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Testing of traffic reduction policies using a transport demand model

Thesis submitted for completion of the Master Degree in Energy for Sustainability specialized in Energy Systems and Policy

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Abstract

This thesis aimed to test the impact of various transport demand management (TDM) measures on traffic road assignment in transport demand macro model developed for the city of Coimbra in software VISUM 12.0. The policies tested in the model were parking policy, carpooling incentives, urban road tolling policy and improvement of public bus transit, as well as strategic combinations of all of those policies. The study measures the impact on aggregated values for private vehicle volumes, fossil fuel consumption and CO_2 emissions from the traffic in the city of Coimbra with complementary geographical representation.

The strategic policy scenario consisting of combination of all the measures that were tested resulted in a 4% reduction of CO_2 emissions (19.76 tonnes), 4% reduction of fuel consumption (6.34 tonnes) and 506’969 vehicles per km in 24 hours of a non-eventful working day. It was able to target the zones with the highest demand for commuting represented as reduction of 2.1% of trip origins and 5% of trip destinations in the zones. These policies were also able to target the most congested or the most polluted roads in the inner city and reduce CO_2 emissions and private vehicle volumes.

It was found that road tolling, higher parking fees and extended paid areas can lead to a different route choice of private vehicle instead of shift to public transport or walking. Thus their effectiveness in reducing CO_2 emissions and private vehicle volumes can be lower. Additionally a road slopes in the city influence the results of policies aiming to reduce CO_2 emissions. It was concluded that the macro model simulation plays important role in obtaining the aggregated results with macro projection of the traffic situation after a TDM policy. In the same time, careful multi-criteria policy modelling and a complementary micro simulation of traffic situation in the city will be necessary part when testing the effect of TDM policies.

Keywords Traffic modelling, TDM policy, CO_2 emissions, traffic congestion, parking, carpooling, road toll, public transportation

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GLOSSARY

Acronyms

AP – Analysed period, 24 hours of normal uneventful working day

CO_2 – Carbon dioxide

EC – European Commission

EU – European Union

GHG – greenhouse gases

HO trip –home-other activity based trip

HS trip –home-shopping based trips

HU trip – home-university based trips

HUC – Hospitals of the University of Coimbra

HW trip – home-work based trips

IT – individual transport

NHB trip – non-home based trip

PuT – public transport

SMM Model – Modelo de Planeamento de Transportes do Sistema de Mobilidade do Mondego

SMTUC – The Municipal Urban Transport Services of Coimbra

TDM – Transport Demand Management

1. INTRODUCTION

We all travel and our world and economic system is based on mobility. Mobility is essential to our existence and it is crucial to economic effectiveness of the region. Related to this, transport entered this century with several socio-economic and architecture tasks that should be addressed to prevent and deal with the sustainability crisis. This crisis is pictured as an outcome of growing population, higher energy and mobility demand stuck in insufficient system of transportation infrastructure. This and further facts represent a complex problem that contributes in lessening the energy and system efficiency. We could mention lack of energy resources causing high costs for transportation; insufficient infrastructure and transport management resulting in unmet demand needs and mobility inequality; human habits and demands of comfort resulting in difficulties with substitution of car-dependent transport structures; or pollution caused by fossil fuel combustion. All of these above mentioned represent an inter-influencing structure of causes and effects which are difficult to address on global level and where the quantitative assessment of measures represents a quite young and yet quickly developing field.

The need for transport demand management policies rises from the fact that our culture and mobility became dependent on private vehicles powered by the fossil fuels. In aim to address these issues in the urban environment, the current trend is to manage the transport more effectively. The switch to walking, cycling or to public and collective transportation (PuT) is seen as one of the suitable and cost-effective way. There had been several attempts to support these aims via public policy. However, it is crucially important to provide these attempts with adequate analysis and assessment of the possible consequences before their implementation. Public policy represents a sensitive issue as it plays the role in change of the human behaviour, effectiveness of the transport network and many other complex issues in between economic, social, environmental spheres or security. One of the ways is seen in testing these policies in transport demand model to analyse the possible outcomes in the network and study if the desired goals were reached.

1.1. Objectives and motivation

The objective of this master thesis is to test traffic reduction policies in a transport demand model with the emphasis on reduction of CO_2 emissions, fuel consumption and vehicle volumes and the results would be supplemented by geographical allocation of CO_2 emissions and vehicle volumes in the city of Coimbra. It will be aimed to test the sensitivity of the transport demand macro model developed for the region of Coimbra in the software VISUM 12.0 (PTV) to individual transport policies and complex policy scenarios. The results on the studied traffic assignment outcomes will be analysed and subsequently an adequate commentary on the results on the policy sensitivity as well as recommendations for future development will be provided.

To achieve this objective the following steps were necessary:

1. To map and understand strategic planning and decision making for sustainable transportation in European Union and Coimbra and develop a framework of transport demand policies to be tested in the transport demand model.
2. To learn about the case studies of testing transport demand policies in transport demand models in aim to provide a background for this study.
3. To learn about CO_2 emission derivation from transport demand macro models.
4. To understand and master the transportation planning process; particularly the processes based on the four-step transport demand modelling.
5. To obtain skills in using transport demand software VISUM 12.0 from company PTV.

6. To study and fully understand how the transport demand model for the city of Coimbra was developed in the software VISUM 12.0.

The city's transport system characteristics, directives and highlights of the Strategic Plan for Coimbra 2007, as well as the directives of European Commission (EC from now on) in the White Paper 2011 will be used as a strategic framework in modelling the policy scenarios.

1.2. The structure of the thesis

One of the initial goals of this work was to present a strategic policy paper which would combine current trends in TDM policies in European Union and its practical implementation in transport planning.

Thus, the master thesis consist of mixture of several different fields – introduction into the legal transport demand policy framework in European Union and the city of Coimbra, the current trends in use of transport demand models to predict the impact of some TDM policies and the estimation of the CO_2 emission using the transport demand model.

This master thesis is structured in seven chapters. Chapter 1 – Introduction – consists of the objectives and motivation of the research. The need and the legal process for transport demand policy and its implementation in the European Union are elaborated in Chapters 1.3 and 1.4 to support the theoretical introduction. Chapter 1.5 provides theoretical insides into current process of transport policy implementation and strategic decision making.

Chapter 2 - The Case Study – focuses on the chosen case study which is the city of Coimbra with its region. In this chapter, a brief analysis of the transportation system of the city is presented (Chapter 2.1) identifying the main transport management issues to be addressed. Complementary to this, the legal or strategic steps and its state-of-art of the local government's actions towards the sustainable transportation are presented in Chapter 2.2.

The methodology is elaborated in Chapter 3, consisting of five sub-chapters. Chapter 3.1 provides an overview of literature sources and similar case studies of testing TDM policies and derivation of CO_2 emissions from transport demand models. Chapter 3.2 is a brief introduction into the transport demand software VISUM 12.0 (PTV) used for the case study. Afterwards, the way the case of the city of Coimbra was modelled in VISUM 12.0 as the transport demand model for the city of Coimbra (the SMM Model) is presented in Chapter 3.3 with sub-chapter of the methodology for CO_2 emissions estimation. The last two sub chapters 3.4 and 3.5 cover the reasoning used in choosing the transport demand policies tested in the SMM Model and the result outputs that were analysed in this master thesis.

Chapter 4 provides the detailed insides on modelling the policies in the SMM Model and different scenarios of each TDM policy tested – the parking policy, carpooling incentives, urban road tolling policy, PuT improvement and strategic combinations of those policies.

Results for chosen aggregated traffic outcomes which were CO_2 emissions, vehicle volumes per kilometre or fuel consumptions, complemented by analysis of the new trips assignment resulted from the policy's effect is elaborated in Chapter 5 accompanied with relevant comments.

Finally the Discussion and Conclusion occupy Chapters 6.

1.3. The need for traffic reduction policies

In Europe nowadays, we face extremely limited resources of fossil fuels and its unsecure future import as well as other negative trends: a growing car dependent population, city sprawl, old and car-based infrastructure in cities and sub-urban areas, low public notion and lack of awareness of local governments for alternative transport possibilities or solutions, higher demand on speed and quality of mobility, inadequate land use or short term project planning.

Automobile dependency and growing car ownership are seen primarily as issues of environmental sustainability due to the consumption of non-renewable resources of energy and production of greenhouse gases (GHG from now on). Some facts about the current situation in the transport sector of the EU should be noted:

- In the European Union, transport depends on oil and oil products for more than 96% of its energy needs. At the same time, Europe imports 84.1% of its crude oil while 57.3% of crude oil for countries of EU-27 are imported from Russia, Norway and Libya.
- Cars are the most popular passenger mode across the EU: they represent some 72% of all passenger kilometres. However, the private car is rarely the most energy-efficient form of transport.
- In 2007, the share of GHG emissions produced by the transport sector reached 25% of the total GHG emission of European Union.
- In 2008, 12,8% of overall emissions are generated by aviation, 13,5% by maritime transport, 0,7% by rail, 1.8% by inland navigation and 71,3% by road transport [1] [2].

1.4. Steps of European Union towards more sustainable transportation

European Union accompanied by countries around the world realizes that the above mentioned facts call for attention and improvement. In aim to address these issues in several ways, various studies, strategic papers, treaties and legislations on environmental sustainability have been developed, signed and, to certain extend, applied. The international Kyoto Protocol treaty, that aimed fighting global warming on a global scope, was initially adopted in 1997, signed by 43 countries, and then re-signed in 2011. It sets a target of at least 5% reduction of GHG emissions against the 1990 levels over the five-year period 2008-2012 [3]. Based on these milestones and local targets, European Union developed complex strategies covering various fields of policy, reconstruction, funding and research and development to reach these goals and assure energy sustainability of its member states in future years. The detailed analysis of this process and its outcome will not be a subject in this master thesis, yet it serves as a background in developing the traffic reduction policies tested in the transport demand model.

One of the first directly addressed strategic papers of EU on transport in 21st century was the White Paper, signed by European Commission (EC from now on) in 2001 [4] . It took the main step in identifying the milestones for sustainable transport up to year 2020.

Since 2006, every year except 2010, EC introduced a strategic paper on different topics considering sustainable transport strategy covering all fields from vehicle production, new technology research, mobility management to assessment of sustainability in transportation. With the aim at building a competitive transport system that will increase accessibility, remove major barriers in key areas and fuel growth and employment and at the same time, dramatically reduce Europe's dependence on imported oil and cut carbon emissions in transport by 60% by 2050, The White Paper was evaluated and extended in 2011 with these main long term goals to be reached by 2050:

- No more conventionally-fuelled cars in cities.
- 40% use of sustainable low carbon fuels in aviation; at least 40% cut in shipping emissions.
- A 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport.
- All of which will contribute to a 60% cut in transport emissions by the middle of the century [5].

Technology development itself cannot be seen as the only way to achieve sustainable goals in transport due to the fact that one of the key ingredients of transportation management and planning is human behaviour and human values. Nevertheless, technology is an important part that still brings higher added value to the efficiency of transportation systems. The switch represented by (1) substituting conventionally fuelled vehicles by vehicles with alternative fuelling lowering the CO_2 emission such as electric vehicles or vehicle fuelled by biofuel (2) re-design of transport infrastructure (3) smart transport technology are one of the most important aspects of the European strategy. We can pose the following question: How can we manage transport (or mobility in general) more efficiently, using the existing conditions of infrastructure to achieve desirable goals such as lower traffic congestion, air pollution and contribute to lowering the fossil fuel dependency?

Transport Demand Management (TDM), also called Mobility Management refers to policies and programs that change travel behaviour to increase transport system efficiency. These strategies cause various types of travel changes including shifts in mode, destination, time, and frequency of the trips [6]. TDM is seen as a cost effective approach to deal with problems such as traffic congestion, pollution emissions or inadequate mobility for non-drivers. The measures represent usually a large framework of TDM systems which compromise regulatory traffic restriction such as access control or reducing parking space, transport-efficient land use, as well as various measures of transport pricing or incentives. The final goal of TDM is to reduce private vehicle trips, vehicle kilometres travelled and motivate travellers to use the collective and environmentally friendly transportation modes.

In EU, the adopting process of transport policies and strategies has been implemented on local and member-state basis covered by a regulatory framework for all member states. A special emphasis has been given on the development and practice of urban TDM covered by several long-term or short-term projects with different scope of action.

1.5. Process of transport policy implementation

In general, the process of public policy implementation can be simplified to six main steps presented in Figure 1:

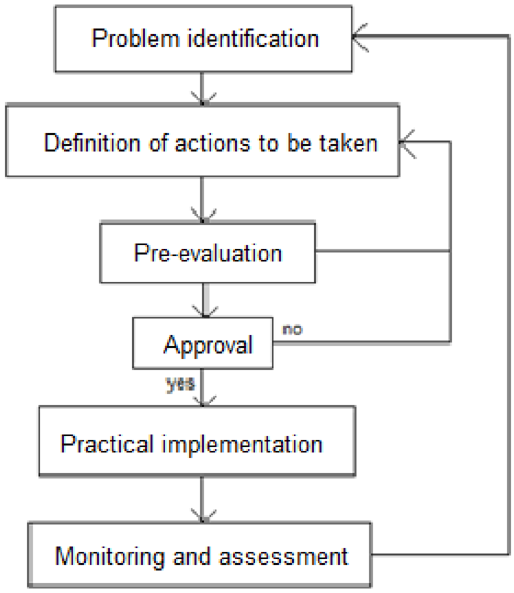

Figure 1 – The process of transport policy implementation

A strategic planning represent a framework crosswise the whole process of policy implementation. Planning is in its basis a futurological technic where goals and the way to achieve those goals are set and evaluated, accompanied by an analysis of risk respecting the economic, environmental and social consequences. Several approaches for strategy analysis and future analysis methods exist, such as scenario technique, forecasting, backcasting or Delphi studies. The frequently used first step in setting goals to develop strategies in sustainable transport is backcasting[1]. Backcasting starts with defining a desirable future and then works backwards to identify policies and programs that will connect the future to the present. The fundamental question of backcasting asks: "If we want to attain a certain goal, what actions must be taken to get there?" [7]. Such tool helps

[1] Frequently used by i.e. United Nations, European Union and Victoria Transport Policy Institute in strategic planning process.

to develop a global framework on which we build scenarios that might be implemented on a local scale (zone, city, greater area, national scale).

However, backcasting does not answer the question of uncertainty of the results on our way to achieve the goals. We cannot predict exactly if a chosen measure provides the desired effect or if it causes unexpected side effects. In transport, backcasting is an important decision making driver, yet forecasting and projection of possible future development and change of traffic still represent a necessary part of the planning process. From the motivation points of this thesis and from aforementioned assumption we can pose another question: How can we test and evaluate traffic reduction policies and their effect on CO_2 emissions, fossil fuel consumption and traffic congestion using modelling techniques before implementing these policies in reality?

To highlight this necessity it could be also stated that the viability of the policy realisations is based on the step number 4 – approval. This step represents a decision making process that includes several stake-holders from public, politic and sector specialist scene dealing with several issues to be addressed on intra-influencing (1) economic, (2) environmental and (3) social spheres. It is clear that the information input for such variety decision makers represents a much broader amount of data than it used to be in the past. For instance, while the government, as a decision maker, might care for the global CO_2 reduction, the transportation specialist will aim to analyse the effects of the policies in the micro spatial traffic assignment as the policy will have micro and macro scope impact on the area. Thus, extension and development of the step three – pre-evaluation of the policy is necessary to provide sufficient information for the decision makers to assure strategic decision.

We can conclude that, the necessity of transport policy assessment extension and new methodologies for impact assessment from policy measures should be developed for more effective transport planning and decision making to reach the social, economic and environmental goals. This conclusion is supported by the fact that sustainability impact assessment for all new major policy proposals in transport, as a tool of improving the quality and coherence of the policy development, was elaborated as a White Paper recommendation of The European Committee of the Regions where the committee recommends:

"..full use be made of assessment methodologies to evaluate the sustainability of new proposals for development or infrastructure. This will ensure that the objectives of spatial planning policies are not undermined by individual decisions which may appear to have pressing merit; the environmental impacts of transport need special consideration and it will be important to implement effectively the EU Strategic Environmental Assessment Directive." (EC, 2002)

2. THE SITE OF THE CASE STUDY

In the following chapters (2.1. and 2.2.) the description of the case study is elaborated with the introduction into the local transportation system and the arising transport demand problems in the region of Coimbra as well as an overview of the sustainable transportation highlights developed by the Municipality of Coimbra and The Municipal Urban Transport Services of Coimbra (SMTUC), in participation with the European project for sustainable urban mobility - CIVITAS.

2.1. The city of Coimbra and its transportation system

Coimbra is a city in the centre part of Portugal. According to the Municipality Directors' Plan Report [8], the city has a population of 148'443 habitants with more than 400'000 habitants belonging to the metropolitan area. The city of Coimbra is one of the most important urban centres in Portugal (right after the cities of Lisbon and Porto), playing a central role in the northern-central littoral and interior of the country. It is the principal centre in the Centre region, the District of Coimbra and the Baixo Mondego sub region. The city is internally connected by an extensive bus and trolleybus network managed and operated by the SMTUC bus service. Coimbra is a hub for interregional bus services for all the country and abroad and has two main rail stations. The principal station

Coimbra-B is on the main line between Porto and Lisbon. From this, a small spur runs to the station of Coimbra, the main station in the city centre. Coimbra is served also by motorway A1 which connects Lisbon to Porto [9].

Everyday mobility in Coimbra is influenced by important commuting movement with reference of 43’461 daily commuters in 2001, where 67% of the trips correspond to work and education trips[2] [10] [11]. Coimbra also represents one of the education centres of Portugal with eight institutions offering higher education for 33’393 students. The University of Coimbra represents the majority, covering 69% of the total students attending higher education[3] [10]. This characteristic contributes to a high level of Coimbra’s non-residential habitants. The most significant volumes of daily commuter have origin in the neighbouring areas with the highest transportation demand from the sub-regions Condeixa-a-Nova, Montemor-o-Velho, Miranda do Corvo, Penacova, Cantannhede, Mealhada and Lousã [10]. The demographic concentration in certain areas also influences the mobility characteristics of the region. In years from 1991 to 2001, a trend of high dispersion of residential areas and higher population concentration in suburban areas of the city of Coimbra has been observed[4] [8]. This along with growing car ownership is one the reason for the growth of the volumes of daily commuters using private car. At the same time, it is estimated that about 69% of daily movements in Coimbra occur only inside the city [11]. The city has about 139,000 daily movements, with demand of 25% for public road and rail transportation companies

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[2] 239% growth since 1990 [10].
[3] 23’133 in 2005
[4] While population of Coimbra grew by 6,8%, some of the neighbouring areas experienced much higher growth: Miranda do Corvo – 11,9%, Condeixa-a-Nova – 17,8%, Mealhada – 13,6 [8].

2.2. The city of Coimbra and steps towards more sustainable transportation

The Municipality of Coimbra identified the importance of reducing the dependence on private vehicles in order to reduce traffic congestion and improve air quality [10]. In the presentation of the project CIVITAS Modern (Mobility Development and Energy Use Reduction) of which Coimbra is part. It is stated that individual transport (IT from now on), mainly the car, is the most common transportation mode in Coimbra. This fact, accompanied by the high IT traffic demand result in daily traffic congestion, lack of parking places, accessibility deficiency, negative effect on alternative modes of transportation such as PuT, higher pollution in the city and overall higher energy use [11].

After The Municipality of Coimbra formulated The Strategic Plan of Coimbra in 2007 [10], the city of Coimbra became a member of CIVITAS[5] in 2008 and developed a more sustainable transportation city plan. The city has made efforts to improve the PuT system and provide incentives for more sustainable modes of transport such as: exploring alternative fuel choices, local production of renewable energy for trolleybus lines, promote an info-mobility centre and mobility marketing, safety oriented driving training, new ticketing system, public inclusion, feasibility study of new mobility services and info-mobility tools for traffic data management [12]. With these measures, the city of Coimbra wants to achieve following goals:

- To raise the municipal employees portion commuting with PuT by 1%.
- To reduce in 0.4% the number of municipal employees that travel by private car.
- To implement at least 3 mobility plans for big institutions in the area of Coimbra (HUC and University Campuses).
- To improve the quality of the urban environment.
- To limit and reduce levels of atmospheric pollution.
- To encourage the change to less pollution vehicles.

[5] The CIVITAS is a EU project and was launched in 2002. Its fundamental aim is to support cities to introduce ambitious transport measures and policies towards sustainable urban mobility.

This plan aims to identify the most recent evolutions in urban mobility and the development of more adequate policies which can be more successful in the struggle against the urban instability affecting every modern town. With the guidance of the Municipality, the SMTUC will develop mobility plans for hospitals (including campaigns for PuT, carpooling, ticket discounts, etc.), during CIVITAS and for the main companies or services established in the region [13].

Majority of these incentives represents PuT improvement or marketing for introducing the notion of sustainable transportation needs to the general public. The identification of traffic reduction policies such as carpooling incentives, parking policy, urban road toll as an instrument of reaching the goals had so far a scarce attention in the plan. This and the strategic assessment methodology of the measures already implemented do not play a role in the programme and call for an attention and further development.

3. METHODOLOGY

3.1. Transport demand models, TDM policy modelling and estimation of CO_2 emissions

Models are simplified representations of reality which can be used to explore the consequences of particular actions. The reason for using models is that quantified estimates can be made of likely outcomes more quickly and at lower cost and risk than would be possible through implementation and monitoring. Models can also be used:

- To identify improvements to support growth;
- To understand the impacts of development;
- To evaluate the benefits/costs of infrastructure investments;
- To understand the impacts of socio-economic policies [14].

Currently, there are transportation models based on three scales of detail. (1) Macro model is used for network or area-wide analysis. This type of model allows the transport demand forecasting. It represents the transport demand for different modes of transportation based on an assumed transport model. Travel demand estimation is based on the travellers decisions on how, where and when to travel. These decisions are affected by many factors such as family situation, characteristics of the person making the trip, and the choices (destination, route and mode) available for the trip. Mathematical equations are used to represent these decision making processes, i.e. model human behaviour in making choices/decisions. Models are calibrated and validated to match existing data. They require a set of assumption to run and are limited by the input data available to make forecast and the limitation in reflecting human behaviour. (2) Meso models are used for sub-area or corridor analysis. (3) Micro models are used for link or intersection analysis. These two models (both meso and micro model) focus on the trip assignment step. They require high detail of the network such as geometric design, traffic signal timing, transit signal priority measures, and vehicle (driver) behaviour. They are used to analyse the operation details of road and transit segment.

The above mentioned models are used widely in practice for analysis of the impact of several transportation policies with different configurations and level of detail [15]. Yet the opinion on accuracy of these techniques varies among the users. There are various opinions in the current literature that macro models can hardly realistically represent the effect of transport demand policies and more microscopic studies are necessary such as studies of professor Mikel Murga [16] . The exhaustive collection of microscopic data is not always possible due to many reasons[6] however it might be possible in the future due to automatic collecting of travel data via GPS.

However, current development and new features of modelling of macro models in software offer flexible and detailed scenario construction and can provide valuable results for decision making when implementing a transport policy measures. In practice this means that policy issues are increasingly being addressed in an integrated approach in evaluating the sustainability impacts of policy plans, programmes or projects. Mott MacDonald and co. (2005) defends and applies the use of macro model policy testing as a necessary supplement of the transport policy assessment. In their study, the authors claim that “in order to estimate the true impact of transport scheme, both macro and micro level effects need to be modelled, quantified and analysed” [17]. This fact was presented at a case study for Swanswell area, England, where the effect of new road infrastructure design was tested on a macro strategic level as well as micro level. The transport model of studied Swanswell area was elaborated in software VISUM and was utilised using the new software developments to apply the route choice and demand elements, as generated by the macro/strategic level traffic assignment package. The strategic implications of the proposed developments were then studied in more detail (at the micro level) using VISSIM. It was modelled as two tier integrated approach between macro and micro simulation with cyclic manner of calibration between these two models. The key objective of using two different modelling formats was to review the traffic impacts of a specific

[6] i.e. short time period for the collection of data, the lack of data from the past, few fund resources.

scheme: (1) Macro/strategic modelling - used to review the strategic impact of developments on routing and path choice of traffic; (2) Micro simulation modelling - used to review the operational aspects of the proposed and existing infrastructure, including traffic signals, capacity and downgrading of Ring Road, bus infrastructure and the operation of car park [17].

Franklin and co. (2002) developed an approach to a policy sensitivity analysis for an integrated land use and travel demand model system being developed for the Wasatch Front area of Utah. The project integrated the UrbanSim land use model system with a four-step travel model that had incorporated non-motorized modes. The sensitivity analysis examined the effects of specific transportation and land use policies on various indicators of traffic operations, mobility, and accessibility levels, and on land consumption and patterns of urban development [18].

J.M. Armstrong and A.M. Khan (2004) developed a methodology with intention to assist the decision-making process for reducing vehicle emissions in urban areas using geographic information systems. The paper presented methodological framework that is required for analysing the emission implications of measures that are intended to reduce vehicle emissions in urban transportation. The methodology was applied in a case study for National Capital Region in EMME/2[7] [19].

The estimation of CO_2 and traffic volume reduction potential of transport demand policies is a relatively new field. Markus Robèrt and co. (2005) used backcasting, where forecasting is applied to derive concrete states and paths in the backcasting framework to analyse a range of specific transport policies and fuel technology related developments with respect to the emission target. Based on this, the testing of the policy reduction potential for CO_2 and traffic volumes will be a strategic planning process where the modelling of tested policies for the forecast will be influenced by targets set by the backcasting method. The transport demand model SAMPERS[8] was used to generate the demand for each policy setting. The travel demand was assigned to a network with

[7] Travel demand forecasting system
[8] The Swedish National Travel Demand Forecasting Tool

EMME/2. The effects from the transport system in terms of emissions and accidents are based on the flow, the vehicle speed, and the vehicle type, on each individual road link [20].

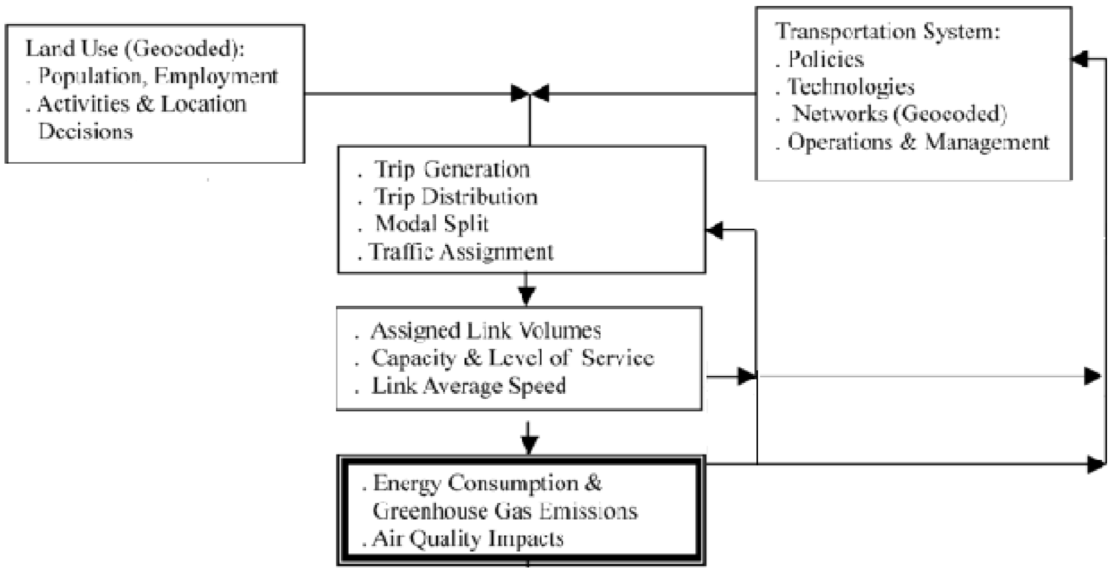
Ana Ferreira (2012) in her master thesis estimated and geographically projected GHG emission from the traffic in the transport demand model developed for the city of Coimbra in software VISUM 12.0. The calculations were based on the Handbook Emission Factors for the Road Transport 3.1 and they took into account the traffic situation, volumes and fleet composition, as well as speed and individual road link characteristics such as slope. Additionally, her conclusion that one of the most significant contributors for the GHG emissions from private vehicles in the city of Coimbra are road slopes and traffic situation were considered when modelling the policies and analysing the results [21].

3.2. The methodology framework

The methodology framework was adapted from J.M. Armstrong and A.M. Khan (2004). The original framework was adjusted for this case study (see Figure 2). It was structured as cyclical calibration of measures tested in the software VISUM 12.0 while the estimation of economic factors and evaluation of system alternatives were excluded due to the limited size of the thesis but could be elaborated in future studies.

The modelling of the policies was based on the empirical results from another studies, guidelines of European Commission and the Municipality of Coimbra for the strategic transport planning and management and mainly based on the detailed study of the modeled infrastructure in the SMM Model which helped to identify the main areas for policy intervention. The detailed study of the model structure helped to identify the possibilities and limitations when modelling the policies.

Figure 2 - The context of emissions estimation in urban transportation planning



Adapted from [19]

3.3. Software VISUM 12.0

Software VISUM 12.0 from company PTV AG is a comprehensive, flexible software system for transport planning, travel demand modelling and network data management. VISUM is used on all continents for metropolitan, regional, state wide and national planning applications.

Designed for multimodal analysis, VISUM integrates all relevant modes of transport (i.e., car, car passenger, truck, bus, train, pedestrians and bicyclists) into one consistent network model. It uses link and junction level speed flow relationships to estimate the travel time on links based on traffic demand and road capacity. VISUM provides a variety of assignment procedures and 4-stage modelling components which include trip-end based as well as activity based approaches [22] [17].

3.4. Transport demand model for the city of Coimbra

The University of Coimbra was kindly provided with an access to the best and recent transport demand model for the city of Coimbra - The SMM Model (in original

Modelo de Planeamento de Transportes do Sistema de Mobilidade do Mondego). The model was developed by Metro Mondego, S.A and TIS - Consultores em Trasnsportes, Inovação e Sistemas, S.A. with cooperation of PTV AG who developed the software: VISUM 12.0 in which the model was built.

Geographically, the model represents the city of Coimbra and the surrounding region in order to describe the internal trips in the city and trips to or from the neighbouring municipalities. Of these, the degree of detail is higher for the municipalities of Miranda do Corvo and Lousã (covered by the future light rail) Idanha-a-Nova and Condeixa-a-Nova (the municipalities with one the highest volumes of commuting to Coimbra). The model considers also trips outside of Coimbra (e.g. internal travels of Figueira da Foz or between Figueira da Foz and Cantanhede). The geographical area is divided into two main areas:

- Internal Area (IA): all the 26 municipalities covered by the Mobility Survey 2008 (See Figure 3)
- External Area (EA): outer region.

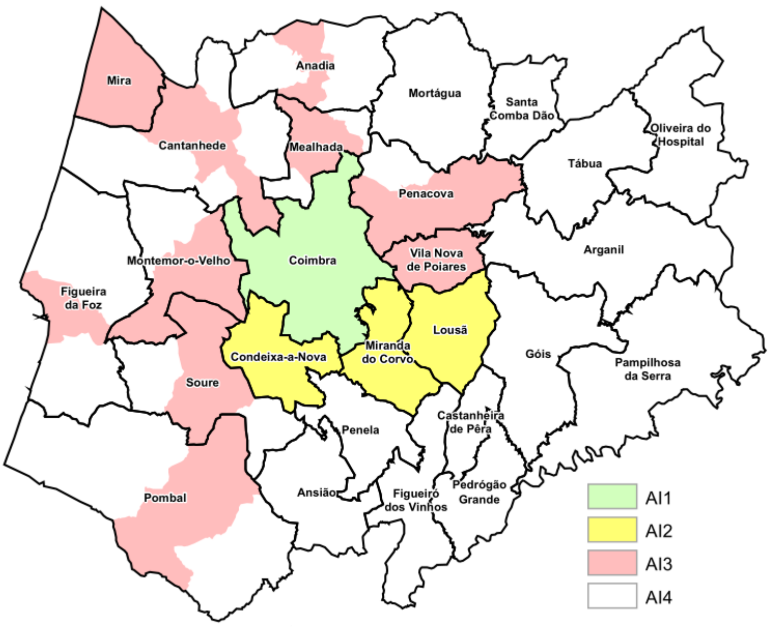


Figure 3 – Municipalities of the internal area of the model [23]

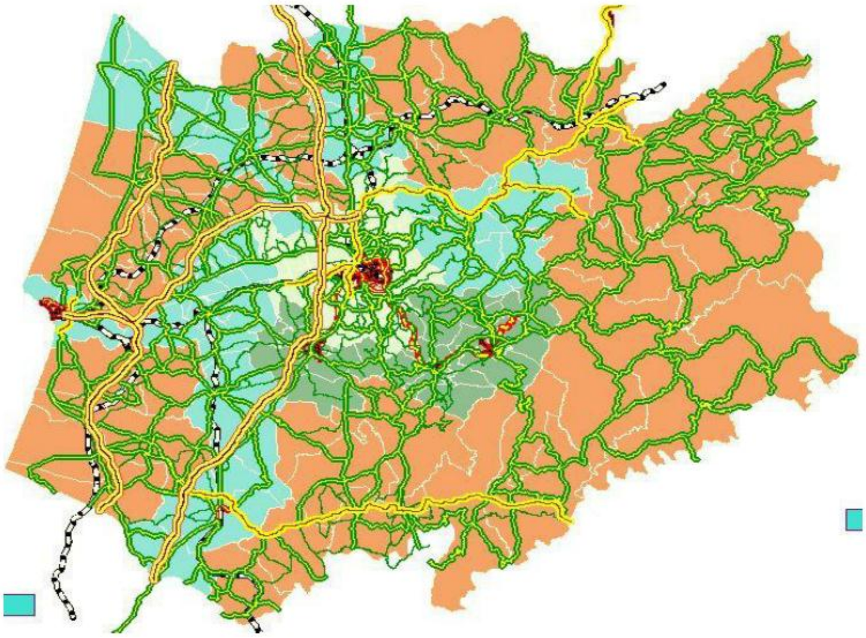


Figure 4 – The SMM model in VISUM 12.0

The SMM Model is a macro model and allows demand estimations of the traffic status in the transport networks for a 24 hours period of an average uneventful working day (AP from now on), traffic flows on the road, network and passenger flows in transit networks, the supply of IT networks and PuT and also transportation costs.

It has the following general characteristics [23]:

- It is a model of strategic planning, to support the sizing of IT networks and PuT networks , with possibility to analyse (1) short term and long term future (2) mobility and transport policies, including investment in new roads or lines rail, intermodal integration of PuT, PuT tariffs, supply and pricing of parking.
- It is a multimodal model that predicts the shifting between IT and PuT and demand and revenue of PuT operators, road network and rail network.

- Technically, the model was developed on the "four steps" principle of traffic modelling and was implemented in software Visum 12.0.

The function of the transport demand model is to calculate the equilibrium that results from a given situation in the activity and the transport system – equilibrium of demand and supply in transport system. The scale, at which traffic services are used, such as the volume of traffic on a road and the number of train passengers on a given route, arises from a number of choices that are made by IT users:

- The choice whether or not to travel
- The choice of the time of departure
- The choice of destination
- The choice of transport mode
- The choice of route [24]

After the zoning of the study area, each zone is an origin or a destination of the trips as the outcome of aforementioned choices in transportation network. These choices are implemented in model that has four sub-models or as aforementioned “four steps”:

The following Figure 2 represents the structure of these four steps developed in VISUM 12.0, with detail in the input and output steps for each stage of the process, as well as the cyclical calibration for the route assignment:

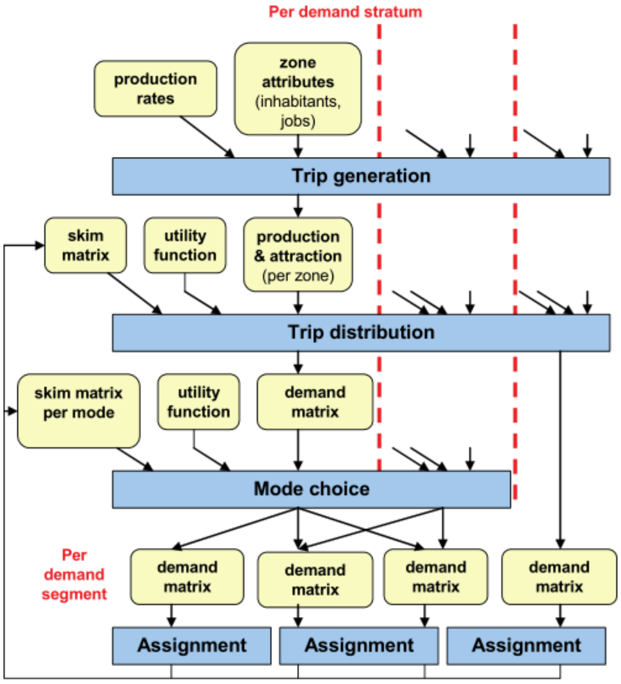


Figure 5 – Structure of the four steps transport demand modelling in VISUM 12.0
Source: [25]

Trip generation determines the frequency of origins or destinations of trips in each zone by trip purpose, as a function of land use and household demographics, and other socio-economic factors. The zone attributes for the population were obtained via Inquérito à Mobilidade na Área de Influência do SMM in 2008 (Mobility Inquiry for the Area of Influence of the SMM, 2008) and the data were developed by Metro Mondego, S.A in 2008 using data from the Ministry of Work and the Ministry of Finance. The demand was segmented into nineteen different population segments combined with seven different trip motifs and three types of households with different car ownership [25] [23].

Trip distribution matches origins with destinations. In the SMM Model, to calculate the number of trips between two zones, the Gravity Model was applied and formulated as:

$$\mathrm{Tij} = \mathrm{Pi} * \frac{Aj*Fij}{\sum k\ Ak*Fjk} \tag{1}$$

Where:

Tij – number of trips between the zones i and j

Pi – trip production of zone i

Aj – trip attraction of zone j

Fij – impedance between zone i and j

k – all route links

The calculation of the impedance between zones was formulated as an exponential function:

$$Fij = e^{(cUij)} \tag{2}$$

Where:

c – constant

Uij – utility or derived costs [23] [25]

In the case of the SMM Model, the utility is derived from the travel time of IT in free traffic flow. Consequently the model was calibrated by the constant c for different demand segments and car-ownership rates [23]. In the following Figure 6 and Figure 7, the sensitivity of Fij and the probability choice (Fij/∑Fjk) on the constant c variation is shown:

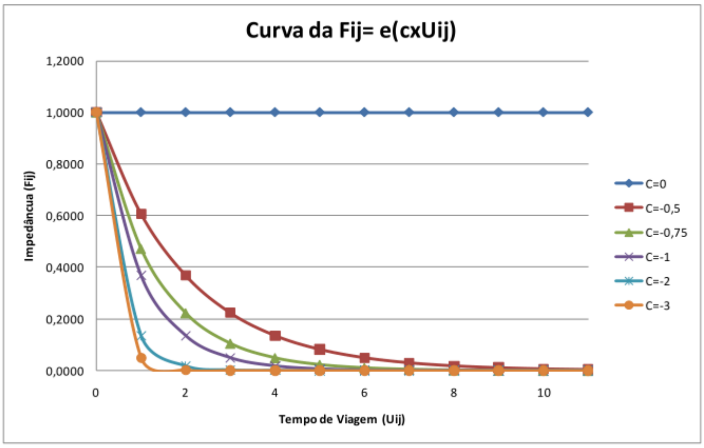


Figure 6 – The curve comportment for the impedance of the trip distribution [23]

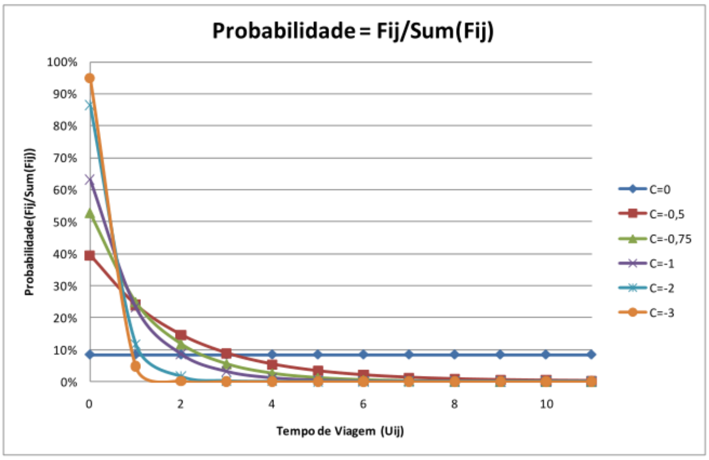


Figure 7 – The curve comportment for the probability of the route choice [23]

Mode choice computes the proportion of trips between each origin and destination that uses a particular transport mode. The SMM Model incorporated four different modes: private car, PuT, motorcycle and walking. For mode choice calculation, the multinomial Logit model was formulated as following:

$$Tijm = Tij * fijm \qquad (3)$$

When:

$$fijm = \frac{\exp(Uijm)}{\sum k \exp(Uijm)} \qquad \text{and} \qquad k \in M \qquad (4)$$

And where:

M – set of alternative modes

Tijm – number of travels between zone i and j by mode m

fijm – probability of the choice of mode m

Uijm – utility of mode m [23] [25]

Utility of each mode used in the SMM Model was formulated separately considering a different set of variables: (1) the PuT mode takes into account travel time (in-vehicle time and off-vehicle time such as waiting for transfers and walking to the bus stop), number of transfers between the specific OD pair, advantage of connection to rail roads, travel costs and calibration constant for the PT developed by the Metro Mondego, S.A. (2) the private vehicle mode takes into account travel time (journey travel time and time to access and park the vehicle), costs (operational costs per km, road toll, parking costs) and calibration constant for IT mode (3) motorcycle mode utility function includes travel time, operational costs, toll costs and calibration constant for motorcycle mode and finally (4) walking mode takes into account walking time and calibration constant for walking.

Cost variables were expressed in the value of time which was set equal for all the modes. The calibration constant was set for each mode and demand segment individually using data from IM 2008 [23].

Route assignment allocates trips between the origin and the destination to a route by a particular mode. For the individual transportation (IT) mode the static Equilibrium Lohse method was applied. This method has the advantage of producing a realistic stable matrix with ensured good distribution of volumes between the alternative paths. It is based on a search of several shortest paths in an iterative process (see Figure 3.3-3) where they are chosen and ordered by route impedance as:

$$C = L * Co + T * Vt + L * P \qquad (5)$$

Where:

C – total costs

L – arc length (km)

Co – operational costs (€/km)

T – travel time

Vt – value of time

P – toll costs/km (€/km) [23] [25]

For the PuT mode, the method for route assignment calculation was applied as "time-table based" with the bus schedules of exact times of departures and arrivals. The main advantage of this method is the possibility of interconnection between other lines of PuT transportation and incorporation of the ticket costs in the impedance formula. The impedance was defined as:

$$imp = \alpha * tpv * \beta * far * \gamma\Delta T(early) * \delta\Delta T(late) \quad (6)$$

Where:

Imp – impedance

α – coefficient

tpv – perceived travel time

β – coefficient

far – fare costs

γ, δ – coefficients

ΔT – ABS (desired departure time – actual departure time) [25] [23]

3.4.1. Estimation and projection of CO_2 emissions in the SMM Model for the City of Coimbra

Software VISUM 12.0 offers an add-on module that allows calculating emission values by link, by territory and network. The calculation is based on the Handbook Emission Factors for Road Transport (HBEFA from now on) version 3.1 (INFRAS, 2010).

In HBEFA, the basic approach for calculation of grams of emissions per km is composed as:

$$Emissions\ \left(\frac{g}{km}\right) = Traffic\ volumes\ (vehicles) * Emission\ Factor\ \left(\frac{g}{vehicles * km}\right) \quad (7)$$

In the following Figure 8, the calculation process of HBEFA in VISUM 12.0 is presented:

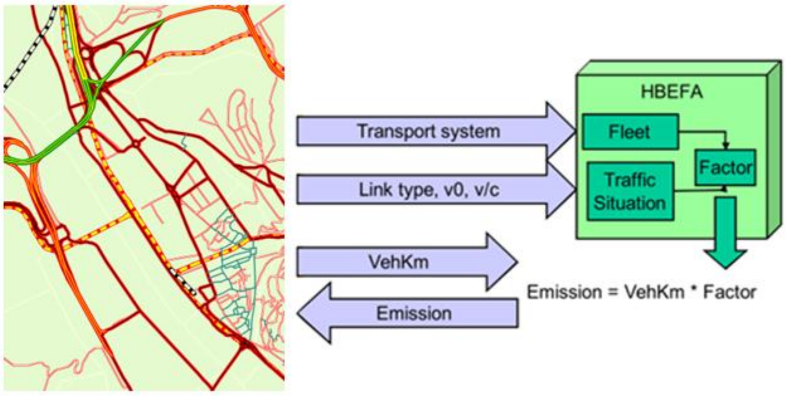


Figure 8 – The HBEFA calculation process in VISUM 12.0 [21]

As software VISUM 12.0 calculates the traffic volumes per each link, this serves as an input into the aforementioned equation 7. In the same time, the emissions can be calculated for one or several demand segments [25].

The methodology of the case study for the city Coimbra, which also include the creation of the fleet composition, estimation of vehicles per kilometre of each link and subsequently the emission factor was developed and applied in the SMM Model by Ana Ferreira [21] and used in this master thesis. The results presented in Ana Ferreira's work are for total CO_2 emissions[9] and subsequently road assignment for average CO_2 emissions per km per each vehicle[10]. For a CO_2 emissions road assignment analysis, in this thesis, the CO_2 emissions grams per km of each link were extracted to create and analyse the maps with the highest CO_2 emission potential.

Based on the projection of highly polluted areas, some of the policy scenarios were developed and applied in the SMM Model (see Chapter 4.4). Subsequently the same emission calculation methodology and graphic projection was used to study the effect of the policies with regard to CO_2 emissions in the city of Coimbra.

[9] Grams (g)
[10] Grams per vehicle per km (g.veh.km)

3.5. Choice of the TDM policies tested in the SMM Model

Originally, the creation of the SMM Model was initiated as a project to map the state-of-art of the current situations of the transport demand in the region of Coimbra and develop a comprehensive future model as a support decision making tool for implementation of the light rail transit connecting Serpins and Lousã to Coimbra B and then this line to the Hospital of the University of Coimbra (HUC from now on).

It was aimed to project the possible future transformation of the transport demand and mode choice after the implementation of the light rail transit. Apart from this, some traffic reduction policy strategies have been tested as the future scenario.

1. Collective transport network:
   - Implementation of the complete network of Metro Mondego
   - Reorganization of the SMTUC network as second proposal of the preliminary SMM Model.
   - Discontinuing of train services of Comboios de Portugal on route Lousã (Serpins-Park) and replacing the service with Metro Mondego on connection Coimbra B - Coimbra.

2. Collective transport pricing tariffs – Introduction of mono-modal pricing tariff of Metro Mondego and bimodal pricing tariff for Metro Mondego and the SMTUC based on tariff study of SMM in 2010
3. IT parking costs – Extension of the paid parking areas surrounding the line of HUC including the University.
4. IT operational costs – Increase of 30% of the driving cost per km after 2008, due to the expected increase of oil prices, not offset by improved efficiency of engines [23].

In aiming for more strategic planning to fulfil the goals of EU and The Municipality Strategic Plan of the City of Coimbra, further policy scenarios were developed in this thesis based on this framework of principles:

1. To target the most polluted and congested areas (roads and zones) of the city of Coimbra – After detailed analysis of areas with the highest emission volumes or highest volumes per road capacity ration, a scenario of policy interventions was developed and the sensitivity of the SMM Model on it was tested. Based on the critical zone identification, the chosen policies and incentives are:
   - Increase of parking prices and extension of paid parking area
   - Urban road toll pricing
   - Improved quality of PuT

2. To target the daily commuters to work and school – After the study of the commuting traffic volumes in Coimbra in the Municipality Strategic Plan of the City of Coimbra and with its verification in the SMM Model's traffic assignment, the effect of carpooling incentives was modelled. The effect on the origin-destination (OD from now on) pairs with highest commuting demand[11] was analysed and commented.

To sum up, based on these principles, the following transport policies were tested:

- Effect of parking price increase and more complex parking scenarios
- Effect of carpooling incentives
- Effect of urban road toll pricing
- Effect of the improvement of the PuT system.

[11] Strategic trip origins – Condeixa-a-Nova, Montemor-o-Velho, Miranda do Corvo, Penacova, Cantanhede, Melhada and Lousã; Strategic trip destinations – Alta, university campuses, Hospital of the University of Coimbra, Arcos do Jardim Bôtanico, BairroAlto

3.6. Choice of the studied traffic outputs

The change of the following aggregated or/and road assigned traffic outputs were analysed for the analysed period of 24 hours of a normal non-eventful working day - AP. Following lists represents these outputs:

1. Aggregated traffic outputs for the city of Coimbra:
   - IT traffic volumes (in vehicles per kilometre)
   - Aggregated total CO_2 emissions (in grams)
   - Aggregated total fuel consumption (in grams)
   - Aggregated total diesel consumption (in grams)
   - Aggregated total gasoline consumption (in grams)
   - Demand for the PT (in number of passengers[12])
2. Traffic outputs assigned to a link with graphical demonstration:
   - IT traffic volumes per road capacity (in percentage)
   - CO_2 emissions per kilometre (in grams per kilometre)

Additionally, for the carpooling incentives, the amount changes of the trip origins or the trip destinations in chosen zones were analysed with the aim to address commuting IT volumes.

[12] VISUM accumulates the number of passengers for each ride separately. Example: If a person travels from Cantanhede to the university campus and make 2 transfers, this is counts as for 3 passengers – 1 in the train, 1 in the bus line no. 7 and then in the bus line no.34.

4. MODELLING THE TDM POLICIES IN THE SMM MODEL

4.1. Modelling the parking policy

In the SMM Model, the parking costs are modelled as costs of parking tied to a zone and demand segment as well as to the purpose of the trip. The parking costs enter in the preparatory calculation to calculate the parking costs matrix for each OD pair and subsequently the value for each OD pair is used as a variable in the calculation of the utility function for the IT mode in step 3 – Mode Choice.

In the original scenario based in 2008, a cost of 0.5 Euro per hour for private vehicles was applied and this was done for two types of trip purposes:

1. Home-work-home trips (HW trips from now on), where parking in a zone of work was set for 8 hours period and
2. Non-home based trips (NH trips from now on), where parking in a zone of other activities was set for 1.5 hour period.

It is important to note that the price change is tangled to a specific zone and separate pricing scenario for different trip purposes was not possible in the SMM Model.

4.1.1. Scenarios for parking costs variation

Initially, testing the sensitivity of the SMM model for changing the parking prices was set as testing the effect of following parking fee variations: 0.5 €/hour, 1 €/hour, 1.5 €/hour, 2 €/hour, 2.5 €/hour, 3 €/hour, 3.5 €/hour and 4 €/hour parking fee. Based on the sensitivity results a complex parking policy scenario was developed and tested. The detailed description is provided in the following Chapter 4.1.2.

4.1.2. Scenarios for different parking policies

To test the sensitivity of the SMM model for different parking policy scenarios, combination of price, extension of charged areas and percentage of free parking for HW trips was combined into different parking policy scenarios. Table 2 represents the detailed overview of six different parking scenarios developed and tested in the SMM Model with six different scenarios.

4.1.2.1. The parking fee change

In these scenarios, the parking fee changes only up to 1 €/hour. This value was estimated due to average parking prices in Lisbon and Porto, considering that in a real world and nearby future this real value would not be higher for the city of Coimbra.

4.1.2.2. The extension of charged parking areas

As mentioned above, in the SMM Model, parking was modelled based on trip purpose and applied for the zone. The zoning of the city of Coimbra was already modelled with the intention of strategic zoning so the creation of new zones in the SMM Model was not necessary. Additionally to the zones that had been already charged with parking fee, 10 more zones were included. They were chosen due to their trip destination demand, mainly for the commuting purposes by HW and HU trip purpose. These zones were chosen after a detailed study of the final OD matrix for these segments in the SMM Model.

4.1.2.3. Reduction of free parking for home-work based trips

Some zones with the parking fee were already modelled with a portion of free parking for some HW trips in the original model. For purposes of traffic reduction policy scenario extension, it was suggested that possible reduction of free parking for HW trips would be tested as well. This option was already considered in the 2008 scenario for the SMM model and was extended for the further testing of additional zones.

Table 1 – The parking policy scenario overview

Zone	Zone no.	Parking fee							% of free parking for HW trips						
		2008	S 1	S 2	S 3	S 4	S5	S6	2008	S 1	S 2	S 3	S 4	S5	S6
Parque	12	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	80%	80%	50%	20%	80%	50%	20%
Portagem	17	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	70%	70%	50%	20%	70%	50%	20%
Fernão de Magalhães	74	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	70%	70%	50%	20%	70%	50%	20%
Câmara	75	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	75%	75%	50%	20%	75%	50%	20%
Mercado	76	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	80%	80%	50%	20%	80%	50%	20%
Açude	80	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	70%	70%	50%	20%	70%	50%	20%
Loja do Cidadão	83	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	70%	70%	50%	20%	70%	50%	20%
Cruz de Celas	88	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	75%	75%	50%	20%	75%	50%	20%
Praça da República	139	0.50 €	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €	80%	80%	50%	20%	80%	50%	20%
Alta (Norte)	9	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		75%	50%	20%	75%	50%	20%
Alta (Sul)	10	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		75%	50%	20%	75%	50%	20%
UC Pólo I	11	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		75%	50%	20%	75%	50%	20%
HUC / UC Pólo III	84	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		100%	50%	20%	100%	50%	20%
Bairro de Celas	85	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		73%	50%	20%	73%	50%	20%
Penedo da Meditação	86	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		90%	50%	20%	90%	50%	20%
Hospital Pediátrico	107	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		100%	50%	20%	100%	50%	20%
Arcos do Jardim	143	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		79%	50%	20%	79%	50%	20%
UC Pólo II	123	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		50%	50%	20%	50%	50%	20%
Jardim Botânico	13	-	0.50 €	0.50 €	0.50 €	1.00 €	1.00 €	1.00 €		50%	50%	20%	50%	50%	20%

4.2. Modelling the carpooling incentives

Based on various studies and results from case studies presented in the study of Todd Litman, carpooling incentives might influence up to 30% of commuters to change their travel behaviour and turn to sharing a car while commuting [6].

In the SMM model, the car occupancy rate is modelled and assigned to the purpose of the trip and applied only after mode choice (step 3) to calculate the traffic assignment (step 4) for the IT mode. In the following Table 2, an overview of base rates for the car occupancy applied in the SMM model is presented.

Table 2 – The car occupancy rates in the SMM Model for different segment and car ownership in the original scenario 2008

	HW	HS	HE	HU	HH	HO	NHB
Household 1 car	1.45	1.68	2.23	1.68	1.99	1.62	
Household 2 cars	1.19	1.53	2.13	1.31	1.71	1.44	
All							1.43

Source: [23]

HW– trips home-work-(shopping)-home; HS – home-shopping-home; HE – home-school-home; HU – home-university-home; HH – home-hospital-home; HO – home-other-home; NHB – non-home based

To be able to test the effect of carpooling incentives and its effect on the chosen traffic outputs, it was necessary to assume that these incentives were successful. The scenario is purely fictional mainly due to the fixed modelling of occupancy in the SMM model rate as it is not possible to change the car occupancy rate via the utility function. As every model, the representation of reality is not perfect and the relationship of mode choice – car occupancy rate is linearly modelled. To target the commuting demand segment only, the four scenarios were modelled and it was assumed that 5%, 10%, 20% and 30% of all trips with purpose to HW and home-university (HU from now on) would be reduced. Thus the occupancy rate was adjusted and the whole four step modelling process was updated to obtain the results.

The following Table 3 provides an overview of four different scenarios with the occupancy rate variation tested in the SMM Model.

Table 3 – The car occupancy rate variation for modelled scenarios

		HW	HS	HE	HU	HH	HO	NB
S1	CO1 -5%	1.53	1.68	2.23	1.77	1.99	1.62	1.57
	CO2 -5%	1.25	1.53	2.13	1.38	1.71	1.44	1.38
S2	CO1 -10%	1.60	1.68	2.23	1.87	1.99	1.62	1.57
	CO2 -10%	1.32	1.53	2.13	1.46	1.71	1.44	1.38
S3	CO1 -20%	1.81	1.68	2.23	2.10	1.99	1.62	1.57
	CO2 -20%	1.49	1.53	2.13	1.64	1.71	1.44	1.38
S4	CO1 -30%	2.10	1.68	2.23	2.40	1.99	1.62	1.57
	CO2 -30%	1.70	1.53	2.13	1.87	1.71	1.44	1.38

4.3. Parking policy and carpooling combination

To test the reaction of the model and the change of the mode choice and traffic assignment, the combination of two different TDM policies was tested. The scenario values were changed for parking policy as well as for the carpooling scenario and the overview of the policy scenarios is pictured in Table 4. For more details about used scenarios see Table 1for parking and Table 3 for carpooling.

Table 4 – The scenario overview for parking and carpooling policy combinations

Combination S1	Parking policy - Scenario 5, Carpooling – Scenario 1
Combination S2	Parking policy - Scenario 5, Carpooling – Scenario 2
Combination S3	Parking policy - Scenario 5, Carpooling – Scenario 3
Combination S4	Parking policy - Scenario 5, Carpooling – Scenario 4
Combination S5	Parking policy - Scenario 6, Carpooling – Scenario 4

4.4. Modelling the road tolling policy

The software VISUM 12.0 allows to model individual toll fees for separate links. That means that a toll can be applied to a road, part of a road or only one direction of a road or part of it. Such high detail of modelling allows to create a strategic and detailed policy scenario and to analyse its effect on the mode choice and subsequently road assignment in the macro model. A toll cost enters in the traffic modelling process in the mode choice (step 3) where it acts as a variable influencing the utility function which is used to calculate the probability of a choice of a specific mode.

To test the sensitivity of the SMM model to this policy, a strategic road tolling policy was created. It targets the areas with the highest CO_2 emissions per km (adapted from Ana Ferreira, 2012 [21]) and the links with the highest volume per capacity density (adapted from the SMM Model) in the city of Coimbra. Thus, Rua da Sofia, Rua de Aveiro, Rua do Brasil, Avenida Professor Gouveia Monteiro, Ponte do Açude and Ponte Rainha Santa Isabel were tolled with fee scenarios of 1 Euro, 2 Euros and 3 Euros toll fee variation. The goal was to provide a restriction in the access to the city centre as well as target the most polluted or congested roads. The reaction of the SMM Model in the mode choice and in the traffic assignment was studied as both of them could be influenced.

4.5. Modelling the public transportation improvements

Modelling the PuT improvements was the most complex single policy adapted in this master thesis. The goal of this scenario was to test the sensitivity of the SMM Model on improvements of the speed of PuT modes and cheaper fare conditions considering both sub-urban and urban bus lines. Just as previous cases, the switch to PuT from IT mode is affected in step 3 – the mode choice, where costs and travel time enter as variables in the PuT utility function in the mode choice.

This policy was modelled as a combination of 10% lower fare for suburban connections, 10 cents discount on transfer fare[13] for the SMTUC urban network and 20% reduction of travel time for all PuT modes[14]. Such changes represent only slight

[13] Originally, the start fare was set as 0.50 € and every additional transfer fare was modelled for the same amount. In the new scenario, each transfer fare was set as 0.40 € fee.
[14] SMTUC urban network, sub-urban buses and train.

modification and were modelled assuming that the PuT network would not go under restructuration or significant changes in reality.

4.6. Testing the complex TDM policy in the SMM Model

Based on the results from individual TDM policy scenarios, the final complex scenario with possible realistic measures was designed combining the parking, urban road tolling policy with the carpooling incentive and PuT improvement. It was modelled as the scenario 6 for the parking policy[15], scenario 1 for the carpooling incentives[16] and scenario of 2 Euros road toll in some urban roads[17]. The aggregated results of the analysed traffic outputs as well as the geographic CO_2 emissions and congestion assignment are analysed in chapter 5.7

[15] 1 Euro fee, extended charged area, only 20% of the home-work trips are free
[16] 5% reduction for home-work and home-university trips by the IT
[17] Rua da Sofia, Rua de Aveiro, Rua do Brasil, Avenida Professor Gouveia Monteiro, Ponte de Açude and Ponte Rainha Santa Isabel

5. RESULTS

In this chapter the results with relevant commentary are provided. The change of following aggregated or link assigned traffic outputs were analysed for the period of the analysed period AP – 24 hours of a normal non-eventful working day.

Figures 9 and Figure 10 represent the sets of maps showing the geographical projection of CO_2 emission road assignment and traffic volumes per road capacity ration from the original traffic estimation for year 2008 in the SMM Model in VISUM 12.0. These maps served as reference situation in the city of Coimbra after applying an individual TDM policy or their combinations.

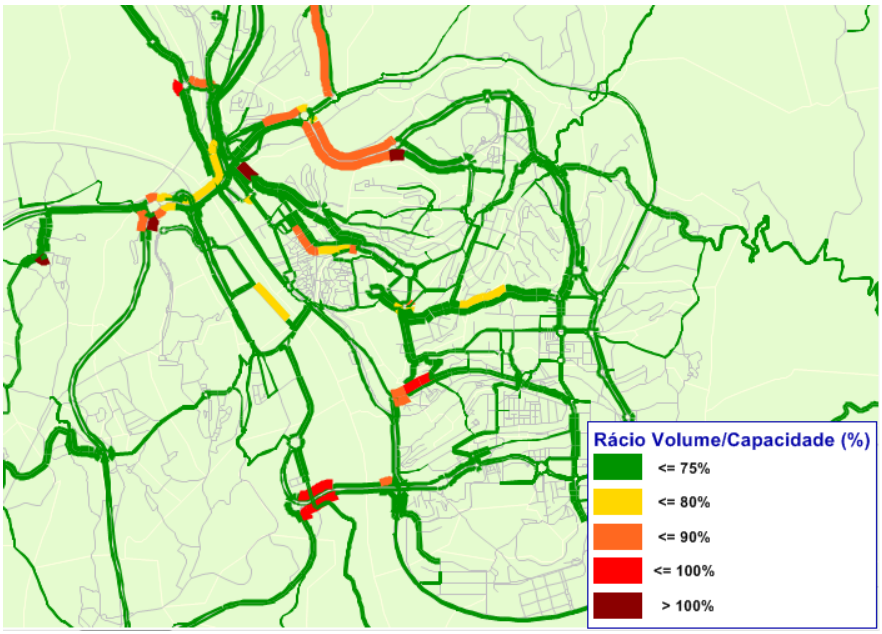


Figure 9 – Traffic volumes per capacity ration assignment for the city of Coimbra in the original SMM model for 2008

Figure 10 – CO_2 emission link assignment for the city of Coimbra in the original SMM model for 2008

5.1. Results for the parking policy scenarios

5.1.1. Parking costs variation

In this chapter the effect of the parking costs variation on the reduction of CO_2 emission, vehicle volumes, total fuel consumption, gasoline consumption and diesel consumption for the city of Coimbra is presented with the results in Table 5. Based on changing the price for already charged parking zones, it was possible to obtain the different traffic outputs of tested indicators.

As initially expected when modelling the policy in the SMM Model, higher parking costs resulted in a reduction of vehicle volumes with direct effect on lower fuel consumption and CO_2 emission. The vehicle volumes reduction is slightly higher while the CO_2 emissions and fuel consumption have similar results. That means that the model reacted on higher parking costs with a change of mode choice from IT to PuT but also in the new IT trip assignment with potential longer trips of some private vehicles.

Table 5 – Aggregated results of the parking cost variation

Parking fee (Euro)	0,5€	1 €	1,5€	2 €	2,5€	3 €	3,5€	4 €
Total CO2 emissions	496148461.1	494464705.6	492556144	491074433.3	489515741.2	488446799	487406294.1	486461973
Reduction compared to 2008		0.34%	0.72%	1.02%	1.34%	1.55%	1.76%	1.95%
Private vehicle volumes	11992917	11939483	11882551	11836040	11792709	11761276	11731879	11706708
Reduction compared to 2008		0.45%	0.92%	1.31%	1.67%	1.93%	2.18%	2.39%
Total fuel consumption	159486078.6	158938230.3	158320129.2	157839541.3	157335849	156989841.9	156654071.5	156350332.3
Reduction compared to 2008		0.34%	0.73%	1.03%	1.35%	1.57%	1.78%	1.97%
Total gasoline consumption	137709444.7	137225634.2	136684068.3	136293953.4	135851094	135550217.2	135259745.6	134996993.1
Reduction compared to 2008		0.35%	0.74%	1.03%	1.35%	1.57%	1.78%	1.97%
Total diesel consumption	178024599.2	177422235.3	176738979.4	176181371.6	175625892.1	175241465.4	174867132	174528500.7
Reduction compared to 2008		0.34%	0.72%	1.04%	1.35%	1.56%	1.77%	1.96%
PuT Demand	2567176	2643420	2720038	2786513	2840467	2876149	2903492	2924270
Growth compared to 2008		2.97%	5.95%	8.54%	10.65%	12.04%	13.10%	13.91%

Based on the model calculations, each 50 cents raised on the parking fee has a potential of approximately 0.4% of marginal reduction on all studied traffic outputs. This means that, for example, with raise of 50 cents in parking for already charger areas, the CO_2 emissions could be reduced by 1,68 tonnes in AP.

In the following Figure 11 to Figure 14 we can observe the results of each traffic outcomes when changing parking price.

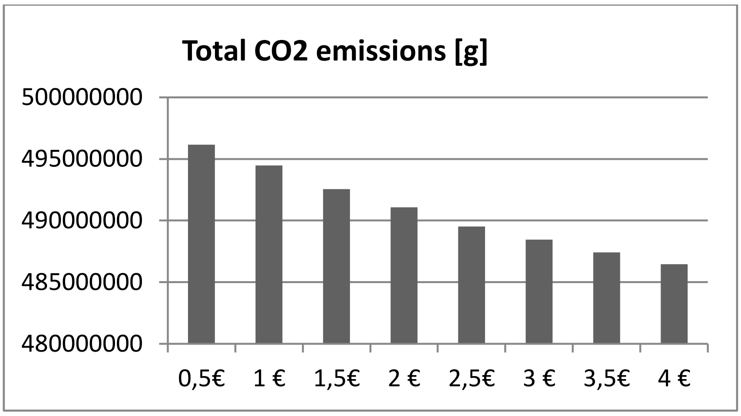


Figure 11 – Effect of the parking costs variation on the CO2 emissions in Coimbra

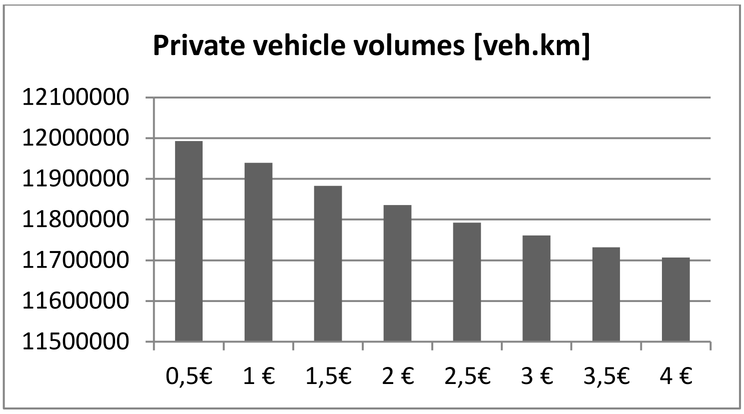


Figure 12 – Effect of the parking costs variation on the private vehicle volumes in Coimbra

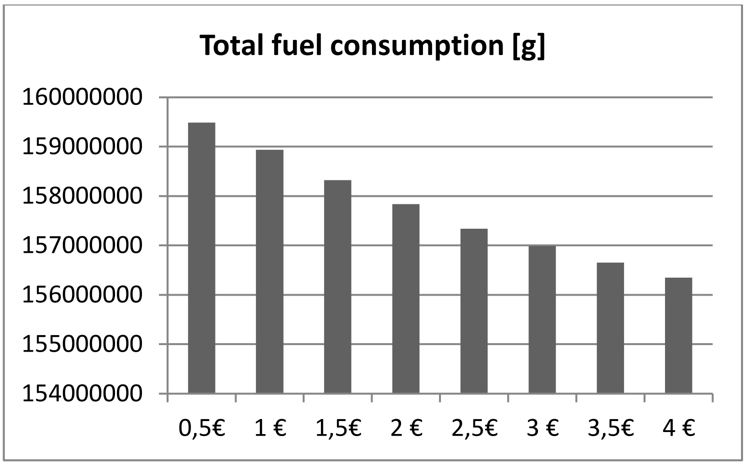


Figure 13 – Effect of the parking costs variation on fuel consumption in Coimbra

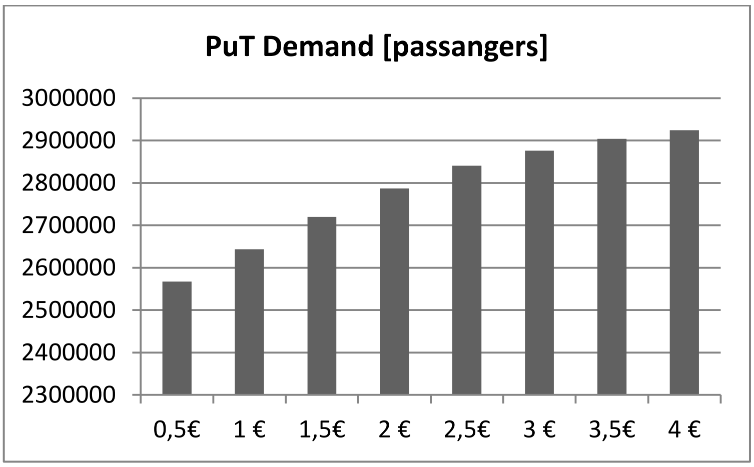


Figure 14 – Effect of the parking costs variation on the PuT demand

These changes come as a result of the exponential Logit mode choice function. In the same time, the outcomes are influenced by the new IT trip assignment as well. The curve represents the classic model of demand curve in competitive market. The elasticity of the curve lowers as the parking prices goes higher and the marginal differences lowers. This resulted in the new road assignment when the prices go too high that it becomes indifferent for some drivers. Such results were obtained mainly thanks to 6-cycle calibration of the last three steps in the four steps modelling in the SMM Model (see Figure 5 on page 22)

As the aggregated change in CO_2 emissions was very little, the graphical road assignment of the CO_2 was not analysed.

5.1.2. The parking policy scenarios

This part represented more complex policy scenarios with raising costs, new charged areas in the city centre and lower percentage of free parking for trips with HW commuting purpose (see Table 2 on page 33).

Table 6 – Aggregated results for various parking policy scenarios

	2008	S1	S2	S3	S4	S5	S6
Total CO2 emissions	496148461.1	494536368	494058376.5	492476196.6	489958923.6	488258689.4	484879854.8
Reduction compared to 2008		0.32%	0.42%	0.74%	1.25%	1.59%	2.27%
Private vehicle volumes	11992917	11949956	11935088	11907378	11809511	11757255	11678546
Reduction compared to 2008		0.36%	0.48%	0.71%	1.53%	1.97%	2.62%
Total fuel consumption	159486078.6	158965325.9	158812619.4	158313163.2	157477139	156930209.4	155846979.3
Reduction compared to 2008		0.33%	0.42%	0.74%	1.26%	1.60%	2.28%
Total gasoline consumption	137709444.7	137278918.4	137122927.7	136692563.5	135981424.1	135502324.2	134568824
Reduction compared to 2008		0.31%	0.43%	0.74%	1.25%	1.60%	2.28%
Total diesel consumption	178024599.2	177427036.5	177277125.7	176718851.2	175776512.2	175171839.1	173961143.3
Reduction compared to 2008		0.34%	0.42%	0.73%	1.26%	1.60%	2.28%
PuT Demand	2567176	2651291	2719496	2827988	2856854	2948584	3213789
Growth compared to 2008		3.28%	5.93%	10.16%	11.28%	14.86%	25.19%

From the Table 6, in scenario one, the results of extending parking areas are presented with a moderate modelling of free parking for HW trips similar to the initial scenario. The sensitivity of the model for new 10 additionally tested areas is modest with approximate reduction of 1.6 tonnes of CO_2 emissions in the analysed period.

The SMM Model has a proportional marginal growth on each of the measures separately but it is non-proportionally sensitive to their combination. While the change from scenario three to scenario four is represented only by raising the parking fee but the free parking rate went from 20% of HW trips with free parking back to original scenario, the results show the most significant difference. From this we can say that in the set of chosen scenarios, the SMM Model is more sensitive to the cost variation than to the extension of the charged area[18]. However the variation between scenarios four, five and six is modelled as almost linearly proportional reduction of the portion of free HW trip parking but in the results for the analysed outcome the marginal differences are not proportional.

Such outcomes tell us that the model is sensitive to complex scenarios. However, slight changes in single scenarios and then their combination might play significant roles in influencing the results. Future real-life verification or meso or micro simulation would be a strong advantage in defending the SMM Model potential for testing the policy and its mode choice calculation sensitivity.

In the Figures 15 and Figure 16 the geographical assignment for traffic volumes per road capacity ration and the CO_2 emission road assignment show the estimated influence of parking policy scenario number 6.

The map in Figure 15 shows the traffic reductive influence on the roads with the highest IT traffic demand such as Rua da Sofia, Rua do Brasil, Rua Miguel Torga, Rua Nicolau Rui Fernandes and some parts of non-urban roads as Circular Externa de Coimbra, roads N1 and IC2. The parking policy has thus due to The SMM model estimation the potential to deal with congestion. The positive change in aim of CO_2 reduction per km is pictured in Figure 16. Some inner city roads as well as outer city roads go under reduction change.

[18]This, of course depends on the destination demand of these new areas.

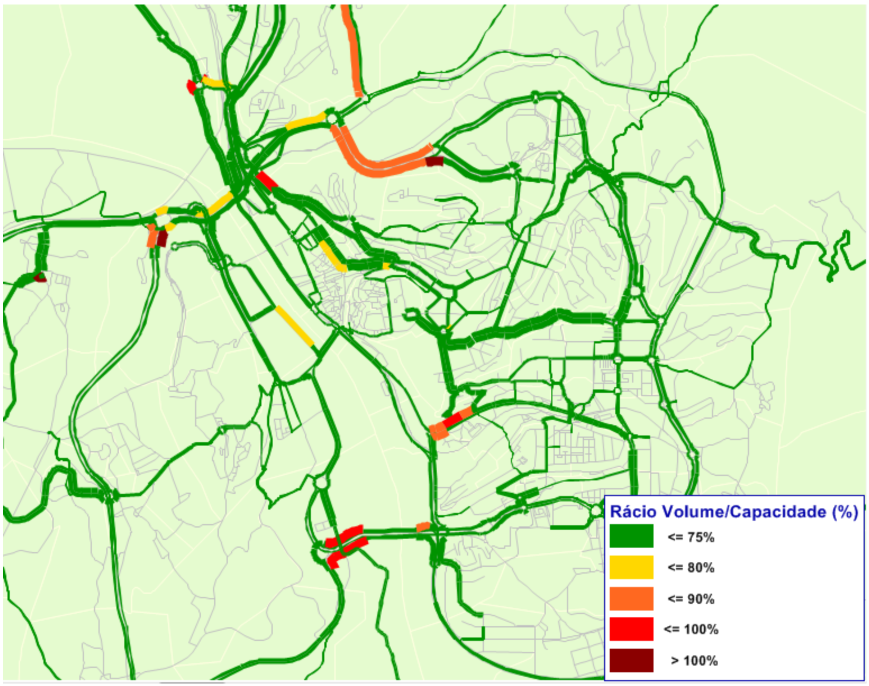


Figure 15 – Traffic volumes per road capacity ration assignment for the city of Coimbra – parking policy

Figure 16 – CO_2 emission road assignment for the city of Coimbra – parking policy

However, as the aggregated results show, the change in travel mode was complemented by a new IT trip assignment. Thus, a detailed analysis of each link was performed and this assumption was confirmed. There are some links that suffer higher CO_2 emissions due to the new traffic assignment for IT mode, yet the changes were so minor, there are not visible in the referent map.

5.2. Results for the carpooling incentives

Following Table 7 shows the results of the potential effect of successful carpooling incentives. The policy was modelled as a set of scenarios with direct reduction of the trips with commuting purposes to work and university to target mainly the commuting peak hours. In this case, the sensitivity of the SMM Model was not an issue, as the amount of trips to work and school was simply changed by adjusting the car occupancy rates. Thus the analysis of the mode choice was not necessary and attention was paid to reduction of CO_2 emissions and lower IT volumes in a strategic roads.

The 5% reduction of HW and HU trips would have outcome in the reduction from 6.6 tonnes of CO_2 up to 36.6 tonnes reduction per day for 30% trip reduction.

Table 7 – Aggregated results for the carpooling incentives

	2008	S1	S2	S3	S4
CO2 emissions	496148461.1	489501749.4	484090552.4	471955191.1	459581208
Change compared to 2008		1.34%	2.43%	4.88%	7.37%
Vehicle volumes	11992917	11836548	11696797	11396966	11100653
Change compared to 2008		1.30%	2.47%	4.97%	7.44%
Fuel consumption	159486078.6	157344413.4	155595590	151681985.9	147691969.1
Change compared to 2008		1.34%	2.44%	4.89%	7.40%
Gasoline consumption	137709444.7	135867910	134358415.7	130977341.2	127510464.9
Change compared to 2008		1.34%	2.43%	4.89%	7.41%
Diesel consumption	178024599.2	175627431.9	173674866.8	169307918.4	164872550.4
Change compared to 2008		1.35%	2.44%	4.90%	7.39%

The purpose of this policy was to reduce mainly the traffic volumes per road capacity ration on some links with higher traffic demand and the vehicle volumes on the links from areas with the highest rate of the trip origins, as well as the influence on the most polluted and congested zones of the inner city of Coimbra. Thus the effect of these policies on the outcomes' geographical assignment was studied accompanied by as the demand matrix analysis of specific OD pairs.

The results for the reduction of some commuting trips are presented in Table 8 with the scenario of 30% reduction of all HW and HU trips.

Table 8 – Reduction of trips origins from chosen zones after carpooling incentives

Zone	Trip Origins 2008	Trip Origins (CP30)	Reduction
Cantanhede	11998	10155	15.36%
Coindeixa-a-Nova	6646	6159	7.33%
Lousã (N)	2742	2480	9.56%
Lousã (S)	4296	3800	11.55%
Mira	10957	10030	8.46%
Miranda	4663	4341	6.91%
Mortágua	6469	5573	13.85%
Oliveira dos Hospitais	12667	10257	19.03%
Penacova	3842	3277	14.71%
Pombal	39323	36499	7.18%
São Julião da Figueira da Foz	11250	9334	17.03%
Serpins	1104	915	17.12%
Tábua	9830	8573	12.79%
SUM	125787	111393	11.44%

Based on the demand ration for HW and HU trips in each zone, the trip reduction varies respectively from approximately 7% up to 19% among zones. In average, the successful carpooling incentives with 30% reduction of some commuting trips have a potential to reduce 11% trip origins from the zones with the highest commuting demand in the Coimbra region.

Subsequently the reduction of trip destinations in some of the most demanded zones in the inner city of Coimbra went under reduction and is shows in Table 9. The reduction scale in these zones is rich, varying from 2% up to almost 17% reduction in some zones. There was observed potential of reducing of average[19] 6% of the trips destinations of IT mode for chosen zones.

[19] Weight average

Table 9 – Reduction of trip destinations to chosen zones after carpooling incentives

Zone	Trip Destinations 2008	Trip Destinations (CP30)	Reduction
Alta (Norte)	1617	1541	4.70%
Alta (Sul)	775	706	8.90%
UC Pólo I	7720	7403	4.11%
Parque	1471	1356	7.82%
Jardim Botânico	72	60	16.67%
Portagem	1868	1713	8.30%
Câmara	4757	4289	9.84%
Mercado	1188	1066	10.27%
Loja do Cidadão	2204	1969	10.66%
HUC / UC Pólo III	15830	14953	5.54%
Bairro de Celas	6483	6098	5.94%
Olivais	3921	3751	4.34%
Cruz de Celas	5594	5222	6.65%
Vale das Flores (O)	6921	6503	6.04%
UC Pólo II	4444	4343	2.27%
SUM	64865	60973	6.00%

In Figure 17 and Figure 18, the geographical assignment for traffic volumes per road capacity ration and the CO_2 emission road assignment show the estimated influence of successful carpooling incentives with 10% reduction of HW and HU trips.

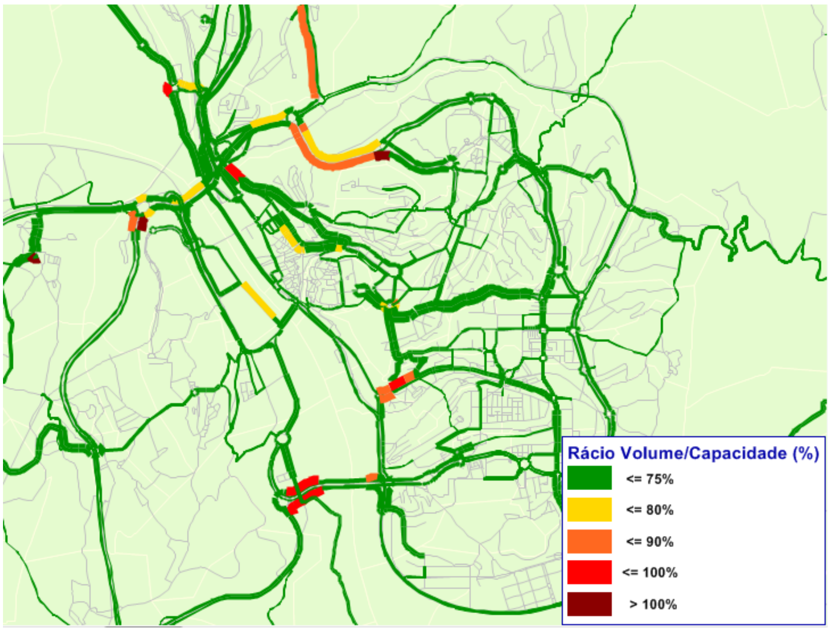


Figure 17 – Traffic volumes per road capacity ration assignment for the city of Coimbra – carpooling incentives

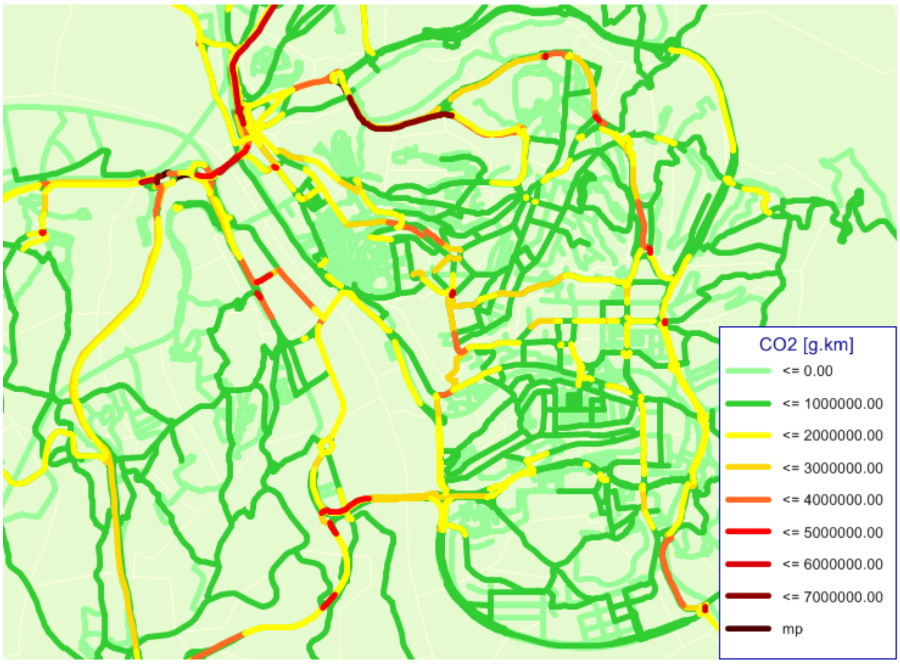


Figure 18 – CO_2 emission road assignment for the city of Coimbra – carpooling incentives

The changes are more visible on the reduction of traffic volumes per road capacity because the projecting scale is more sensitive. A positive reduction effect was allocated on roads Rua Nicolau Rui Fernandes, Rua do Brasil, Avenida Professor Gouveia Monteiro, Rua Miguel Torga, Ponte do Açude and some outer city roads such as IC2. The reduction of CO_2 is less visible also due to the chosen scale. Important to note that in case of Coimbra, or other hilly city, the road slopes can reduce the effectiveness of the policy in the CO_2 emission reduction.

5.3. Results for the combination of parking policy and carpooling incentives

The SMM Model shows high sensitivity on combining the policies however it also uncovers some shortcomings for the modelling of TDM policies. A set of combinations of parking policy and carpooling incentives has a potential to reduce from 15.3 tonnes up to 54.9 tonnes of CO_2 emissions of AP.

Table 10 – Aggregated results for the parking and carpooling combination

	2008	S1	S2	S3	S4	S5
CO2 emissions	496148461.1	480953001.5	473641161.6	460157807.3	443505085.1	441297470.2
Change compared to 2008		3.06%	4.54%	7.25%	10.61%	11.06%
Vehicle volumes	11992917	11580572	11409243	11063358	10644683	10587372
Change compared to 2008		3.44%	4.87%	7.75%	11.24%	11.72%
Fuel consumption	159486078.6	154573513.5	152217351	147859804.5	142479890.9	141771827.2
Change compared to 2008		3.08%	4.56%	7.29%	10.66%	11.11%
Gasoline consumption	178024599.2	172543506.2	169912317.4	165068246.5	159110402.3	158323530.3
Change compared to 2008		3.08%	4.56%	7.28%	10.62%	11.07%
Diesel cosumption	137709444.7	133464712	131431614.3	127645573.1	122944537.1	122329047
Change compared to 2008		3.08%	4.56%	7.31%	10.72%	11.17%
PuT Demand	2567176	2948319	2948011	2947029	2946534	3211415
Growth compared to 2008		14.85%	14.83%	14.80%	14.78%	25.10%

As the results in Table 10 represent aggregated values, there must be a special attention paid to which trips might have been influenced by only one policy separately in the mode choice and which trips might have been influenced by both of them at the same time. The results, mainly for the aggregated values for PuT, prove that the SMM Model assumes that some of the commuters from the 20% HW trips that started to share the car to commute to work and university are the ones who have free parking on the place of work or study (50% of free parking for those trips was assumed in this scenario) and are not influenced by the parking policy. This effect is a result of the way these two policies were modelled in the SMM Model. The parking costs are tied to the HW and non-home based trips and the carpooling incentives were modelled for HW and HU trips. In reality, trips that do not represent the carpooling trip portion for commuting or have another purpose of the trip, such as home-school or non-home based trips might have been the ones that would have changed the transport mode due to higher parking prices and extension of the charged parking area. Here the shortcomings of the SMM Model play a role.

On the other hand, there might be a realistic use in practice of TDM policy in a scenario where a programme of free parking would be presented for all carpoolers to their work place. However, for more realistic calculation the extension of modelled demand segments that pay for the parking, such as university students, should be modelled in the SMM Model in the future for the possibility to target this demand segment.

In Figures 19 and Figure 20, the geographical assignment for traffic volumes per road capacity rations and the CO_2 emission road assignment are demonstrated for the combination scenario 3[20]. From the figures, we can observe both lower and higher CO_2 emissions for some links. The reduction was assigned for Avenida Professor Gouveia Monteiro, Largo Don Dinis, Guarda Inglesa, Avenida António Portugal and Ladeira do Seminário. Some links, especially outer city circuits suffered higher IT demand and higher CO_2 emissions such as some parts of roads IC2 and N17.

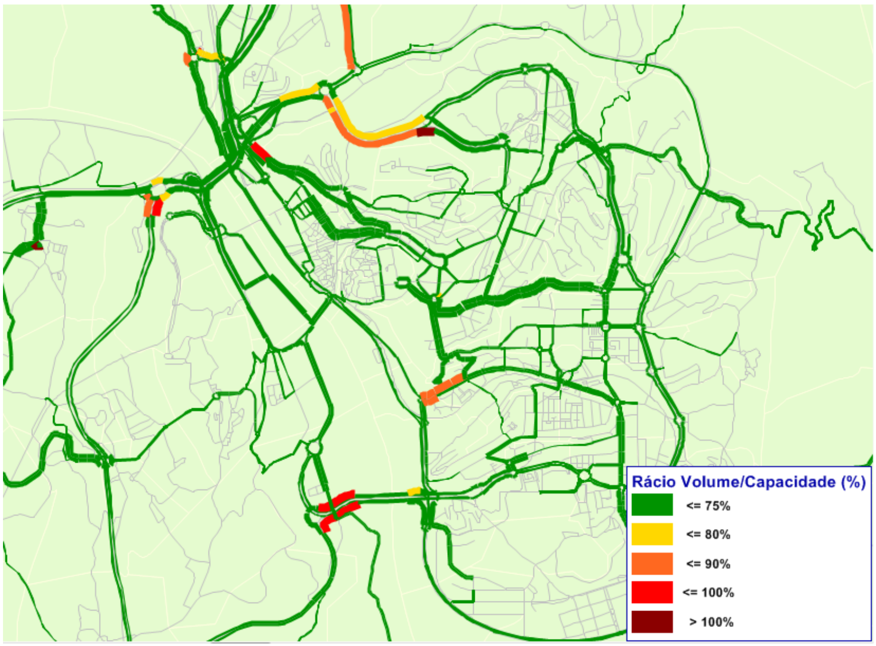


Figure 19 – Traffic volumes per road capacity ration assignment for the city of Coimbra – carpooling incentives and parking policy combination

[20] 20% HW and HU trip reduction, 1Euro parking fee, 50% of free parking for HW trips and extended parking areas

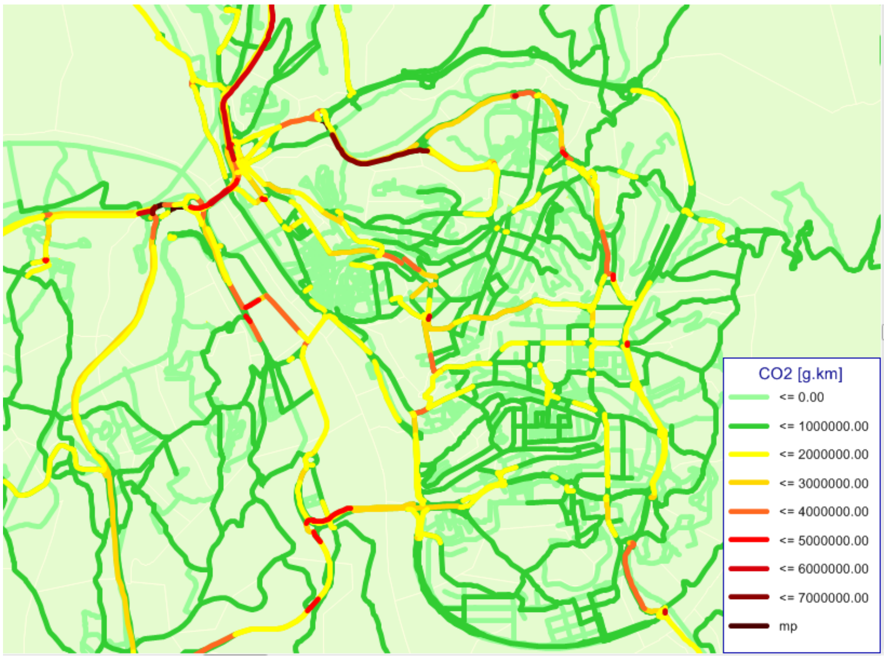


Figure 20 – CO_2 emission road assignment for the city of Coimbra – carpooling incentives and parking policy combination

5.4. Results for the road tolling policy

The SMM Model reacted on the modelled road tolling policy as the change of mode choice and final IT trip assignment. From the results we can assume that the function of CO_2 or fuel consumption reduction in an exponential function and with higher toll price the additional marginal value for potential reduction lowers (see Table 11).

Table 11 – Aggregated results for toll pricing of some urban roads

Toll fee (Euro)	0 €	1 €	2 €	3 €
Total CO2 emissions	496148461.1	495733595.1	495360084.8	495121737
Reduction compared to 2008		0.08%	0.16%	0.21%
Private vehicle volumes	11992917	11989100	11985835	11971441
Reduction compared to 2008		0.03%	0.06%	0.18%
Total fuel consumption	159486078.6	159354534.4	159236649	159160501.7
Reduction compared to 2008		0.08%	0.16%	0.20%
Total gasoline consumption	137709444.7	137610042.4	137504129.4	137448400
Reduction compared to 2008		0.07%	0.15%	0.19%
Total diesel consumption	178024599.2	177865692.5	177737614.8	177644085.7
Reduction compared to 2008		0.09%	0.16%	0.21%
PuT Demand	2567176	2566346	2566867	2566931
Growth compared to 2008		0.03%	0.01%	0.01%

From a preparatory analysis, which does not make a part of the scenario modelled for the Master thesis, the results obtained from such modelling were highly unstable, depending on the chosen link, the link's direction or price of the toll fee and combination of all aforementioned. Some resulted in higher traffic volumes, or much higher CO_2 emission as the change of mode choice was not affected but the change of the trip assignment was. Thus, a level of attention must be paid modelling and testing urban road toll policies in the SMM Model. More microscopic analysis of the driver's behaviour should be developed to verify and confirm the results.

The geographical outcomes of CO_2 emissions and traffic volumes per capacity assignment for chosen road tolling policy scenario 2 are presented as Figures 21 and 22. While the traffic volumes per capacity assignment uncover reduction of traffic volumes on some roads such as targeted Avenida Professor Gouveia Monteiro, Rua do Brasil, Avenida Fernão Magalhães, or entrance of the Bridge of Rainha Santa Isabel, the CO_2 projection[21] uncovers a side effect of road tolling policy, which is new trip assignment. Roads such as Rua Miguel Torga expose higher CO_2 emission. This finding led to an assumption that some road had suffered higher CO_2 emission due to new trip assignment but were not displayed in the map because they were so small that the marginal difference did not influence a change due to the chosen scale on the map[22]. Thus a detailed analysis was performed for each modelled link of the city of Coimbra. The results confirmed the assumption and there were found some small inner city roads with up to twice higher emissions.

[21] Apart from the reduction on some outer roads such as Rua Afrânio Peixoto.
[22] Difference between analysed categories is 1 tonne of CO_2 on scale from 0 to 7 tonnes.

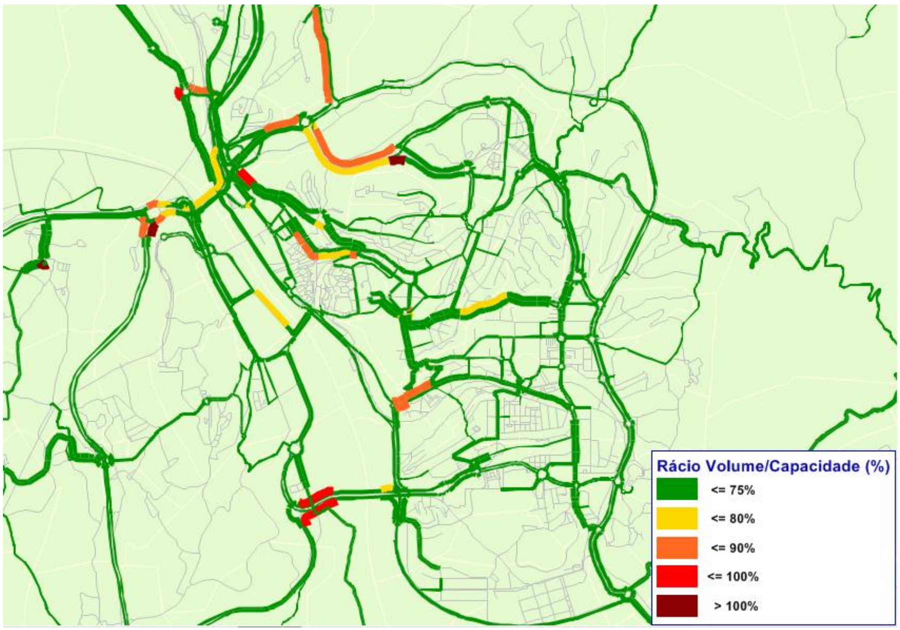


Figure 21 – Traffic volumes per road capacity ration assignment for the city of Coimbra – road tolling policy

Figure 22 – CO_2 emission road assignment for the city of Coimbra – road tolling policy

5.5. Results for the public transport improvement

Shorter waiting time and higher frequency of the service did not resulted in any changes in the mode choice or trip assignment as waiting time is dependent on the time-table schedule and thus service frequency. At the same time, changes in frequency were not significant enough to cause changes in the mode choice. Thus a different method had been modelled. This chapter presents the results on modelling some improvements of PuT such as speed of service and cheaper transfer tickets.

The following Table 12 presents the changes in the analysed attributes after the policy. The changes were minor with only significant rise on the side of the PuT demand by 76’244 passenger ride (growth by 2.97%). For this reason, the geographical assignment of CO_2 emissions and traffic volumes per road capacity was not performed but the policy was used in the final TDM policy scenario as a supplement policy.

Table 12 – Aggregated results for the improvements of the public transportation

	Original 2008	Better PuT
Total CO2 emissions	496148461.1	496019172.9
Reduction compared to 2008		0.03%
Private vehicle volumes	11992917	11989449
Reduction compared to 2008		0.03%
Total fuel consumption	159486078.6	159444433.7
Reduction compared to 2008		0.03%
Total gasoline consumption	137709444.7	137673465.4
Reduction compared to 2008		0.03%
Total diesel consumption	178024599.2	177422235.3
Reduction compared to 2008		0.34%
PuT Demand	2567176	2643420
Growth compared to 2008		2.97%

5.6. Results for the complex TDM policy

The combinations of policies tested as the complex policy consists of:

- 1 Euro parking fee, extended charged parking area, only 20% of the HW trips have free parking;

- Successful carpooling incentive with outcome of 5% reduction for HW and HU trips by the IT mode and finally.
- There have been applied 2 Euro toll fee for Rua da Sofia, Rua de Aveiro, Rua do Brasil, Avenida Professor Gouveia Monteiro, Ponte do Açude and Ponte Rainha Santa Isabel.
- Above mentioned policies were supplemented by PuT improvement modelled as in Chapter 5.5.

Table 13 shows that this scenario could have a potential reduction of 19.76 tonnes of CO_2 emissions per AP. The positive outcome rises on the side of higher reduction of the IT volumes in the city of Coimbra with potential of reducing 506'969 vehicles.km. From the results of previously modelled single policies there was assumption of reduction of the private vehicles in the city but some trips were reallocated and thus some roads show higher CO_2 emissions. This again contributes to lower effectiveness of the policy to reduce fuel consumption and CO_2 emission changes.

Table 13 – Aggregated results for the complex TDM policy

	2008	Complex policy scenario
Total CO2 emissions	496148461.1	476386572.5
Reduction compared to 2008		3.98%
Private vehicle volumes	11992917	11485948
Reduction compared to 2008		4.23%
Total fuel consumption	159486078.6	153112601
Reduction compared to 2008		4.00%
Total gasoline consumption	137709444.7	132206539.4
Reduction compared to 2008		4.00%
Total diesel consumption	178024599.2	170910000.5
Reduction compared to 2008		4.00%
PuT Demand	2567176	3231481
Growth compared to 2008		25.88%

Subsequently, the reduction of private traffic volumes and potential reduction of the traffic congestion in some strategic roads in the inner city of Coimbra were analysed. For such analysis, the traffic volume per road capacity geographical assignment from the SMM Model was used again (see Figures 23).

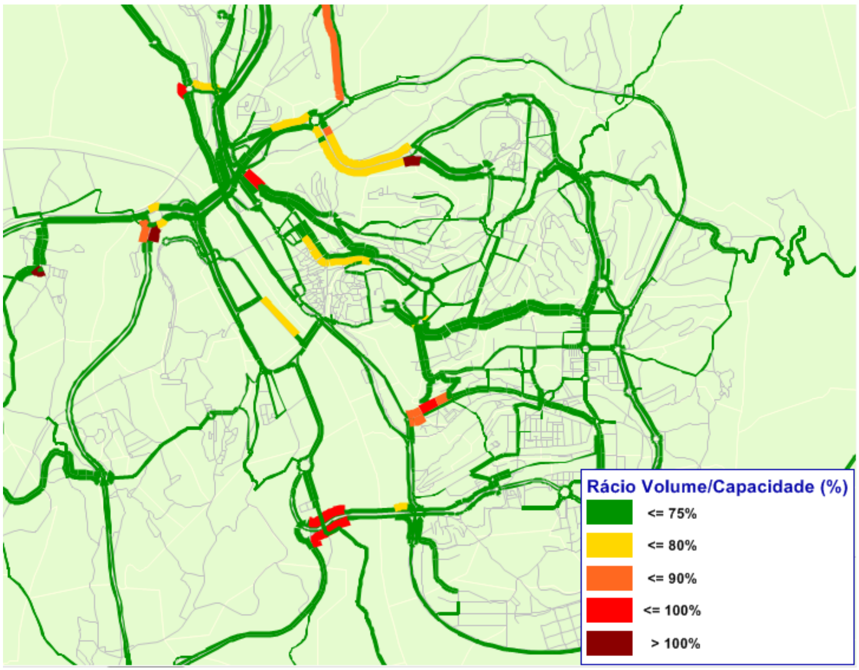


Figure 23 – Traffic volumes per road capacity ration assignment for the city of Coimbra – complex TDM policy

It was possible to observe reductive outcomes in strategic roads such as Avenida Professor Gouveia Monteiro, Rua da Sofia, Rua Miguel Torga, Ponte do Açude and Ponte Rainha Santa Isabel. The critical congestion-like roads seemed to be targeted, mainly due to the specific road assignment for road tolling policy, strategic choice of charged or newly added parking zones and reduction of trips with commuting purpose which represent a great portion of traffic demand in the inner city. Thus, due to the SMM Model assumption, the policy could have the potential to solve traffic congestion issues in the city of Coimbra.

Afterwards, the analysis of the CO_2 emission road assignment was performed. The reductive effect appeared mainly on the outer circuits of Coimbra such as Avenida Professor Gouveia Monteiro or Rua Afrânio Peixoto (see Figure 24). In this case, the detailed analysis of each link's studied outcome was done again, as road tolling policy could have a negative effect due to new trip assignment. This could be, nevertheless, reduced by the contribution of the other complementing TDM policies. Few links shows up to 300% rise of CO_2 emission.

Figure 24 – CO_2 emission road assignment for the city of Coimbra – complex TDM policy

However, after detailed geographical analysis, these links represent very tiny portion from the aggregated kilometres. An example can be the cruising route on a roundabout. Statistically, majority of the important inner and outer city roads have shown reduced CO_2 emission (see Table 14).

For this analysis, the assumption was confirmed by the example of Rua da Sofia. In sum, the road suffered higher values of each traffic outputs. However, each road in the VISUM 12.0 is modelled as a set of one or several links, depending on the road (one way road, two ways road or more). In case of Rua da Sofia, the direction where the road tolling policy was modelled had significantly lower results (in average -35% on all studied outcomes), while the opposite direction shows higher values due to new IT trip assignment.

Table 14 – Results for CO_2 emissions, vehicle volumes and fuel consumption of chosen strategic roads after implementation of complex TDM policy

	CO2 (Original)	CO2 (Policy)	Change %
Alameda Dr. Júlio Enriques	3607436	3525215	-2.28%
Av. Conímbriga	3233357	3146926	-2.67%
Av. Prof. Gouveia Monteiro	6576530	5787632	-12.00%
Largo Don Dinis	5184363	4490017	-13.39%
Ponte Açude	4591360	4318233	-5.95%
Rua Afrânio Peixoto	3547727	3135366	-11.62%
Rua da Figueira	4384108	4400509	0.37%
Rua da Sofia	2773939	3007331	8.41%
Rua de Aveiro	2906538	2843691	-2.16%
Rua do Brasil	2313260	2293442	-0.86%
Rua Miguel Torga	3583638	3285590	-8.32%
Sá Bandeira	3490185	3370737	-3.42%
	Veh. Volumes (Original)	**Veh. Volumes (Policy)**	**Change %**
Alameda Dr. Júlio Enriques	18808	18166	-3.41%
Av. Conímbriga	15737	15316	-2.68%
Av. Prof. Gouveia Monteiro	21346	18860	-11.65%
Largo Don Dinis	16342	14112	-13.65%
Ponte Açude	31525	29650	-5.95%
Rua Afrânio Peixoto	17191	15006	-12.71%
Rua da Figueira	16322	16387	0.40%
Rua da Sofia	14607	14636	0.20%
Rua de Aveiro	13273	12969	-2.29%
Rua do Brasil	12703	12603	-0.79%
Rua Miguel Torga	14301	13848	-3.17%
Sá Bandeira	9489	9164	-3.43%
	Fuel Consumption (Original)	**Fuel Consumption (Policy)**	**Change %**
Alameda Dr. Júlio Enriques	358311	349575	-2.44%
Av. Conímbriga	427239	415283	-2.80%
Av. Prof. Gouveia Monteiro	1600423	1408369	-12.00%
Largo Don Dinis	91130	78703	-13.64%
Ponte Açude	543766	511217	-5.99%
Rua Afrânio Peixoto	128004	113288	-11.50%
Rua da Figueira	255276	256034	0.30%
Rua da Sofia	79272	85628	8.02%
Rua de Aveiro	265864	259994	-2.21%
Rua do Brasil	113677	112543	-1.00%
Rua Miguel Torga	259690	238520	-8.15%
Sá Bandeira	87235	84190	-3.49%

Attention was also paid to the strategic OD pairs for commuting. Following Tables 15 and 16 present the reduction of trips with origin or destination in the chosen zones.

Table 15 – Change in the number of trip origins after complex TDM policy

Zone	Trip origins 2008	Trip origins (Policy)	Reduction
Cantanhede	11998	11646	2.93%
Coindeixa-a-Nova	6646	6534	1.69%
Lousã (N)	2742	2679	2.30%
Lousã (S)	4296	4174	2.84%
Mira	10957	10793	1.50%
Miranda	4663	4594	1.48%
Mortágua	6469	6315	2.38%
Oliveira dos Hospitais	12667	12257	3.24%
Penacova	3842	3729	2.94%
Pombal	39323	38819	1.28%
São Julião da Figueira da Foz	11250	10925	2.89%
Serpins	1104	1052	4.71%
Tábua	9830	9616	2.18%
SUM	125787	123133	2.11%

Table 16 – Change in the number of trip origins after complex TDM policy

Zone	Trip destination 2008	Trip destination (Policy)	Reduction
Alta (Norte)	1617	1392	13.91%
Alta (Sul)	775	678	12.52%
UC Pólo I	7720	6741	12.68%
Parque	1471	1343	8.70%
Jardim Botânico	72	62	13.89%
Portagem	1868	1597	14.51%
Câmara	4757	4483	5.76%
Mercado	1188	1146	3.54%
Loja do Cidadão	2204	2001	9.21%
HUC / UC Pólo III	15830	15149	4.30%
Bairro de Celas	6483	6197	4.41%
Olivais	3921	3882	0.99%
Cruz de Celas	5594	5359	4.20%
Vale das Flores (O)	6921	6741	2.60%
UC Pólo II	4444	4322	2.75%
SUM	64865	61093	5.82%

6. DISCUSSION AND CONCLUSION

Currently, the transport planning and management entered several new spheres in developing, testing and practical implementation of transport demand management policies. With successful case studies as a reference, the information technology development with advanced modelling tools contributed to the fact that the transport planners and decision makers can now support more complex decisions in transport planning and management. The estimation of traffic volumes and its road assignment is now an insufficient criterion for such decisions and more tools and support information have to be provided. These criterions and characteristics can represent an inter-disciplinary set of possible consequences from a transport demand and network conditions such as return on investment, social equity or environmental issues.

This master thesis presented the testing of transport demand management policies in the transport demand model for the city of Coimbra developed by Metro Mondego,S.A. in VISUM 12.0. The results were presented as changes in aggregated sums for the fossil fuel consumption, CO_2 emissions, vehicle volumes and demand for public transport in the city of Coimbra. Complementary geographical representations of CO_2 emission and vehicle volumes per road capacity were extracted from the software and analysed. For some trips the reduction of origins and destinations of trips from strategic zones was studied as well to address the commuting problems of the city.

The set of policies tested in the transport demand model for the city of Coimbra consisted of parking policies, carpooling incentives, urban road tolling policy, PuT improvements and finally their strategic combinations. Each of the policy was developed with goals and legal background set by the European Commission in the White Paper on Transport 2011 and The Strategic Plan of Coimbra developed by the municipality of Coimbra. Specific scenarios were developed because no uniform transportation policy can be adapted for all the cities of Europe and there is always need for a local and strategic approach. After analysis of the transport system of the city and region, the thesis aimed to target the most congested or polluted roads or zones of Coimbra and the city sprawl problems of the region.

To accomplish this, it was necessary to study the four step transport modelling processes in software VISUM 12.0 and the SMM Model. After understanding the way the SMM Model was built, it was possible to provide adjustments of the calculations' inputs to obtain relevant results on the change of traffic situation. These inputs were - change of costs, travel time, car occupancy rate or extension of zones with a certain TDM policy. It was understood that to reduce fuel consumption, CO_2 emissions and obtain lower IT vehicle volumes, a transport mode switch, direct reduction of trips using private car or more effective trip road assignment had to be influenced by the policy. In this master thesis, the main emphasis was weighed on the transport mode choice and trip reduction.

Firstly, complex parking policy scenarios were modelled combining higher but realistic parking prices, extension of paid zones and demand segments that pay for parking. This policy resulted in up to 2.3% reduction of CO_2 emissions and fuel consumption, while the passenger demand for PuT rose by 25%. In a detailed link analysis it was possible to observe reductions of CO_2 emissions and vehicle volumes for strategic inner city roads such as Rua da Sofia, Rua do Brasil, Rua Miguel Torga, Rua Nicolau Rui Fernandes and some parts of non-urban roads as Circular Externa de Coimbra, roads N1 and IC2.

Carpooling incentives obtained the most significant results for a single modelled policy. Due to the SMM Model and the carpooling scenarios modelled, it was possible to reduce up to 7.4% of CO_2 emissions and fuel consumption in the inner city of Coimbra in the AP. The reduction of private vehicles was not studied as this was actually the result of the carpooling incentives and was modelled through the adjustment of the car occupancy rate. Additionally to the aggregated sums, the reduction on trip origins and destination in strategic zones acting in the commuting problems of Coimbra was analysed. The carpooling incentives with a reduction of 30% trips commuting to work and university had a potential to reduce 11.4% of the trip origins in the most demanded zones and 6% reduction for the trip destination in the most demanded zones. The 20% reduction of the home-work and home-university trips also helped to reduce traffic volumes on the most congested roads in Coimbra, mainly Avenida Professor Gouveia Monteiro and Rua da Sofia.

Urban road tolling policy was the most successful policy in targeting the access to the city centre and the most congested roads in Coimbra. However, aggregated results show the lowest variation of the studied outcomes. The changes of only 0.08% to 0.21% of the CO_2 emissions and fuel consumption were observed and the switch to PuT mode was even lower (0.01%). This was caused by the way the toll fees were assigned to the chosen roads. It resulted not in a switch of the transport mode but in a new IT trip assignment for longer but still cheaper trips in the inner city.

The very light improvement of the PuT services via 20% faster travel time for both urban and suburban lines and 10 cents cheaper transfer ticketing resulted as well in minor modification in the CO_2 emissions and fuel consumption with potential to reduce 0.3% of these indicators. Satisfactory results came with 2.9% higher passenger demand for the PuT.

The final testing part was combining these policies in a realistic scenario that could occur in real life. The parking policy scenario, carpooling incentives, road tolling policy on some roads and PuT improvement were modelled together in a final complex TDM policy. It resulted in a potential 4% reduction on aggregated volumes of CO_2 emissions (19.76 tonnes) and fuel consumption per day and in the reduction of 506’969 vehicles.km in the inner city of Coimbra. Such policy has the possibility to target emissions and traffic volumes on the strategic roads, in this case it was Avenida Professor Gouveia Monteiro, Rua da Sofia, Rua Miguel Torga, Ponte do Açude and Ponte Rainha Santa Isabel and Rua Afrânio Peixoto. When comparing these results with results for simple combination of parking policy and carpooling incentives where there was higher reduction of traffic volumes on some important roads such as Rua da Sofia, we can conclude that the SMM Model is also able to identify negative effect of TDM policies and road assignment.

Interesting results were obtained when two TDM policies are tested together. This was the case of combining the parking policy and carpooling incentives. As we reduced trip portions for trips commuting to work and university and in the same time we implied parking policy scenario with only some percentage of free parking for HW trips, it were these reduced trips that the model assumed as the ones with free parking. Only when the percentage of carpoolers overpassed the percentage of HW trips with free parking, then the SMM Model reacts with a mode switch to PuT. Simply said, the model assumes that the carpooling trips are the ones affected by free parking. This of course can have a realistic use in practice; however, it calls for attention while combining such policies because the modeller might not wish to have exactly this scenario in results.

Additionally, to confirm the deduction on why some policies (mainly road tolling) have very little reduction potential a detailed road analysis was performed. It was assumed that higher costs with its geographical allocation for IT mode not only contributed to switch to PuT mode but also to new trip assignment. This was confirmed and the policies resulted in some longer but cheaper trips causing that the emissions, fuel consumption and IT vehicle volumes of those links were higher. Such reactions of drivers would be normal also in reality. Undoubtedly, a micro simulation or more complex functions with more variables for calculation of final road assignment would bring higher added value to the results.

In the case of Coimbra, an attention should be paid when modelling and implementing the TDM policy in aim to reduce CO_2 emissions. Confirmed from results of Ana Ferreira (2012), the main contributor to GHG emissions are high road slopes in the inner city and not only the roads with highest demand or traffic congestion pre-dispositions. Considering this fact could raise the efficiency of the future traffic reduction management in regulating the CO_2 emissions.

Obstacles were found in modelling of the PuT improvements. The SMTUC and sub-urban bus connections are modelled as time-table based connection with distance-based calculation of travel fare. The time table is dependent on the modelled bus stops and commercial speed of a bus line which is calculated from the distance between bus stops and commercial speed for each link between those stops. Thus, to model more detailed policy targeting only some bus lines would be highly laborious as each link separately would have to be changed. Also, the coefficients setting the un-comfort values for travel time or numerous transfers in the utility function of a mode choice were not set originally for Coimbra or Portugal but were adapted from another case studies developed by the company PTV. A closer analysis or development of these coefficients would be an interesting new study for the SMM Model to support more realistic projection of the transport demand curve's behaviour.

A big advantage of the SMM Model stands in the large variety of modelled demand segments which allowed, in some cases, targeting specific demand groups. In the same time, here stand the shortcomings of modelling, as models are non-perfect representation of reality. For example parking costs are tied to a zone, but there is free parking portion of trips modelled for only two types of trip purposes – home-work and non-home based. Thus, only this two demand segment could be addressed and targeting, for example, home-university trips with various parking policy was not possible.

Nevertheless, the model had some limitations; there is the possibility of future development to provide better background for TDM policy testing or multi-functional use. This would be possible also due to the high flexibility of the software VISUM 12.0 in transport demand modelling and its compatibility with micro modelling software VISSIM also from company PVT AG.

VISUM 12.0 offers very user friendly platform for geographical projection. The software's graphic interface allows modelling and adjusting maps with user defined attributes in any detail which becomes very useful in deeper analysis of the TDM policy results.

To conclude, the SMM Model with its high detail of modelling and flexible adjustment possibilities in VISUM 12.0 has the potential to produce realistic traffic outcomes when testing some TDM measures and their combination. However, the model is highly sensitive to some policy combinations and geographical allocation of costs and results should be deeply analysed and in the best case complemented by a micro modelling study of the possible traffic reaction. These results supported by more policies tested such as fossil fuel taxes or support analysis such as cost-benefit analysis or public response analysis would be undoubtedly very valuable criterions when managing the transportation in Coimbra with the aim to reduce fossil fuel consumption and with it related GHG emissions originated on traffic.

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