new metro line, being the measure in discussion the most expensive one, from the social cost side.

	Total cost [M €]	Total ton CO2eq reduction yearly	Total kg NOX reduction yearly	Total kg PM2.5 reduction yearly
Results	1703	14358	47387	14526

Table 13: Public transport measure results, no parking slots reduction

The effects are definitively beneficial, but the amount of the total cost is huge. This quantity, despite being presented here as the bare cost of construction, acquisition of new vehicles, and the service cost for one year, is overestimated. The construction of a new metro line is not performed in one year; therefore, this cost is not paid all at once. Moreover, a similar social debt, should be driven by depreciation and reduction evaluations, to understand what the actual sustained annual cost would it be.

To keep the work simple on this side, however, we put the complete process price in the cost estimation, with the goal of keeping the new line construction suggestion as a reserve measure.

MEASURES FIELD	MEASURES SUBFIELD	Field directly affected	Activation condition achieved	Activation choice	Activation verified
Increased Transport Network	1 Extra Line construction	Heavy Rail	Yes	No	No
		Light Rail	Yes	Yes	Yes
		Bus	Yes	No	No
		Trolleybus with dedicated lane	Yes	No	No
		Tram	Yes	No	No
	Extra Vehicles acquisition	Heavy Rail	Yes	No	No
		Light Rail	Yes	No	No
		Bus	Yes	No	No
		Trolleybus with dedicated lane	Yes	No	No
		Tram	Yes	No	No
Parking slots	Decreasing the number of parking slots	Car parks	Yes	Yes	Yes

Table 14: Public transport measure activation, parking slots reduction

This time the measure is being activated jointed with the activation of the extra parking slots reduction measure. The effect on cars modal split is around 1% reduction, being slightly higher in the combined activation condition.

	Total cost [M €]	Total ton CO2eq reduction yearly	Total kg NOX reduction yearly	Total kg PM2.5 reduction yearly
Results	1726	18679	52002	19962

Table 15: Public transport measure results, parking slots reduction

In conclusion, for a measure of this cost, the activation of the extra measure, decrementing the number of parking slots, this time is more efficient, since the starting cost is so high that the increment is not that consistent when compared with the decrement in emissions.

Moreover, the transition from private car to public transport may be more effective when compared with other transitions, such as the private car, private bike one. This could generate a process that, if well integrated with park and ride facilities, could bring less and less cars to the city, increasing public transport occupancy in new offered services.

Concluding this chapter, the last consideration is that theoretically, activating many measures, the totality of urban parking slots could be removed, while still providing the population with sustainable mobility modal alternatives. However the cost could be prohibitive, therefore a similar model could be useful to evaluate on which cluster to invest first.

A similar reduction in the urban area, should be jointed with the provision of several park and ride facilities in the outskirts of the town, to prevent the isolation of a share of the population that unlucky lives in non-served small areas.

4 Conclusion and future developments

The result of this study was the production of a model, able to provide a first estimation of the modal split and the associated emissions for urban environment mobility, starting from a small number of aggregated, easy-accessibility inputs. This estimation, although being approximative, is the base for the model reliability when moving to his next function, the main one, of assessing the possible solutions that may be chosen when transitioning toward urban mobility through planning.

The model is also able to estimate the costs associated to a number of proposed measures that may be activated one by one or as a bundle, and then predicts the associated costs and reduced emissions which would come as a result of the modal change connected to the activated measures.

After the calibration and validation process, the degree of accuracy is sufficient, but a further calibration could be beneficial to extend the model accuracy also for cities outside the country of Italy. In this regard also the implementation of the cost model could be modified to fit the different national laws of the different cities under investigation.

In a nutshell, an evaluation and prediction urban mobility model was produced, with the utility of giving support to decision-makers and politicians that are working on the urban mobility context. The main goal of the model was reached: to support the decisional process by estimating costs and benefits, in terms of offered service and reduced emissions.

Being more specific, the work started to delineate during the state-of-the-art evaluation phase. As mentioned in the introduction, this process was interesting but not as simple as expected. The complexity arises from the different fields pertinent to the topic of transport, being quite various and difficult to integrate one another.

The real achievement was the definition of the method that could drive the method, starting from the aggregated transport data and reaching the emissions. The first conceptual accomplishment was considering the transport production in the status quo condition as a driving element for the mobility configuration, described by the modal split. Then, in function of distinct factors, the actual value of utilized transport can range, but it still needs to remain between a reasonable upper and lower-bound. The model presented is the result of this method and offers a practical tool to assist decision makers in the mobility field.

The next challenge was the data recovery. The data found from the literary sources were the less demanding ones. This activity became harder when searching for the data related to the municipalities. The case of Milan was chosen also for this reason.

Data were plenty accessible and reliable, being produced by transport companies themselves, or by state-founded territorial mobility agencies. The hardest case from the data retrieval side was for the city of Lecco. Being it a relatively small municipality, data were not easy to find and, additionally, were not always coming from reliable sources. Hence a double-check was needed.

The last assignment, useful but time consuming, was the calibration and validation process. To achieve an acceptable error threshold this process needed both to dialogue with the accessible data and to be performed on the four cities at the same time. Then, to refine the evaluation on the case study, an iterative interaction between calibrations and validations was performed. A one-by-one analysis on the multipliers was conducted to better understand and eventually correct their first guess. The correct parameters were identified only when a full convergence was achieved.

This work brought to an interesting theoretical method, derived into a simple support tool, however some practical improvements could be achieved starting from the current state of work.

The first improvement that could be reach is the evaluation of emissions of carbon dioxide, ozone, and particulate matter, from an economical estimation. A particular article cited before did something similar [15], however further literature research could bring to a more robust knowledge on the topic.

A second improvement could be the implementation of a supplementary measure, the construction and provision of park and ride facilities. This measure could brace the urban parking slots reduction measure, acting as a relocation of parking area from urban territory to the surrounding multi-modal stations, also ensuring the use of sustainable transport modes when entering town. The analysed literature over this matter is wide. Nevertheless, a limit of the produced model should be overcome when proposing a park and ride measure. To propose a similar urban planning measure the current geography of the town should become and input itself, and the model should become georeferenced. Another way of reaching this result, keeping the model at the current level of resolution, could be the definition of general parameters to describe accessibility, focusing more on what is outside of the urban area. This could be a possible direction for this kind of future development, without working with georeferenced data.

The last goal that was too far to be reached during the development of this work, but that could give and interesting addition to this model, is the evaluation of the medical-economical life quality improvement. Even if carbon dioxide has not a direct effect on human health, being more a threat for the whole environment, the ozone and particulate matter produced as subproducts of transport process, may be harmful for the human health. To achieve this addition other articles may need to be reviewed, starting from [29]. The medical and economical effects of sustainable transition could also be estimated under the accidents and related injuries incidence associated to different modes of transport. By the reduction of kilometres travelled by cars in the urban environment road safety could increase considerably for bikes [30], e-scooters [31], and the other micro-mobility modes of transport.

From a more conceptual point of view, the presented tool could be used for a first step analysis for more specific and detailed methods, similar to the ones found in literature.

A final suggestion could be the development of a similar tool concerning transport and mobility outside of the urban area. Adding this dual model to the one proposed in this thesis could bring to a complete coverage of the so-called *metropolitan area* of modern cities, focusing on both urban and extra-urban measures. The two models could be integrated to have a common output, in which it could be possible to predict the effects of urban and extra-urban measures. This could be done on the one hand to compare them in terms of economic efficiency and on the other hand to evaluate the mutual influence that measures taken in different contexts could have.

5 Bibliography

[1] S. Werland, “Diffusing Sustainable Urban Mobility Planning in the EU,” *Sustainability,* 2020.

[2] A. Romero-Ania, “Managing Sustainable Urban Public Transport Systems: An AHP Multicriteria Decision Model,” *Sustainability,* 2021.

[3] “Climate Action,” [Online]. Available: https://climate.ec.europa.eu/eu-action/european-green-deal/2030-climate-target-plan_en.

[4] J. Moore, “Ecological Footprints and Lifestyle Archetypes: Exploring Dimensions of Consumption and the Transformation Needed to Achieve Urban Sustainability,” *Sustainability,* 2015.

[5] K. Lee, “Particulate Matter (PM10 and PM2.5) and Greenhouse Gas Emissions of UAV Delivery Systems on Metropolitan Subway Tracks,” *Sustainability,* 2022.

[6] L. Yang, “Research on the Deployment of Joint Dedicated Lanes for CAVs and Buses,” *Sustainability,* 2022.

[7] P. Camps-Aragò, “Encouraging the Sustainable Adoption of Autonomous Vehicles for Public Transport in Belgium: Citizen Acceptance, Business Models, and Policy Aspects,” *Sustainability,* 2022.

[8] A. Abbas, “Potential of Connected Fully Autonomous Vehicles in Reducing Congestion and Associated Carbon Emissions,” *Sustainability,* 2022.

[9] E. Gonzàlez-Gonzàlez, “Autonomous Mobility: A Potential Opportunity to Reclaim Public Spaces for People,” *Sustainability,* 2021.

[10] M. Finkbeiner, “A Systemic View of Future Mobility Scenario Impacts on and Their Implications for City Organizational LCA: The Case of Autonomous Driving in Vienna,” *Sustainability,* 2022.

[11] K. e. a. Pietrzak, “Environmental Effects of Electromobility in a Sustainable Urban Public Transport,” *Sustainability,* 2020.

[12] V. Franzitta, “Energy Saving in Public Transport Using Renewable Energy,” *Sustainability,* 2017.

[13] “DPCM 152 28/05/2018,” Gazzeta Ufficiale della Repubblica Italiana, 2018. [Online]. Available: https://www.gazzettaufficiale.it/eli/id/2021/11/06/21G00166/sg.

[14] National Academies of Science, Engineering and Medicine, Quantifiying Transit's Impact of GHG Emissions and Energy Use - The Land Use Component, Washington, DC: National Academies Press, 2015.

[15] L. D'Acierno, “Adoption of Micro-Mobility Solutions for Improving Environmental Sustainability: Comparison among Transportation Systems in Urban Contexts,” *Sustainability,* 2022.

[16] J.-A. Pattinson, “Combining Tradable Credit Schemes with a New Form of Road Pricing: Producing Liveable Cities and Meeting Decarbonisation Goals,” *Sustainability,* 2022.

[17] J. R. e. a. Kenworthy, “Exploring the Energy Saving Potential in Private, Public and Non-Motorized Transport for Ten Swedish Cities,” *Sustainability,* 2022.

[18] J. Y. e. a. Wang, “Locating and pricing park-and-ride facilities in a linear monocentric city with deterministic mode choice,” *Transportation Research Part B: Methodological,* vol. 38, no. 8, pp. 709-731, 2004.

[19] M. Nieuwenhuijsen, “Implementing Car-Free Cities: Rationale, Requirements, Barriers and Facilitators,” in *Integrating Human Health into Urban and Transport Planning,* 2018, pp. 199-219.

[20] C. Teodosiu, “Aging Passenger Car Fleet Structure, Dynamics, and Environmental Performance Evaluation at the Regional Level by Life Cycle Assessment,” *Sustainability,* 2022.

[21] N. Zhang, “The Unintended Consequences of Urban Community Infrastructure Investment for Consumption in China,” *Sustainability,* 2022.

[22] O. Marquet, “Assessing Environmental Performance of Micromobility Using LCA and Self-Reported Modal Change: The Case of Shared E-Bikes, E-Scooters, and E-Mopeds in Barcelona,” *Sustainability,* 2022.

[23] L. Oreskovic, “Enabling Sustainable Lifestyles in New Urban Areas: Evaluation of an Eco-Development Case Study in the UK,” *Sustainability,* 2022.

[24] D. Vergara, "Energy Consumption of the Urban Transport Fleet in UNESCO World Heritage Sites: A Case Study of Ávila (Spain)," *Sustainability,* 2022.

[25] M. Kii, "Reductions in CO2 Emissions from Passenger Cars under Demography and Technology Scenarios in Japan by 2050," *Sustainability,* 2020.

[26] F. Filippi, "A Paradigm Shift for a Transition to Sustainable Urban Transport," *Sustainability,* 2022.

[27] N. M. Kumar, "Selected Aspects of Sustainable Mobility Reveals Implementable Approaches and Conceivable Actions," *Sustainability,* 2021.

[28] F. Adobati, "The Breath of the Metropolis: Smart Working and New Urban Geographies," *Sustainability,* 2022.

[29] C. Reche, "Vehicular Traffic in Urban Areas: Health Burden and Influence of Sustainable Urban Planning and Mobility," *Atmosphere,* 2022.

[30] E. Macioszek, "The Analysis of the Factors Influencing the Severity of Bicyclist Injury in Bicyclist-Vehicle Crashes," *Sustainability,* 2022.

[31] G. C. Luigi Buongiorno, "Slow and Steady Wins the Race: A Comparative Analysis of Standing Electric Scooters' European Regulations Integrated with the Aspect of Forensic Traumatology," *Sustainability,* 2022.

[32] B. Maas, "Literature Review of Mobility as a Service," *Sustainability,* 2022.

[33] M. Z. P. S. Monika Hamerska, "A Sustainable Transport System—The MMQUAL Model of Shared Micromobility Service Quality Assessment," *Sustainability.*

[34] S. AlQuhtani, "Ridesharing as a Potential Sustainable Transportation Alternative in Suburban Universities: The Case of Najran University, Saudi Arabia," *Sustainability,* 2022.

[35] A. Papagiannakis, "Do Citizens Understand the Benefits of Transit-Oriented Development? Exploring and Modeling Community Perceptions of a Metro Line under Construction in Thessaloniki, Greece," *Sustainability,* 2022.

[36] F. Schwinger, "Comparing Micromobility with Public Transportation Trips in a Data-Driven Spatio-Temporal Analysis," *Sustainability,* 2022.

[37] L. Gebhardt, ""I'll Take the E-Scooter Instead of My Car"—The Potential of E-Scooters as a Substitute for Car Trips in Germany," *Sustainability,* 2021.

[38] M. v. d. Koogh, "Are We Satisfying the Right Conditions for the Mobility Transition? A Review and Evaluation of the Dutch Urban Mobility Policies," *Sustainability,* 2021.

[39] B. Risimati, "Spatial Integration of Non-Motorized Transport and Urban Public Transport Infrastructure: A Case of Johannesburg," *Sustainability,* 2021.

[40] M. Kilani, "A Multimodal Transport Model to Evaluate Transport Policies in the North of France," *Sustainability,* 2022.

[41] O. Survilé, "Smart Urban Mobility System Evaluation Model Adaptation to Vilnius, Montreal and Weimar Cities," *Sustainability,* 2022.

[42] M. Menendez, "Implementing Design and Operational Measures for Sustainable Mobility: Lessons from Zurich," *Sustainability,* 2022.

[43] J. B. e. al., "An evaluation of the car-free city potential for the city of Munich regarding mobility data," in *12th International Conference on Ecological Vehicles and Renewable Energies, EVER 2017*, Monte-Carlo, 2017.

[44] J. Crawford, CarFree Cities, International Books, 2000.

[45] D. Duclos-Bastìas, "Promoting Sustainable Mobility: Impact of an Urban Biking Programme on University Students," *Sustainability,* 2021.

[46] P. Wałdykowski, "Sustainable Urban Transport—Why a Fast Investment in a Complete Cycling Network Is Most Profitable for a City," *Sustainability,* 2021.

[47] M. Tarkowski, "Connectivity Benefits of Small Zero-Emission Autonomous Ferries in Urban Mobility—Case of the Coastal City of Gdańsk (Poland)," *Sustainability,* 2021.

[48] A. Comi, "Sustainable Urban Delivery: The Learning Process of Path Costs Enhanced by Information and Communication Technologies," *Sustainability,* 2021.

[49] I. Saadi, "A Participatory Assessment of Perceived Neighbourhood Walkability in a Small Urban Environment," *Sustainability,* 2021.

[50] N. Mikušová, "Possibility of a Solution of the Sustainability of Transport and Mobility with the Application of Discrete Computer Simulation—A Case Study," *Sustainability,* 2021.

[51] N. Komninos, "Next City: Learning from Cities during COVID-19 to Tackle Climate Change," *Sustainability,* 2021.

[52] C. Kara, "Predict and Simulate Sustainable Urban Growth by Using GIS and MCE Based CA. Case of Famagusta in Northern Cyprus," *Sustainability,* 2021.

[53] J. Cai, "Bikeway Provision and Bicycle Commuting: City-Level Empirical Findings from the US," *Sustainability,* 2021.

[54] T. Stojanovski, "Urban Form and Mobility Choices: Informing about Sustainable Travel Alternatives, Carbon Emissions and Energy Use from Transportation in Swedish Neighbourhoods," *Sustainability,* 2019.

[55] R. Sidorchuk, "Local Resident Attitudes to the Sustainable Development of Urban Public Transport System," *Sustainability,* 2021.

[56] D. Fang, "Optimal Strategies for Elderly Public Transport Service Based on Impact-Asymmetry Analysis: A Case Study of Harbin," *Sustainability,* 2022.

[57] M. Longo, "15-Min Station: A Case Study in North Italy City to Evaluate the Livability of an Area," *Sustainability,* 2021.

[58] Y. Liu, "Comprehensive Public Transport Service Accessibility Index—A New Approach Based on Degree Centrality and Gravity Model," *Sustainability,* 2019.

[59] C. Wang, "Identification and Optimization Strategy of Urban Park Service Areas Based on Accessibility by Public Transport: Beijing as a Case Study," *Sustainability,* 2022.

[60] J. Ortega, "A Comprehensive Model to Study the Dynamic Accessibility of the Park & Ride System," *Sustainability,* 2021.

[61] N. Ali, "Analysis of Bus Fare Structure to Observe Modal Shift, Operator Profit, and Land-Use Choices through Combined Unified Transport Model," *Sustainability,* 2021.

[62] J. Ortega, "Mapping the Catchment Area of Park and Ride Facilities within Urban Environments," *International Journal of Geo-Information,* 2020.

[63] H. T. &. T. Pharoah, “Car-free city centres,” *Transportation,* vol. 21, no. 3, pp. 231-247, 1994.

[64] G. Tortosa, “The setting-up of a car-less city center in Oslo: a genuine automotive restriction policy, or a mere redevelopment of the public space following the removal of motorized traffic?,” *Flux,* vol. 127, no. 1, pp. 48-64, 2022.

[65] E. M. e. al., “Residents’ acceptance towards car-free street experiments: Focus on perceived quality of life and neighborhood attachment,” *Transportation Research Interdisciplinary Perspectives,* vol. 14, 2022.

[66] A. H. S. e. al., “Feasibility Study on Walkable City through Implementation of Car-Free Zones and its Effect on Traffic Movement in Georgetown, Penang Using GIS Network Analysis,” *IOP Conference Series: Earth and Environmental Science,* vol. 767, no. 1, 2021.

[67] M. Alameri, “The Car Free City Model,” *WIT Transactions on the Built Environment,* vol. 116, pp. 143-154, 2011.

[68] M. J. N. e. al, “Car free cities: Pathway to healthy urban living,” *Environment International,* vol. 94, pp. 251-262, 2016.

[69] Istat, “8milaCensus,” Istat, 2011. [Online]. Available: https://ottomilacensus.istat.it/.

[70] Antonio Caputo (ISPRA), “Ispra ambiente,” ISPRA, 5 May 2021. [Online]. Available: https://www.isprambiente.gov.it/files2021/pubblicazioni/rapporti/r343-2021.pdf.

[71] AMAT, “Sistema Statistico Integrato comune di Milano,” AMAT, 2021. [Online]. Available: http://sisi.comune.milano.it/.

[72] ACI, “Comuni-Italiani Numero auto nei comuni,” ACI, 2021. [Online]. Available: http://www.comuni-italiani.it/03/statistiche/veicoli.html.

[73] ATM, “ATM La società in numeri,” Azienda Transporti Milanesi, 2021. [Online]. Available: https://www.atm.it/it/IlGruppo/ChiSiamo/Pagine/Numeri.aspx.

[74] Dipartimento Mobilità e Trasporti Roma Capitale, “ROMAMOBILITA',” 2019. [Online]. Available: https://romamobilita.it/it/media/pubblicazioni/rapporto-mobilit%C3%A0-2021.

[75] Comune di Firenze, “Città di Firenze,” 2021. [Online]. Available: https://www.comune.fi.it/dalle-redazioni/piano-generale-del-traffico-urbano-aggiornamento-2021.

[76] AgenziaTPL, “LineeLecco,” 2021. [Online]. Available: https://lineelecco.it/linee-lecco/.

[77] G. Laratta, “Polimi-Politesi,” 2014. [Online]. Available: https://www.politesi.polimi.it/bitstream/10589/96601/4/2014_10_Laratta_1.pdf.

[78] University of Naples, “UniNA Fondamenti di Ingegneria dei Trasporti,” [Online]. Available: https://www.docenti.unina.it/webdocenti-be/allegati/materiale-didattico/34014340.

[79] A. Spinosa, “Cityrailways,” Ministero dell Infrastrutture e dei trasporti, 2019. [Online]. Available: https://cityrailways.com/dati-e-software/tcsp-modello/.

[80] Ministero dell infrastrutture e della mobilità sostenibili, “Governo Italiano MIT,” Ministero dell infrastrutture e della mobilità sostenibili, [Online]. Available: https://www.mit.gov.it/taxonomy/term/400.

[81] Comune di Milano, “Comune Milano Pendolarismo,” 2011. [Online]. Available: https://www.comune.milano.it/aree-tematiche/dati-statistici/pubblicazioni/pendolarismo-a-milano.

[82] Comune di Milano, “Metro 5,” Comune di Milano, 2015. [Online]. Available: https://www.metro-5.com/linea-5/.

[83] Comune di Firenze, “Città Metropolitana di Firenze, PUMS,” 2020. [Online]. Available: https://www.cittametropolitana.fi.it/pums/.

[84] Leccoonline, “Lecco online "Le esigenze infrastrutturali del territorio",” Regione Lombardia, 2016. [Online]. Available: https://www.leccoonline.com/articolo.php?idd=27531&origine=1&t=%27%27Le+esigenze+infrastrutturali+del+territorio%27%27%2C+Confindustria+apre+un+tavolo+tecnico+territoriale.

[85] Polinomia Srl, “FondazioneCariplo Il caso dell'area urbana di Lecco,” 2013. [Online]. Available: https://www.fondazionecariplo.it/static/upload/qua/quaderno_09_il-caso-dell-area-urbana-di-lecco/quaderno_09_il-caso-dell-area-urbana-di-lecco.pdf.

List of Figures

List if Tables

Acknowledgments

I miei primi ringraziamenti vanno ai professori Paolo Gandini e Marco Ponti, per l'interesse che hanno saputo stimolare durante lo svolgimento delle lezioni dei loro corsi, e per il sostegno, in qualità di relatore e correlatore, con cui hanno saputo indirizzare e valorizzare il mio lavoro durante lo svolgimento di questa tesi.

Ringrazio l'insegnante di liceo Francesco Prestipino, primo ad avermi fatto appassionare alla realtà e alla descrizione matematica di essa, passione senza cui mi sarebbe stato impossibile concludere i miei studi d'ingegneria.

Per i preziosi confronti, sebbene avvenuti in tempi e spazi differenti, ringrazio Mattia, Roberto, Ludovica, Elena, Emanuele, Andrea, Riccardo, Sara e Margherita. Un ringraziamento speciale va a Ferruccio e Laurens per l'aiuto datomi nelle ultime fasi della stesura.

Ringrazio i miei genitori e mia sorella, per avermi permesso di concentrarmi sull'università.