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Transportation Modelling for Environmental Impact Assessment

Porto Metropolitan Area Case Study

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgment has been made in the text.

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ACRONYMS

BAU - Business as Usual

BPR - Bureau of Public Roads

CARB - California Air Resources Board

CBA- Cost Benefit Analysis

CO - Carbon Monoxide

CO_2 - Carbon Dioxide

COPERT - Computer Program to Calculate Emissions from Road Transport

CARB - California Air Resources Board

EA - Environmental Assessment

EEA - European Environment Agency

EIONET - European Topic Centre on Air and Climate Change

EIA - Environmental Impact Assessment

EU - European Union

EC - European Commission

FTP - Federal Test Procedure

HOV - High Occupancy Vehicle

HDV - Heavy-Duty Vehicle

INE - Portuguese National Statistics Institute (Instituto Nacional de Estatística)

ITS - Intelligent Transport Systems

LOS - Level of Service

NMVOCs - Non Methane Volatile Organic Compounds

NO_2 - Nitrogen Dioxide

NO_x - Nitrogen Oxides

O_3 - Ozone

PMA - Porto Metropolitan Area

SO_2 - Sulphur Dioxide

TAZ- Transport Analysis Zone

TCM - Traffic Control Systems

S.T.C.P- Sociedade de Transportes Colectivos do Porto

VHT - vehicle-hour of travel (veh.h)

VKT - Vehicle Kilometre Travelled (veh.km)

VOCs - Volatile Organic Compounds

“Simulation is a powerful tool, and like all powerful tools it can be dangerous in the wrong hands. The increased emphasis on simulation studies and the corresponding lack of experience on the part of some people who attempt to apply the method can lead to a type of pseudo simulation. Pitfalls exist in simulation as in every human attempt to abstract and idealize. Some rules to follow in avoiding these pitfalls are no assumption should be made before its effects are clearly defined, no variables should be combined into a working system unless each one is properly explained and its relationships to the other variables are set and understood, and it must be remembered that simplification is desirable but oversimplification can be fatal.”

Drew (1968)

ACKNOWLEDGMENTS

This master dissertation is the result of one year of intense research in the theme proposed, having had the opportunity of working in sophisticated software's and models, studying a theme and a scenario that is very meaningful to me.

The first acknowledgement must go to my supervisors. I would like to thank Professor Álvaro Costa and Professor Margarida Coelho for guiding me through this project and for always backing me up in the natural doubts that I had during this year of intense study and research. My special thanks to Pedro Abrantes for teaching me a lot about transport modelling and for encouraging me to always go farther in my investigation and for teaching me how to interpret results and model outputs. I'd like to give special thanks to Sandra Melo, Patricia Carvalhido, Ricardo Cardoso, Pedro Moia, Frederico Moura e Sá, Manuel Guimarães, Ayça Kolukisa and all FEUP investigation team, for always listening to my doubts and helping me out with the day by day tasks. Last, but not least, I would like to acknowledge my dear family for the support and constant presence during this year of hard but fulfilling work.

ABSTRACT

Large scale urban transportation planning models are recognized as an essential input in the decision making processes of the majority of the urban planning. One of the main challenges is to find ways to use these sophisticated tools to provide a relevant policy and timely set of meaningful outputs that can accommodate the diverse set of stakeholders needs.

The developments of transportation and emission models have always followed separate routes, these models have been conceived for two different purposes and this fact explains the current difficulty using these models in an integrated way. In broad terms the transportation models have been built considering several aspects of the same problem (mobility), while the emission models have been developed under the incentive of air pollution, to forecast the emissions produced by different sources.

The main objective of this research is to present an overview of the role that integrated transportation and emissions models (including analysis of multi-modal factors of mobility and road network assignment) can play in the environment impact assessment of transportation related policy instruments and other non-transportation instruments. The model (which relates urban mobility and emissions from private and public transport vehicles) is developed using *EMME/3* transport planning software and intends to analyze the mobility environmental impacts induced by the major regional development tendencies and policies in the Porto Metropolitan Area.

The main conclusions of this dissertation focus on the methodology proposed and the opportunities of improving the interaction between transportations models and environment models.

RESUMO

A utilização de modelos de planeamento de transportes de escala urbana é reconhecida como um importante contributo para os processos decisórios do planeamento urbano. Um dos principais desafios é encontrar formas de utilizar essas ferramentas sofisticadas para fornecer respostas relevantes e oportunas, adequadas às necessidades dos agentes decisores. O desenvolvimento dos modelos de transportes e dos modelos ambientais (emissões atmosféricas) têm seguido caminhos separados, estes modelos foram concebidos para duas finalidades diferentes e este facto explica a actual dificuldade em utilizar esses modelos de forma conjunta. Em termos gerais, os modelos de transporte foram concebidos considerando diversos aspectos do mesmo problema (a mobilidade), enquanto os modelos de emissões foram desenvolvidos para a previsão das emissões produzidas por diferentes fontes.

O principal objectivo deste trabalho é apresentar uma visão geral do papel integrado que os modelos de transportes e os modelos de emissões (incluindo a análise de dos factores multi-modais e factores de afectação de redes) podem desempenhar na avaliação do impacto ambiental do transporte relacionando instrumentos políticos e não políticos de avaliação.

O modelo (que relaciona mobilidade urbana e de emissões de veículos de transportes privados) é desenvolvido utilizando o software *EMME/3* de planeamento de transportes, e entende analisar os impactos ambientais induzidos pelas principais tendências políticas do desenvolvimento regional na Área Metropolitana do Porto.

As principais conclusões deste trabalho focalizam-se na metodologia proposta e as oportunidades de melhoria na relação entre modelos de transportes e modelos ambientais.

CHAPTER 1

INTRODUCTION

1.1 Background

Over the past decades, transportation demand has increased dramatically in the European Union (EU). Growth rates vary significantly between prevailing transportation modes. Road usage increased exponentially, while the use of inland waterways and rail decreased. The European Commission (EC) and the legislative body in the EU, is concerned that the trend will continue in the absence of timely intervention. The EC currently intervenes in the organization of European transportation by imposing fuel taxes, and designing environmental guidelines and regulations. The EC proposes to further alleviate the problems by means of new and stricter common transport policies, which, in essence, pass on polluters the true costs to society and the environment. Therefore, public authorities, assisted by urban planners and road managers, are faced with extremely complex operational, design and management challenges. Traffic congestion makes cities less pleasant and reduces the efficiency of the transport system by increasing journey time, fuel consumption and driver stress. Thus, environmentally, economically and politically, it is important that the transport system is designed and used in the most effective way so that it satisfies the needs for personal and freight transport without creating unacceptable conditions. Its costs must be kept in check and its adverse effects on the natural and anthropological environment should be minimized.

Pure intuition is no longer sufficient to elaborate global solutions, the need for dedicated models, helping to understand the complex mechanisms of the system and to evaluate the impacts of several policies is essential. A model can be defined as a simplified representation of a part of the real world which concentrates on certain elements considered important for its analysis from a particular point of view (Ortuzar and Willumsen, 1994). In this context, the representation is built from mathematical equations that are claimed, under some assumptions, to reproduce a part of reality.

The problems must be addressed with a consistent and comprehensive approach and with planning methodology that helps to design strategies for sustainable cities. This includes an integration of socio-economic, environmental and technological concepts to improve forecasting, assessment and strategic policy level decision support. The use of transport equilibrium modelling to evaluate alternative transportation policies, including multi-modal systems, technological development and socio-economic development, and spatial and structural urban development in general, can overcome potential misleading in transportation planning. The combined use of transport models and emissions models, to understand the impact on emissions due to mobility have always followed separate routes; these models have been conceived for two different aims and this fact explains the current difficulty using them in a joined way:

Transport models have been built considering several aspects of the same problem: the mobility. These models, dealing with transport demand and its effects as congestion, are used as to forecast the demand of new infrastructures as to understand how the users utilizes the actual infrastructures. This is done following the principle that the users want to minimize their travel cost. This one (generalized cost) is intended as the sum of the operating cost of the vehicle and the cost of the travel time. So, it seems to be clear that the main and last purpose of the past and present models has been to solve traffic congestion: the vehicles must circulate in a not congested stream and this means to give the correct supply to the users. This argument considers the resources as they were infinite and the only restraint is the road capacity. This is a mechanism that leads to the building of new transport infrastructures that induce new traffic (induced traffic);

Emission models have been developed under the incentive of growing air pollution, to forecast the emissions produced by different sources. Mobile sources and, particularly, the road transport give an important contribute to air pollution, overall in respect of CO_2, CO, NO_x and VOCs. This study will be conducted considering new constraints in urban planning: the environmental road capacity. So, the first step should be to quantify the emissions produced by traffic, the emissions inventory.

1.2 Aims and Objectives

The decline of urban air quality has induced policy-makers to make great efforts to determine the best policies to adopt in order to improve environmental conditions, especially in urban areas. Policy choices need to be based on the verification of the sustainability of the alternatives. In European towns and cities, one of the biggest problems is air pollution produced by urban traffic. This means that traffic control measures and urban traffic planning should be examined in terms of their impact on environment. The quantity of pollutants produced by given traffic conditions have to be calculated in order to understand the best policy to adopt.
The aim of the present dissertation is to give support to policy-makers and technicians in the evaluation of the consequences of their choices in terms of urban traffic, and has four main objectives:

1 - Define a methodology for developing an interface application for the evaluation of the emissions impact using transport modelling;

2 - Apply the computer application thus defined, and carry out an evaluation of pollutant emissions caused by different scenarios in Porto Metropolitan Area;

3- Understand what rule transportation modelling can play in the assessment of the emissions impact of transport related policy instruments;

4- Determine the major pitfalls of the proposed methodology and potential improvements in both transport and emission models.

1.3 Study Area

Porto is located in the Northwest of Portugal, on the North bank of the Douro River, on the European Atlantic coast. The city has approximately 300.000 inhabitants (INE, 2002). However, accounting with the various satellite towns, the population of Greater Porto raises to approximately 1.5 million people, in an area of approximately 817 km^2 and a population density of 1835 people/km^2 (INE, 2002).

The territory of Porto Metropolitan Area (PMA) is mostly urban and dense, and comprises a group of municipalities (9 municipalities), as demonstrated in figure 1, which have been generating new focuses of centrality in relation with the traditional centre of the city of Porto. Without a basic structuring project, the metropolitan areas have been taking advantage of the opportunities afforded by the European Community funds, central government programs or occasional initiatives taken by their own municipalities. In the case of Porto an "opportunistic" strategy has been developed by means of complementary relations between municipalities regarding inter-mobility or the environment, which consolidates the idea of "network agglomeration".

The period between 2001 and 2005 was marked by a set of interventions that consolidate this strategy. Programs like the Porto Light Rail Metro, Porto 2001, the Polis Program and the Euro 2004 complement the urban policies currently being discussed, and place on the local agenda the public transport, mobility policy and the environment. The project for the light rail metro network in Porto was the first step towards possible complementary efforts between municipalities by proposing a new network which provides support to fast transport between the various centres, thus assuring that desired inter-mobility is achieved. Being mainly a surface light rail train, it is capable of competing directly with some bus services already in place. In consequence, PMA is currently witnessing a major restructure of its public transport system, prompted by the construction of the 1st stage of its light rail train network and the introduction of complete fare integration. Until now, its public transport system consisted of an extensive bus network (S.T.C.P – Sociedade de Transportes Colectivos do Porto) several small/medium private companies and three suburban railway lines. With regard to physical integration, S.T.C.P has been re-designing its network to optimize integration with the new mode, eliminating redundant routes, and improving the remaining bus services. The introduction of a light rail metro network brought significant accessibility improvements to the transport system, changing the mobility patterns in the metropolitan area with its environmental consequences. This recent integration of policies that should increase personal travel choices by improving alternatives to the individual transport (car) and to secure mobility that would be sustainable in the long term are the centre of a new and more embracing concept of "desire for integration", not only between modes of transport and other government policies, including environmental policies, but also between transport planning and land use planning.

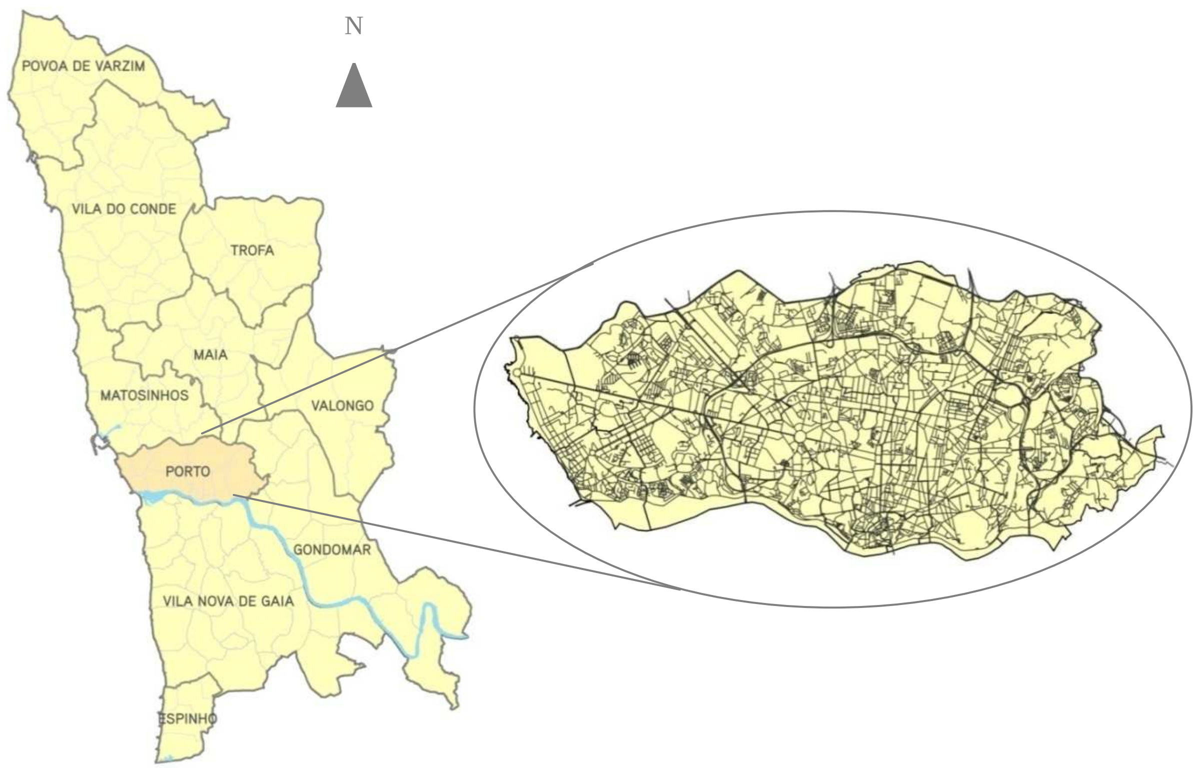

Figure 1: Porto Metropolitan Area [(1)] (+ Trofa) and Porto City

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(1) During the rest of this dissertation the reference to the Porto Metropolitan Area will include Trofa municipality. This is due to the fact that the transport model was build to give responses to the expansion of the light rail metro network including the expansion to Trofa municipality.

1.4 Dissertation Outline

This dissertation deals with the modelling of vehicle emissions, fuel consumption and the possibility of using emissions/energy and transport models in an integrated way. A critical review of the currently available models is considered in detail, including a discussion on the factors affecting vehicle emissions and fuel consumption, a description and evaluation of macroscopic emission/fuel consumption modelling techniques and the integration with the transport models available for this project dissertation, figure 2 shows the scope of this dissertation underlined by red flow boxes.

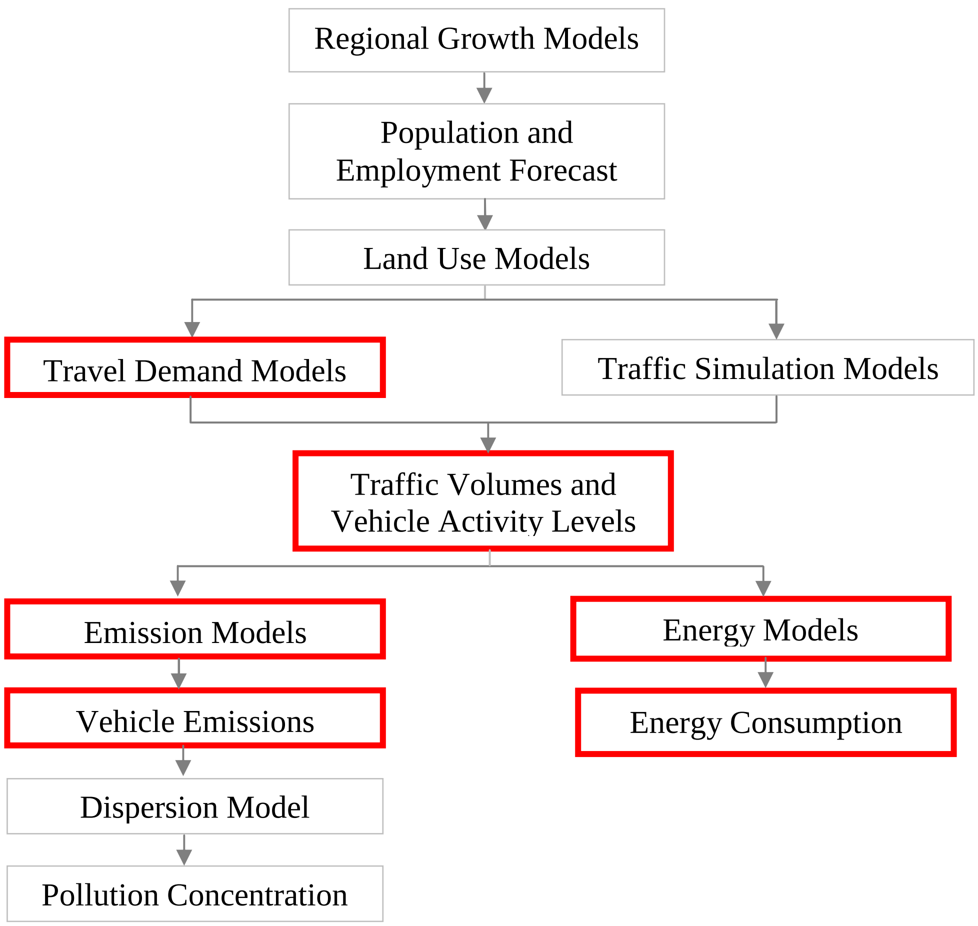

Figure 2: Dissertation scope diagram.

1.5 Dissertation Layout and Contents

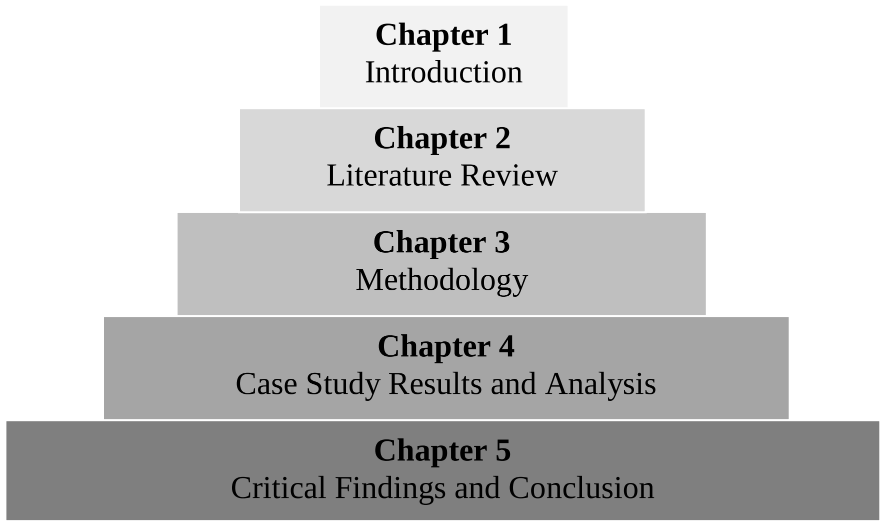

Figure 3: Dissertation layout

As showed in figure 3, the dissertation layout is divided in five chapters and starts with an introduction and the definition of the dissertation objectives. Then, in Chapter 2, a full review in emission models and transport modelling techniques considering all well-known authors and the main approaches that have been used over the years. A specific review of the models that have joint transport models with emission and fuel consumption is also carried out. In the end of this chapter there is a summary of findings of the literature review that summarizes the state of the art in transport modelling and emission/energy models.

Chapter 3 explains the methodology of emission and energy consumption considering a specific methodology for the introduction of the *COPERT IV* (Ntziachristos and Samaras, 2000) in the transport model that is going to be evaluated. There is then an explanation of all the variables that are needed to relate the emission and energy models with the transport model used, and also a demonstration of the way it is going to be implemented in the *EMME/3* (INRO Consultants). The PMA model is then explained and the variables used and the subsequent sub-models that are used during the transport modelling process are demonstrated.

Chapter 4 gives the results of the case-study, considering the methodology proposed in Chapter 3. During this chapter a number of scenarios are evaluated concerning several aspects of transport planning that can have impact in emissions and energy variables. Finally, during Chapter 5 the conclusions are delivered and discussed, considering all the scenarios that were tested and all the conclusions that can be extracted from the methodology proposed. This chapter ends with some recommendations for future work in the theme proposed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Decline in the quality of the environment has induced policy-makers to make great efforts to determine the best policies to adopt in order to improve environmental conditions, especially in urban areas. Policy choices need to be based on the verification of the sustainability of the alternatives. The transport sector is still considered to be a burden to the environment in spite of progress made in a number of areas over the last decades. More success has been achieved in improving the environmental performance of vehicles than in addressing the ever increasing transport demand.

The vehicle emission control program (2) has achieved considerable success in reducing carbon monoxide (CO) (3), oxides of nitrogen (NO_x) (4) and volatile organic compounds (VOCs) (5). Cars coming off today's production lines typically emit 90 percent less CO, 70 percent less NO_x and 80 to 90 percent less VOCs over their lifetimes than their uncontrolled counterparts of the 1960´s (EEA, European Environment Agency). In transport policy, environmental indicators are becoming more important in the assessment of current local transport policies and in the development of future policies and programmes.

(2) Motor vehicle emissions have originally been regulated by Directive 70/220/EEC and 88/77/EC and amendments to those directives. A whole series of amendments have been issued to stepwise tighten the limit values. The Auto-Oil Programme focused on the emissions of carbon monoxide (CO), Volatile Organic Compounds (VOCs), nitrogen oxides (NO_x) and particles. It resulted in the Euro 3 and Euro 4 stages for light-duty vehicles as laid down in Directive 98/70/EC and in the Euro III and IV standards for heavy duty vehicles (Directive 1999/96/EC, now repealed), as well as the fuel quality Directive 98/70/EC.

(3) CO - Carbon monoxide is responsible for health problems, where it can exacerbate cardiovascular disease and contribute to respiratory conditions in combination with other pollutants.

(4) NO_x - Nitrogen oxides cause national and transnational pollution, contributing to acid deposition and, in combination with ozone, the formation of secondary pollutants, which give rise to photochemical smog.

(5) VOCs - Volatile organic compounds comprise a variety of chemical compounds. The major environmental impact of VOCs (other than methane, CH_4) lies in their involvement in the formation of ground-level ozone, which can affect human health and damage plants.

Because of the limited data and resources available for monitoring, it is crucial that the environmental indicators, which are collected and monitored, are representative of environmental impacts, widely available, inexpensive and easy to collect.

A first step in reducing the impact of the transportation sector on the environment is to predict the amount of fuel consumed and pollutants emitted from motor vehicles based on representative travel characteristics. The objective of this chapter is to provide the reader with a background of the current state of the art review in a number of transport modelling techniques and emission and fuel consumption models. These modelling techniques are evaluated in terms of the capability of simulating the effect of traffic flow on emission and fuel consumption levels. But first the factors affecting vehicle emissions and fuel consumption are discussed in a concise way.

2.2 Factors Impacting Vehicle Emissions and Fuel Consumption

Motor vehicle emissions and fuel consumption depend on a large number of factors which can be grouped into two broad categories (Cloke, 1998): technical factors related with the design and engineering of the vehicle; operational factors related with the way in which the vehicle is used.

The more important technical factors, among many others include (i) *Engine type* - Diesel engines emit less CO, VOC, and NO_x but more particulate (Saleh, 1998) (ii) *Engine size* (capacity) - Engine capacity has been found to be an important parameter affecting pollutant emissions and fuel consumption. (iii) *Exhaust after treatment* - Pollutant emissions rates can be reduced by introducing exhaust after treatment devices such as catalytic converter and particulate traps. Catalytic converters remove CO, HC as well as NO_x from the exhaust gas after it leaves the engine. Particulate traps are used for diesel vehicles to remove exhaust particles (Cheung, 1999) and (iv) *Age and distance travelled*- Older vehicles generally produce higher emission levels.

The more significant vehicle operating factors impacting emissions and fuel consumption include (i) *Average speed and speed variation* - The average speed over a trip is a dominant factor in estimating emissions and fuel consumption (Joumard, 1995).

However, there can be significantly different emission results for cycles with approximately the same average speed (Joumard, 1995); (ii) *Instantaneous speed and acceleration* - the acceleration rate is a direct measurement of instantaneous speed variations (Joumard, 1995). Contribution of acceleration rate on vehicle emissions and fuel consumption should be significant at signal controlled junctions, where frequent stops and starts are likely to happen; and (iii) *Vehicle driving mode* - Vehicle emissions and fuel consumption behave differently at various modes, e.g., idling, accelerating, cruising and decelerating (Cernuschi, 1995). Transient modes (e.g. acceleration and deceleration) are generally more polluting than steady state driving modes (e.g. idling and cruising). Matzoros and Vliet (1992) stated that emissions and fuel consumption are higher near junctions than at mid-links and Coelho *et al.* (2005a, 2005b, 2006) estimated the emissions increased in traffic interruptions, where the vehicles are subjected to stop and go situations and accelerations and decelerations.

2.2.1 Cold Start Emissions

Total emissions are calculated by the sum of emissions from three different sources, namely the thermal stabilised engine operation (hot), the warming-up phase (cold start or excess start emissions) and the fuel evaporation. Concentrations of most pollutants during the warm-up period are many times higher than during hot operation and a different methodological approach is required to estimate over emissions. This is caused mainly by the ineffectiveness of vehicle emission control devices (such as catalytic converters) and incomplete fuel combustion at start-up. Excess start or cold start emissions are an important part of emissions inventory models considering two principal reasons: the average trip length of passenger cars in Europe is about 5 to 8 km (Laurikko *et al.*, 1989), whereas urban trips are even shorter (2 to 4 km according to André *et al.*, 1999). Consequently, a high proportion of distance can be driven under cold start conditions; secondly, the engine temperature affects the emission rate, and the ratio of cold start emissions to hot start emissions has been shown to vary between around 1 and 16 according to the vehicle technology, the pollutant, and other parameters (Joumard *et al.*, 1995).

2.2.2 Evaporative Emissions

Hydrocarbon emissions occur as a result of evaporation from the fuel system, especially for petrol vehicle. Evaporative emissions occur as a result of the volatility of the fuel and the variations in temperatures during a 24-hour period or the temperature changes in the vehicle's fuel system which occur during normal driving. Evaporative losses from vehicles are known to depend on four major factors: vehicle technology (equipped or not with carbon canisters); ambient temperature and its diurnal variation; gasoline volatility (depending on the temperature variation); driving conditions (average trip length, parking, time, etc).

2.3 Empirical Base on Emission Models

Emission models are developed from several types of emission measurements. There are different emission measurement methods available, namely laboratory engine bench testing, laboratory chassis dynamometer testing, on-road measurements and road measurements. These methods and their use with respect to emission modelling are briefly reviewed:

a) Laboratory Measurements:

When exhaust emissions are measured in a laboratory, a vehicle is fixed to and operated on a chassis dynamometer according to a specific driving cycle, which simulates certain driving conditions (in an urban area). A driving cycle is a predefined driving pattern in which operating conditions in terms of instantaneous speed, and in some cases gearshift points, are purposely defined. Driving cycles are models of driving behaviour that are thought to be representative of certain conditions and which are developed for a specific class of vehicles and for a specific period of the day (e.g. entire day, peak hour). The test-driver “drives” the vehicle in such a way that the speed-time profile follows, within specified tolerances, the driving cycle that is displayed on a driver's aid placed in view of the driver.

b) On-Board Measurements:

In addition to dynamometer testing, researchers have been using vehicles with on-board measurement systems to collect emissions and at the same time driving pattern data. In this way real-world exhaust emissions may be collected by on-board measurement instruments (Frey *et al*., 2001; Rouphail *et al*; Unal *et al*., 2002) or in a sample bag (Brown, 1998), which can be analysed after completion of the trip to obtain average emission rates [g/km]. Alternatively, emissions may be analysed and data processed and stored in real-time to obtain instantaneous emission rates [g/s]. Real world vehicle emissions have been used in the development of emission models, such as EPA MOVES model (EPA, 2004) based on the Vehicle Specific Power (VSP) methodology (Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission System).

c) Road Measurements:

Three types of road measurements were identified in the literature: remote-sensing; in-traffic emission sampling; and fixed-point emission sampling. Remote-sensing provides a practical approach to routinely measure instantaneous on road exhaust emissions from large fleets of individual vehicles at certain locations in the road network resulting in fuel-based emission factors, i.e. g/kg of fuel (Zhang *et al.*, 1995). Remote sensing has contributed to an increased understanding of real world emission behaviour of vehicles and it is a promising technique for emission model validation purposes (Sjödin, 1996). In-traffic emission sampling was reported in only one study (EPAV, 1999). A vehicle in a moving traffic stream was used to sample air about 1 meter above the vehicle and emissions computed by making assumptions about average fuel consumption and the ratio of pollutant concentrations to CO_2. This approach was an innovative way of determining average vehicle fleet emissions, but its accuracy limited by its assumptions and its application limited to a few road sections and operating conditions. It may therefore be most useful as a validation tool. Fixed-point emission sampling has been used for indirect estimation of mean emission factors from traffic streams ("inverse" dispersion modelling). Ambient air pollutant concentrations are monitored at the kerbside (e.g. Zweidinger *et al*., 1988) or at a point above the road (e.g. Morawska *et al*., 2001).

2. 4 Considerations in Emissions Modelling

Vehicle exhaust emissions and fuel consumption rates are dependent on a range of technical and operational factors. Clearly, it is not cost-effective to take into account all factors at the same time. Therefore, it is important to identify those that are most related to modelling emissions and fuel consumption in transport models.

Much of the international research so far has concentrated on the effects of factors such as engine capacity, fuel type, speed and rate of accelerations. It is recognised that cold start and evaporative emissions can be significant under certain conditions. The cold start period and the amount of evaporative emissions are dependent on the ambient conditions and the period of parking, which is out of the scope of this study, considering the lack of consistent information. Moreover, the cold start period is not well-defined in terms of the transition to hot emissions (Cloke, 1998). Therefore, emissions and fuel consumption considered in this study case are from hot stabilised engines only.

2.5 Emission Modelling Approaches

The general approach in estimating emissions and fuel consumption from road traffic is the sum of the product of emission or fuel consumption factors and the traffic variables (Cloke, 1998). There has been an array of emission and fuel consumption models derived for different spatial and temporal requirements. Emission models can be categorized into three main groups: Emission factor models **(**2.5.1), Average speed models (2.5.2) and Modal models (2.5.3).

2.5.1 Emission Factor Models

Emission factor models employ single emission factors for individual types of vehicles operating in a particular type of driving conditions (e.g. urban driving). The emission factors are calculated as a mean value of repeated measurement of total emissions over a given driving cycle, which are usually expressed in terms of the mass of pollutant emitted per unit distance travelled (e.g. g/vehicle.km). The German-Swiss model (Hassel *et al*., 1993) is the result of a five year joint German/Swiss research project undertaken in order to determine the emissions of all relevant categories of road vehicles in the two countries. The results of the German/Swiss model in terms of emission factors can be used in a wide range of applications. These models are designed to provide emission inventory information on a large spatial scale, such as national and regional levels, where there is little detail on traffic flows and operation. This approach is easy and simple to apply in emission estimation, but the major disadvantages is that these models are not sensitive to a vehicle's operating modes.

2.5.2 Average Speed Models

The average speed approach is the most commonly used method for estimating emissions from road traffic, like the *COPERT IV* (Computer Program to Calculate Emissions from Road Transport) data base (Ntzachristos and Samaras, 2000). *COPERT IV* is a software programme aiming at the calculation of air pollutant emissions from road transport. The development of *COPERT* has been financed by the European Environment Agency (EEA), in the framework of the activities of the European Topic Centre on Air and Climate Change (EIONET). These tools allow for a transparent and standardised, hence consistent and comparable data collecting and emissions reporting procedure in accordance with the requirements of international conventions and protocols and EU legislation. This model is based on the emission rates generated for various driving patterns. The average emission rate for each driving pattern as a whole is measured, and assigned to the mean speed of the driving pattern in question. The measurements for several vehicles of the same technology (engine type, model year and emission standard) and engine capacity class, obtained over several driving patterns, are grouped together. Then, a speed-dependent emission function is derived. This is repeated for all vehicle classes. This means that in addition to vehicle type, the average speed of the vehicle is the only decisive parameter used to estimate its emission rates. This restricts the approach to regional and national emission estimates. The dynamics of a driving pattern - which are especially important during urban driving - are only taken into account implicitly.

The MOBILE model (US EPA, 1994) has emission rates that are derived from a laboratory based test procedure known as the Federal Test Procedure (FTP) (6) in the United States, which has been used to determine compliance of vehicles with federal emission standard since 1972. However, the FTP driving cycle has been criticized to be underrepresented the common driving pattern characterized by the high-speed driving and high acceleration rates. Some driving cycles used to develop speed correction factors for adjustment of the baseline emission rates, are also not considered to be adequately representative of urban driving conditions.

EMFAC (Emissions Factor Model) is a US on-road mobile sources emission factor model developed by the California Air Resources Board (CARB). This model is one of four Motor Vehicle Emission Inventory (MVEI) models that are used together to develop emission inventories in California. EMFAC accepts input from CALIMFAC, which provides basic emission rates, and WEIGHT, which estimates vehicle activity by model year, to produce emission factors.

The last model BURDEN combines vehicle travel data (VKT (7), number of vehicles) with EMFAC's emission factors to produce the emission inventory.

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(6) The Federal Test Procedure (FTP) is a standardized laboratory test method used in the United States for new vehicle testing. Selected pre-production prototypes of new vehicle models are driven by a trained driver in a laboratory on a dynamometer. The same test parameters and driving cycles are used to ensure that each vehicle is tested under identical conditions, and that the results are consistent and repeatable.

(7) VKT – Vehicle Kilometres Travelled is the total kilometres travelled by motor vehicles on the road system during a given period of time.

EMFAC 2000 model computes basic hot running emission rates, expressed as g/mile, for light-duty petrol vehicles, which are classified in terms of model year, vehicle technology (carburetted, throttle-body injected and fuel injected) and “emissions level regime” (normal, moderate, high, very high and super) and for three different air pollutants (CO, HC, NO_x) and CO_2.

2.5.3 Modal Models

The so-called “modal modelling” emissions are measured continuously at the exhaust during chassis dynamometer tests and stored at a particular time interval (usually every second), this approach categorizes the vehicle operation into four modes: idle, acceleration, deceleration and cruise. The operational condition of the vehicle - defined in current models by instantaneous driving speed and acceleration (calculated from the speed – time curve) is recorded simultaneously with the emission rate. In this way, it is possible to generate emission functions by assigning exactly-defined emission values to particular operational conditions.

For example, the emission function for each pollutant can be defined as a two-dimensional matrix, with the rows representing a velocity interval (km/h), and the columns being assigned to an interval of acceleration time’s velocity (m^2/s^3). All instantaneous emission data are put into one cell of the emission matrix, according to the velocity and acceleration of the measured vehicle at that time. The emission function is the arithmetic mean of all emission quantities in each cell of the emission matrix. Therefore, the emission function is stepwise and two-dimensional, assigning a mean emission level to every pair of velocity and acceleration values. In the modal modelling approach, the emission functions are used to calculate emissions from a vehicle over any driving cycle, given the second-by-second velocity and acceleration values of the cycle.

2.5.3.1 Speed and Acceleration Based

A convenient method to characterize vehicle modal events is to set up a speed/acceleration matrix (Zachariadis, *et al*., 1997; Kishi, *et al.*, 1996; Hansen, *et al.*, 1995; Watsons, *et al.*, 1985). The speed/acceleration matrix gives the instantaneous emissions and fuel consumption rates for different combinations of instantaneous speed and acceleration. For each cell of speed and acceleration, the emission or fuel consumption rates are averaged to give a mean value.

Other researchers use the product of speed and acceleration instead of the acceleration rate. The MODEM [(8)] emission model is developed by this method (Joumard, 1995). Emissions and fuel consumption data are classified into different classes of speed and the product of (speed $\times$ acceleration). Instantaneous emissions and fuel consumption are then estimated by selecting values from the corresponding combination of speed and acceleration. Cernuschi *et al*. 1995) grouped the data into five different acceleration classes, representative of high and low decelerating modes, cruising speed modes as well as high and low accelerating modes.

For every class defined, best-fit lines were obtained by regression analysis on the emission-instantaneous speed plots. This method is in fact applying a specific case of the speed/acceleration map by restricting the acceleration ranges to only five classes. This reduces the data requirement in the construction of speed/acceleration map. The problem of this approach is the resolution of the speed/acceleration classes. Theoretically, the finer is the resolution of the matrix the higher is the accuracy. However, it is highly data intensive to construct a full and useful map as fine as 0.1 km/h resolution. Owing to time and manpower resources constraints, it is very difficult, if not impossible, to collect such huge amount of data. Kenworthy *et al.* (1999) stated that constructing acceleration/deceleration maps to 0.1 km/h is an unrealistic, if not impossible task.

[(8)] The MODEM model (Modelling of Emissions and Fuel Consumption in Urban Areas) was derived from the DRIVE research program.

2.5.3.2 Emission Map Based on Engine Power and Speed

Another modal emissions modelling approach is to develop an emission and fuel consumption map based on engine power and speed (West, 1997). Instantaneous engine operational data such as engine speed and exhaust temperature are obtained on-road as a function of speed and acceleration. The engine conditions are then duplicated on the laboratory dynamometer vehicle testing and taking corresponding emissions and fuel consumption measurements. The data sets are then merged to provide the emissions and fuel consumption against functions of speed and acceleration. These maps serve as a lookup table of emissions and fuel consumption as combinations of speed and acceleration. Again, the resolution of the lookup table is a problem. Moreover, the emission mapping method can be very time consuming in matching the engine conditions to emissions, fuel consumption and speed profiles (Barth, 1996) .

An example of a map based on engine power and speed emission model is EcoGest (Silva *et al.*, 2004). This model can solve the dynamic laws of vehicles for specific acceleration and deceleration curves of typical driving modes (slow, normal and agressive). Main inputs of EcoGest are the type of driving mode, vehicle characteristics, number of passengers, time spent at idle and the route - characterized by the topography, number and localization of stop signs and maximum allowed speed. Based on those inputs EcoGest is capable of calculating along the trip the localization of the vehicle, vehicle velocity, position of the accelerator pedal, gearbox selection, and the engine rotation speed. In addition, using the throttle position and the engine speed, this model is capable of estimating instantaneous fuel consumption as well as instantaneous and average NO_x, CO, CO_2 and HC exhaust emissions. These calculations are done using emissions and fuel consumption distribution maps as a function of engine speed and throttle position. These maps could be obtained either numerically, or experimentally.

2.5.3.3 Physical Power-Demand Modal Modelling Approach

Barth and co-workers developed the Comprehensive Modal Emission Model (CMEM) which employed the physical power-demand modal modelling approach. In this approach, the emissions process is stratified into different components that correspond to physical phenomena associated with vehicle operation and emission production (Barth, 1996). Each component is then modelled as an analytical representation consisting of 55 parameters that are characteristic of the process. Data from dynamometer tests of different vehicle types are used to calibrate the parameters.

This approach provides explanation for the variations in emissions among different parameters and can potentially handle all the factors in the vehicle operating environment that affect emissions. However, this approach is highly data intensive. There are a large number of physical variables for various vehicle types to be determined. Moreover, too high degree of parameterisation may complicate the modelling exercise. In CMEM, 24 vehicle categories are identified based on fuel and emission control technology of the vehicles. Normally, vehicles in traffic models are classified into limited types in terms of the vehicle size. Thus, such high resolution of vehicle classifications may be too complicated for interface with traffic models.

2.5.3.4 Models Based on Second by Second On-Board Emission Measures

Models based on second by second on-board measurements are based on a modal emission approach but with a different perspective (Frey *et al.*, 2001; Rouphail *et al*.,2001; Unal *et al.*,2002). This approach considers the variable Vehicle Specific Power (VSP) which has been identified as a useful explanatory variable for emission estimation for light duty gasoline vehicles (Jimenez-Palacios, 1999); it is based on on-board emission measurements (Frey *et al*., 2002, 2003, 2006) and is a function of vehicle speed, road grade, and acceleration. This fact imply that it can be possible to obtain representative on-board emission measurements and values to better suited the current reality of the Portuguese scenarios or in a more local area like Porto Metropolitan Area. Models based on second by second on-board emission measurements use relatively large sample sizes of repeated runs as a basis for developing average emission rates and confidence intervals for the averages. After data collection from on-board measurements and laboratory dynamometer, this information is then compiled for use in developing a conceptual modelling approach. This methodology is better suited for microscopic and mesoscopic analysis, and can be important for situations where the evaluation of emissions are to be taken in small scale scenarios, like the different impact between a roundabout and traffic light controlled crossing (Coelho *et al.*, 2005a, 2006).

2.6 Estimation of Vehicle Fuel Consumption

Substantial energy savings can be achieved through urban traffic management strategies aimed at improving mobility and reducing delay. Fuel consumption and emissions have thus become increasingly important measures of effectiveness in evaluating traffic management strategies. Substantial research on vehicular energy consumption has been conducted since the 1970's, resulting in an array of fuel consumption models. In this section, a number of such models which have been widely adopted are reviewed.

2.6.1 Models for Estimating Vehicle Fuel Consumption

Many models have been proposed by researchers to estimate vehicle fuel consumption rates. These models can be grouped into three main categories: (2.6.2) Average-speed models that estimate fuel consumption based on the average trip speed. (2.6.3) Modal models that estimate each portion of total fuel consumption associated with each operating condition along an entire trip; and (2.6.4) Instantaneous models, also termed microscopic models that relate fuel consumption to the time history of driving patterns and road gradient; these models are described in further detail in the following sub-sections.

2.6.2 Fuel Consumption Models Based on Average Speed

Average speed fuel consumption models relate fuel consumption to trip time, or the reciprocal of average trip speed (Evans and Herman, 1978). These models (also called Elemental Models) are suitable for estimating the total fuel consumption in large urban traffic systems and for assessing the impact of transportation management schemes that likely to have impacts on average speeds and the level of travel demand. Average speed models can be applied when the average speed ranges between 10 and 50 km/h, however these models have limited application at very low speeds and at high speeds where the aerodynamic drag becomes a dominant factor and thus the fuel consumption cannot be explained solely by the average speed.

Lam (1985) developed a second-degree statistical model for estimating vehicle fuel consumption based on a vehicle's average speed. The Model was developed using high speed and uniform speed driving cycles. Lam proposed two models. The first of these models relates a vehicle's fuel consumption to the average trip speed, engine size and vehicle mass for urban driving. The second model computes the fuel consumption using the same explanatory variables, except that the model is valid for rural driving conditions.

2.6.3 Drive Modal Fuel Consumption Models

Areas of application of drive modal fuel consumption models are similar to those of instantaneous models. Specifically, these models are applied to the evaluation of the energy impacts associated with operational-level traffic improvement projects. Drive modal fuel consumption models attempt to capture the fuel consumption associated with different vehicle operating conditions in a typical trip. These models are based on the assumption that each driving mode of a vehicle, e.g. cruising, acceleration/deceleration, and idling, is independent of one another and the total fuel consumed in a trip is simply equal to the sum of the fuel used for each driving mode. Unlike the instantaneous models, the drive modal models require a number of explanatory variables, including the vehicle's cruise speed (or the initial or terminal speed of each driving mode), number of vehicle stops (complete stops, effective stops, first time stops, and subsequent stops), stopped time, and/or total delay along a trip. However, because the "average" coefficients, which account for the "average manoeuvre" taken by drivers, are implicit in the mode, these models are unable to capture any differences that result from differing driver characteristics, or any differences that result from travel conditions that differ from the "average travel condition."

An attempt to overcome these limitations was made by Baker (1995) who employed a simple acceleration/deceleration-speed relationship to capture the differences in driver behaviours. The basic models were derived from data collected using a TravTek vehicle in Orlando, Florida. The models developed predict fuel consumption rates as a function of vehicle's speed during idle, cruise and stop/go modes of driving. Using the acceleration/deceleration-speed relationship, a more microscopic speed profile for a vehicle can be defined and then used to compute time spent during each mode (i.e. cruise, deceleration, and acceleration mode). This model suffers from the general limitations of modal models in that it assumes that two drivers who drive at the same speed will have the same acceleration/deceleration characteristics and is unable to capture differences that arise from different travel conditions.

Dion *et al*. (1999) developed a mesoscopic model that estimates average vehicle fuel consumption based on an average speed, an average number of vehicle stops per unit distance, and average stop duration for eight light duty gasoline vehicles under hot-stabilized conditions. Similar to the modal models, the model estimates separately fuel consumption rates per unit distance during each mode of operation of a vehicle (deceleration, idling, acceleration, and cruising) using relationships derived from a microscopic fuel consumption model (Ahn *et al*., 2002).

2.6.4 Instantaneous Fuel Consumption Models

Instantaneous fuel consumption models compute a vehicle's fuel consumption based on instantaneous measurements of explanatory variables. Examples of explanatory variables include the vehicle speed, the roadway gradient, and the vehicle's power. The instantaneous fuel consumption models are ideal for the evaluation of the energy impacts that are associated with operational-level traffic improvement projects because they are sensitive to vehicle-to-vehicle and vehicle-to-control interactions.

The most common of these fuel consumption models uses the vehicle's instantaneous power as an explanatory variable based on the principle of conservation of energy. The total fuel consumed by a vehicle is an input source of energy that is transformed into kinetic energy for the movement of the vehicle and required to overcome the internal energy that results from friction or resistance. These models attempt to determine the proportion of the total input energy required to meet the vehicle's steady-state speed drag and inertial power requirements for vehicle acceleration. The original power-based model was developed by Post *et al.* (1983) where it computed aggregate fuel consumption estimates for on-road driving within two percent of the actual measured fuel usage for an individual vehicle.

The model can be applied to any traffic situation provided on-road power demand is known. The instantaneous power demand is a function of a vehicle's mass, drag, speed, acceleration and road gradient. The Australian Road Research Board extended the original power-based model to produce more accurate estimates of fuel consumption in different driving modes based on vehicle speed and road geometry data (Akçelik, 1996). Unlike the original power-based model, this model predicts vehicle fuel consumption in different driving modes by applying different efficiency parameters to overcome the inadequacy as a result of use of an average efficient factor for all driving modes. Ahn *et al.* (2002) developed a microscopic fuel consumption model based on second-by-second speed/acceleration data and fuel consumption and emission measurements that were collected by the Oak Ridge Laboratory Lab for eight light-duty vehicles and light-duty trucks. A composite vehicle was derived as a typical average vehicle by taking average fuel consumption and emission rates for all eight vehicles at various speeds and accelerations.

2.7 Transport Models

Urban transportation planning is the process that leads to decisions on transportation policies and programs. In this process, planners develop information about the impacts of implementing alternative courses of action involving transportation services, such as new highways, bus route changes, or parking restrictions. This information is used to help decision-makers in their selection of transportation policies and programs.

The transportation planning process relies on travel demand forecasting and transport models, which involves predicting the impacts that various policies and programs will have on travel in the urban area. The forecasting and modelling process also provides detailed information, such as traffic volumes, and turning movements, to be used by engineers and planners in their designs. A travel demand model might include the number of cars on a future freeway or the number of passengers on a new express bus/metro service. It might also predict the amount of reduction in auto use that would occur in response to a new policy imposing taxes on central-area parking. The travel demand models have always been used in the traditional transport planning process. In this section a brief overview in transport models is given and the concept underlying them is presented. These models can be classified in two different categories: *the travel demand models and the traffic simulation models*. The two modelling techniques have distinct, yet complementary data needs: travel demand models require more regional level data (macroscopic scale), while traffic simulation models require corridor, link and individual vehicle level data (microscopic scale). Each of these required data elements is discussed in more detail in the following subsections.

2.7.1 The Travel Demand Models

The basic modelling approach used in most of the travel demand models consists in a sequential four step process by which the number of daily or hourly trips is estimated, distributed among origin and destination zones, divided according to mode of travel, and then assigned to roads and transit networks. The classical four main steps are trip generation, trip distribution, modal choice and assignment. These components are described in detail in the literature (e.g., Warner, 1985), and are briefly outlined below: *Trip generation*: As the first step of the process, it deals with the decision to travel. Trip generation models are used to predict the trip ends generated by a household or a zone, usually on a daily or peak-period basis. Trip ends are classified as being either a production or an attraction (separated models are used to predict productions and attractions). Variable used as predictors of trip productions included household income, auto ownership and size, number of workers per household, residential income, auto ownership and size, number of workers per household, residential density, and distance of the zone from the central business district. Trip attraction predictor includes zonal employment levels, zonal floor space, and accessibility to the work force. Trip generation, as applied in regional transportation planning, is usually based on mathematical relationships between trips ends and socioeconomics or activity characteristics of the land use generating or attracting the trips. Forecasting the number of person-trips that will begin from or end in each traffic analysis zone in the region on a typical day of the target year, estimated separately for a number of trip purposes;

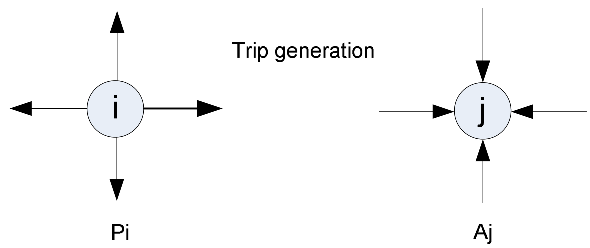

Figure 4: Trip generation step

__Trip distribution__: The second step involves the task of a trip distribution model that "distributes" and "link's up" the zonal trip ends, that is, the production and attraction for each zone as predicted by the trip generation model in order to predict the flow of the trips Tij from each production zone i to each attraction zone j.

Many types of trip distribution models exist. These include growth factor techniques such as the *Fratar Method*, which were used in early transportation studies, but which are now used mostly for short-term updating of trip tables and estimations of "through trips" for urban areas (Hutchinson, 1974; Ortuzar and Willumsen, 1994). Intervening opportunities models, which have seen limited use over the years, are difficult to calibrate, and have never enjoyed generalized acceptance. The most used trip distribution model is the gravity model. It received its name from its earliest derivation as an analogy drawn between the "spatial interaction" of trips making and the gravitational interaction of physical bodies distributed over space. The most typical version of the gravity model used in transportation planning applications is:

$$T_{ij} = \frac{P_i \lfloor A_j f_{ij} k_{ij} \rfloor}{\sum_{n=1}^{m} A_j f_{ij} k_{ij}}$$ *(Equation 1)*

P_i= total number of trips produced in zone i

A_j= total number of trips attracted to zone j

f_{ij}= friction factor

k_{ij}=adjustment factor for trip interchanges between zones *i* and *j*

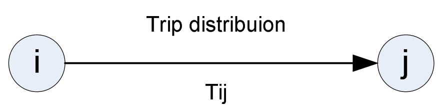

Figure 5: Trip distribution step

Modal choice: The third step involves the choice of travel mode. Factors that affect the mode selected include: trip characteristics (length of trip, time of day, orientation to central business district), trip purpose (home based work, non-work), transportation system characteristics (relative service level and costs associated with available modes) and trip-maker characteristics (auto-ownership, income). The dominant model approach during the last decades is the multinomial logit model, that model the trip choices of individuals on the basis of their utilities (or disutility's) associated with travel times (with various means of transport) and other parameters (including trip costs) determined through a statistical analysis. A basic reference to the topic is Ben-Akiva and Lerman (1987). Typically the logit model used in transportation planning applications can be defined as:

$$P_{ij} = \frac{e^{v_{ij}}}{\sum_{z} e^{vi}}$$ *(Equation 2)*

P_{ij}= probability of trips from zone i choosing destination j

V_{ij}= A_j-α t_{ij}+β t^2_{ij} where α and β are parameters to be estimated

A_j=trip attractions estimated for zone j

t_{ij}= road travel time to zone j from zone i

Z= total number of zones

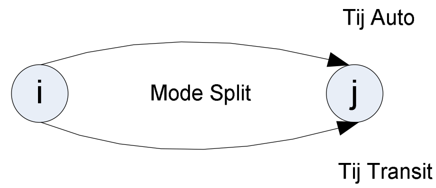

Figure 6: Mode choice step

<u>*Network assignment*</u>: The fourth step involves the choice of route or paths between pairs of zones for each travel mode. The traffic assignment problem deals with the analysis of how travel demand between all pairs of origins and destinations in a traffic network is distributed on the links. The solution obtained provides flow volumes on all links in the network, often based on the principle that all travellers only use the routes with the shortest travel times although many alternatives exist. When congestion exists in the traffic network the solutions are obtained by solving a non-linear optimisation problem. An excellent introduction to the topic is available in Sheffi (1985), and a more recent, in-depth presentation is given in Patriksson (1994).

A number of issues must be considered, including: average vehicle-occupancies, patterns of demand; assignment by time of day (to investigate performance during peak periods when capacity limitation become critical) and trip direction (e.g. flows during morning peak times are predominantly toward major activity centres).

Trips are assigned between nodes on the network by either minimising individual user cost (user equilibrium) or by minimising overall cost to the system (system equilibrium). Using the data collected through travel surveys, traffic counts and studies, these models are created, calibrated and applied to evaluate the present system and analyse the future performance of the system.

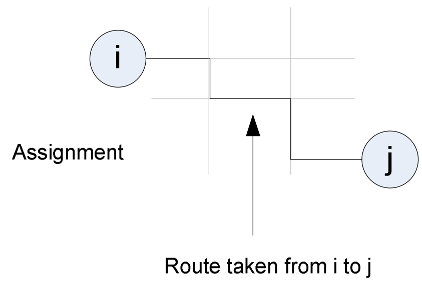

Figure 7: Assignment step

The calibrated results of the four-step model are used to identify the number of vehicle trips taken, vehicle distance (kilometres) travelled (VKT) and average speeds under varying infrastructure scenarios.

To provide a structure overview of these modelling achievements, the models have been classified according to level-of-detail (microscopic, mesoscopic, macroscopic). Other criteria have been considered as well, namely scale of the independent variables (continuous, semi-discrete, discrete), representation of processes (deterministic, stochastic), operationalization (analytical, simulation) and application area (e.g. links, networks) (Papacostas and Prevedouros, 1993). With respect to model applicability, microscopic simulation models are ideally suited for off-line simulations, for instance to test roadway geometry. From the view-point of applicability to model-base destination, prediction and control, the absence of a closed analytical solution presents a problem that is not easily solved. Moreover, several authors argue that microscopic models are unsuitable to represent true macroscopic characteristics of traffic flow (queue lengths, capacities) due to unobservability of several parameters in microscopic flow models and the non-linear dependence of model outcomes on these parameters.

2.7.2 Traffic Simulation Models

Traffic simulation models simulate the traffic flow at a vehicular level and can be classified in two different scales, macroscopic and microscopic models.

The macroscopic models simulate a vehicle fleet that flows on the links while the microscopic models can keep track of each vehicle in the simulated network. These last ones include vehicle manoeuvring models which can be used to study the vehicle acceleration/deceleration characteristics under different levels of traffic flow. The first order macroscopic models (Lighthill and Whitham, 1955) make the hypodissertation that the system is always in equilibrium condition and so the user reaction is neglected, the second order macroscopic models (Payne, 1971) use a dynamic equation of speed in which acceleration is present.

The microscopic models attempt to describe the individual vehicle behaviour; the vehicle is defined by the position on road segment, the speed and the acceleration. To correctly modelize the flow, the model has to consider the maximum speed imposed on the segment and the driver sensitivity to present interactions. Traffic simulation models use link level data and produce microscopic measures of effectiveness while simulating the movements of individual vehicles. Specific vehicle movements such as turning movements, acceleration/deceleration rates, lane changing behaviour, yellow-signal reaction, aggressiveness/defensiveness in driving, passing, gap acceptance and even accidents can be modelled using traffic simulation models. Link level measures of effectiveness such as volume, density, level of service, stop delay, moving delay, volume to capacity ratio, queue backup; numbers of signal cycles are also produced.

2.8 Transport Models with Integrated Emission Module

<u>Travel demand models with an emission module</u>: The most significant example of an improved travel demand model is the STEP package (Orcutt, 1976), designed for planning applications and policy analysis. STEP is a travel demand analysis package composed of an integrated set of travel demand and activity analysis model of transport supply. STEP is based on micro-simulation – a modelling technique which uses the individual or household as the basic unit of analysis rather than dealing with population averages.

A number of versions of STEP are currently available, including options that permit the analysis of activity data as well as travel data, and versions that use either MOBILE or California EMFAC emissions data.

Integrated Transportation/Emission Modelling (ITEM) set (Barth *et al*., 1996) is based on a hybrid macroscale/microscale modelling approach. Detailed vehicle activity is determined through microscale simulation modules which are stratified by road facility type. A macroscale model (referred to as the wide area model) capable of simulating regional areas is then used to integrate all of the microscale simulation models together. There is strong interaction between the macroscale model and the microscale modules. Transportation parameters determined by the macroscale wide-area model are used to drive the input parameters of the modules. In addition, information sent back from the microscale modules is used as feedback to the wide-area model, which helps improve the system's overall traffic estimation.

<u>Traffic simulation models with an emission module</u>: The match between traffic simulation and emissions models is more frequent in literature. Some cases have been developed starting from a traffic simulation model and, afterwards, the link with the emission calculation has been searched. Other cases have followed the inverse path, they have been conceived as modal emission models, but thinking about a link with the traffic simulation models. This classification in two groups will be followed in the exposition and a list of the models contained in the two groups is given here the first group contains the models dealing with a traffic simulation concept and that have or can have an emission module (STRADA; MICRO2; SATURN [9]; INTEGRATION; FHWA's TRAF-NETSIM; TRANSITY7F; aaSidra) the second group contains emissions models that are linkable with the traffic simulation models (UC Riverside's Modal Emissions Model; Georgia Tech's GIS-Based Mobile Emissions Model).

There also integrated models that were developed to be focused in particular objectives, such as, for example, the impact of traffic interruptions in the traffic performance and emissions (Coelho *et al*. 2008).

[9] SATURN LANES (Links and Network Emissions from SATURN) model is an aggregate modal model. This model is a postprocessor emission model for the SATURN model.

2.9 Summary of Findings

A review of the current state-of-the-art in vehicle energy and emission modelling demonstrates considerable research efforts in this arena. These research efforts have resulted in the development of several types of energy and emission models, including macroscopic and microscopic models.

These models attempt to capture the impact of a number of factors on vehicle emissions and energy consumption, including travel-related, driver-related, highway-related, and vehicle-related factors. While the macroscopic models attempt to capture all factors, they use average speed as the sole explanatory variable of travel and driver-related factors. Alternatively, microscopic models attempt to capture instantaneous changes in travel and driver-related factors in estimating emissions.

While the literature provides significant information on the various modelling approaches, it does demonstrate a void in terms of using emission models and transport models in a joined way. The objective of this research effort is to create a methodology to evaluate the impact of travel patterns on vehicle fuel consumption and emission levels. The following table summarizes the literature review considering all the emission models and authors.

Literature Review - Summary

Type of Model		Model Name		Authors
Pollutant Emissions	Emission Factor Models	German Swiss Emission Hand Book		Hassel *et al.*, 1993
	Average Speed Models	MOBILE		US EPA, 1994
		EMFAC		California Air Resources Board (CARB)
		COPERT IV		(Ntzachristos and Samaras, 2000
	Modal Models	Speed and acceleration based	MODEM	Joumard *et al.*, 1995
		Emission map based on engine power and speed	West *et al.*, 1997	
			Ecogest	Silva C.M, Farias T. L, 2006
		Physical power demand modal modelling	CMEM	Barth *et al.*, 1996
		Models based on second by second on-board emission measures	MOVES	US EPA, 2004
			Frey *et al.*, 2001; Rouphail *et al.*,2001; Unal *et al.*,2002	
Fuel Consumption	Models for Estimating Vehicle Fuel Consumption	Instantaneous Fuel Consumption Models	Post *et. al.* (1984); Akçelik *et.al.* (1996); Ahn *et al.* (1999)	
		Drive Modal Fuel Consumption Models	Baker *et. al.* (1994); Dion *et al*. (1999, 2000)	
		Fuel Consumption Models Based on Average Speed	Elemental	Evans and Herman, (1978) Lam *et al.* (1985)
Transport Models with Integrated Emission Module	Travel Demand Models with an Emission Module	STEP package	STEP	Orcutt, 1976
		Integrated Transportation/Emission Modeling	ITEM	Barth et al., 1993
	Traffic Simulation Models with an Emission Module	Have Emission Model	STRADA; MICRO2; SATURN (LANES); INTEGRATION; FHWA's TRAF-NETSIM; TRANSITY7F; aaSidra	
		Linkable Emission Model	UC Riverside's Modal Emissions Model; Georgia Tech's GIS-Based Mobile Emissions Model	

Table 1: Emission and fuel consumption models literature review.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In general terms, the estimation of the mobility-related emissions can be based on the equation “*E = e.a*” *(Equation 3)*, where “E” is the amount of emission, “e” is the emission rate per unit of activity, and “a” is the amount of transport activity (product between travelled kilometres and number of vehicles). This equation applies to every level, from a single engine to a whole fleet, from a single road to the whole of Europe. A more desegregated model is desirable and the need to preserve the true variability in the data for model estimation rather than remove it through aggregation is the key. Based on this overview, this chapter reveals the proposed emission calculation principals and the methodology proposed to evaluate the scenarios that are considered in the Porto Metropolitan Area study case. In order to consider the possible link between mobility models and emission models it is important to consider which emission model will be used and what are the input data requirements by emission models and the outputs of the transport models, in order to carry out the calculation of emissions in the context of transport modelling background. As the mobility models considered in the framework of this study address a relative low level of resolution (metropolitan area level), it was considered for this case study that *COPERT IV* model is able to work at this spatial resolution, and can deliver a common platform for emission and fuel consumption. First in this chapter, a simple and concise description of the Metropolitan Area model is revealed, considering all the important parameters that may influence the calculation methodology and the final results. The travel demand forecasting software that is going to be used in this study case is the *EMME/3* (short name for *Equilibre Multimodal, Multimodal Equilibrium*). A brief description of this software is given to better understand the working procedures and the possible outputs that this specific commercial software can give in the Porto Metropolitan Area travel demand model.

3.2 Porto Metropolitan Area Travel Demand Model

The Porto Metropolitan Area travel demand model used for the emission calculation in this project dissertation has been developed by TRENMO [10] since 2005, and is still in continuous revision. The model was built using the commercial software *EMME/3*, to be part of several consultancy studies evolving transportation investment appraisal and cost benefit analysis (CBA), particularly for scenarios concerning the expansion of the light rail metro (Metro do Porto) network and the evaluation of the new redesigned local bus network (S.T.C.P). Most of the data in the built model (road network, intersection delays, demand matrices and transit networks) was collected considering the information that was presently available, and other that was collected through *in loco* measurements (traffic counts and road geometry). This information is considered updated and it is calibrated bearing in mind a scenario based year (2005). This is particularly relevant in the demand side since it is the information that is going to have the higher impact in the emissions calculation final results. Considering the objectives of this project and the information that was available, the Porto Metropolitan Area model can give a set of outputs that will satisfy the demand of the environmental variables as showed in the next discussion points.

3.2.1 Travel Demand Model Software

The software used to evaluate the Porto Metropolitan Area study case was the *EMME/3* package by Inro. This software is an interactive-graphic multimodal urban transportation planning system. It offers to the user a complete and comprehensive set of tools for demand modelling, multimodal network modelling and analysis, and for the implementation of evaluation procedures. *EMME/3* is also a decision support system which provides uniform and efficient data handling procedures, including input data validation.

[10] TRENMO Engenharia Lda, is a transport consultancy company. During the past years TRENMO has been developing several transport modelling projects, including the PMA transport model.

Its data bank is structured to permit the simultaneous description, analysis and comparison of several contemplated scenarios. The software provides a general framework, supported by a consistent user interface, for implementing a wide variety of travel demand forecasting procedures.

An essential aspect of any urban transportation planning endeavour is the construction of a data bank which will support the quantitative analysis and evaluation of the contemplated changes. The data bank is a representation of the transportation infrastructure, the economic activities and the socio-economic characteristics of the population in the urban area studied. *EMME/3* also offers the user a wide variety of tools for the direct comparison of future scenarios which may reflect changes in the road and transit networks or changes in the socio-economic characteristics of the urban area studied. Once the data bank is set up, the planner can engage in the planning process with the advantage of instantaneous visualization of input data, results of interactive computations, assignment results and other information retrieved from the data bank. All the data can be entered into the data bank interactively, using the appropriately designed interactive editors which are part of *EMME/3*, or in batch mode.

The algorithms of allocation implemented in the *EMME/3* model are different for private transport and for public transport. For private transport, *EMME/3* uses the technique of allocating at equilibrium. In other words, the hourly mobility demand, expressed in private vehicles, is assigned to the network in such a way that the trip times for different logical routes between an origin and a destination are equal; consequently, knowing the state of the network, this model will use the route which minimises the cost function, i.e. the trip time. The algorithm implemented in the model is based on the standard Frank and Wolf optimisation rule and requires the availability of correct cost functions for different links, which determine the relationship between trip times and the traffic flows (flow curves). The result of the allocation relates to the configuration of the network flows, the trip times on links and between origin/destination pairs, and the trip speed on single network links.

The public transport allocation is handled in a different manner. In fact, the allocation technique is based on research for an optimal strategy and consists of a group of rules followed by users as they attempt to reach their final destination by minimising trip times, calculated by the linear addition of all the partial trip times needed to reach the final destination. In this way, the calculation of minimal trip times accounts for all the sub-components of public transport. The system considers, therefore, the trip time, by foot, from the trip origin to the access point of the public transport system (bus stop, station, etc.), the waiting time (which obviously depends on the frequency of trips), the time spent aboard the vehicle, the time to disembark and the time needed to reach by foot the final destination (from the last relevant point on the public transport system). All of these components are weighted in order to account for the real impact of the diverse sub-systems on the user. The results of the public allocation are: the configuration of the passenger flows, the speed and trip times on the different links, and the average time between origin and destination points.

Despite all the above instrument description, *EMME/3* software does not have a specific emission calculation methodology. During this chapter a methodology is proposed to implement an emission model considering the data structure of this specific software.

3.2.2 Road Network and Volume Delay Functions

The road network modelled contains information that will be crucial for the implementation of an emission calculation set. This network is composed by nodes and links (representation of the physical road network) that contains information (geographical and user defined) about a specific street or intersection in the Porto Metropolitan Area. It must be clear that the representation of the network (as it is showed in the next page on the Figure 8) is purely representative and an abstraction of the reality, and so, concise geographical information extracted from the model should be dealt with careful attention. The road network (considered to be part of the supply side in a supply/demand model) information is evaluated and used during the model assignment procedure, and contains same variables that are going to be used in the emission calculation methodology proposed in this dissertation. Typically, the information that is coded in the road network consists of the geographical coordinates, the length of the link, the link type (road, highway, freeway or ramp), the volume-delay function and other type of information important for the purpose of the model.

Considering the objective of this work, one of the most important information's that needs to be coded, and can have strong influence in the environmental and energy outputs, is the volume delay functions. In most traffic assignment methods, the effect of road capacity on travel times is specified by means of volume-delay functions *t(v)* which is used to express the travel time (or cost) on a road link as a function of the traffic volume *v*. Usually these functions are expressed as the product of the free flow time multiplied by a normalized congestion function *f(x):*

$$t(v) = t_0 . f(\frac{v}{c}) \qquad (\textit{Equation 4})$$

where the argument of the delay function is the *v/c* ratio, *c* being a measure of the capacity of the road. By far the most widely used, and the one that is used in this model, is based on the BPR functions (Bureau of Public Roads), which is defined as:

$$t^{BPR}(v) = t_0 .(1 + (\frac{v}{c})^a) \qquad (\textit{Equation 5})$$

Considering that the road network is also constituted by delays in road intersections, a specific handling of delays at the stop-line is introduced. Link flows and turn flows may depend on the neighbouring link flows. The possibilities are with one in-flow link (associated with one stop-line delay and one link flow interaction delay) and three out-flow links, of which the left and right ones are associated with time penalties for turning and link interaction. Interaction delays are dependent on the flow volumes of the incoming links. The link flow and the turn delays are regular, link flow dependent, travel time and delay functions (only dependent on its own flow). The stop line delay is of the same kind. The interaction delays are dependent on the flows of up to three regular link flows (not turn flows). Currently they are modelled as piecewise linear functions of the summed in-flow.

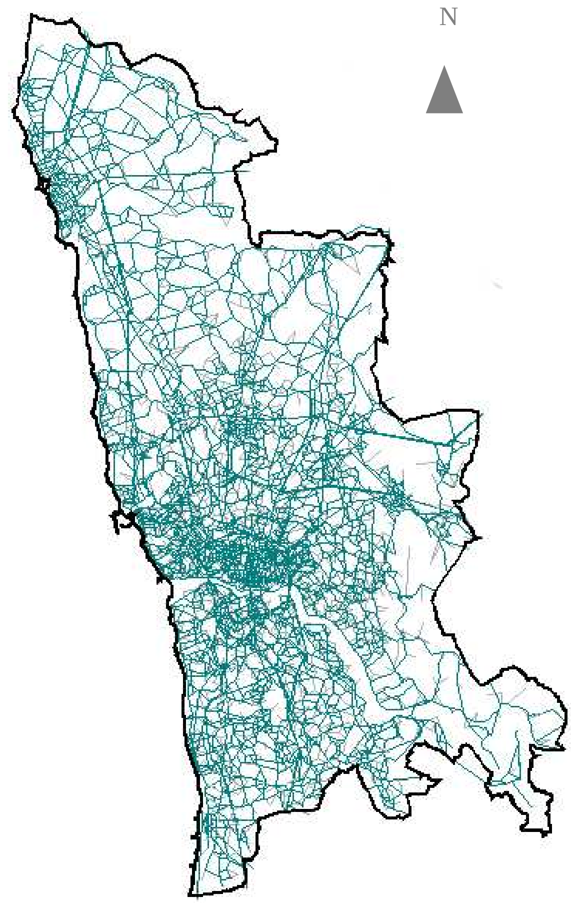

Figure 8: Porto Metropolitan Area (+ Trofa) road network coded in *EMME/3*.

3.2.3 Traffic Analysis Zones (TAZ´s)

Travel modelling requires that an urban area can be represented as a series of disaggregated trip producers (where trips begin) and trip attractors (where trips finish). In Porto Metropolitan Area model, a zoning system was built considering several aspects of the transport modelling procedure. These were mainly restrictions considering the municipality limits and the smallest administrative division (Parish) perimeters, main highways, natural barriers such as the rivers or natural parks and other restrictions considering the zoning system (called statistic subsections) from the local transport inquiries . The zones are then represented by a centroid that represents the centre point of the zone considered, and are then connected to the road network. By using traffic analysis zones (TAZ´s), centroids, and a road network as the inputs, traffic demand modelling aggregates trips from the locations of individual trip makers to TAZ's centroids and estimates trips generated between TAZ's on the network.

This TAZ's [(11)] system that was also designed considering a commercial licence restrictions that has a limitation of 1500 zones, despite this fact it is considered that the number of zones is well suited for the dimension of the model, considering a more detailed information in highly populated areas (small zone) a less detailed information in low populated areas (bigger zones).

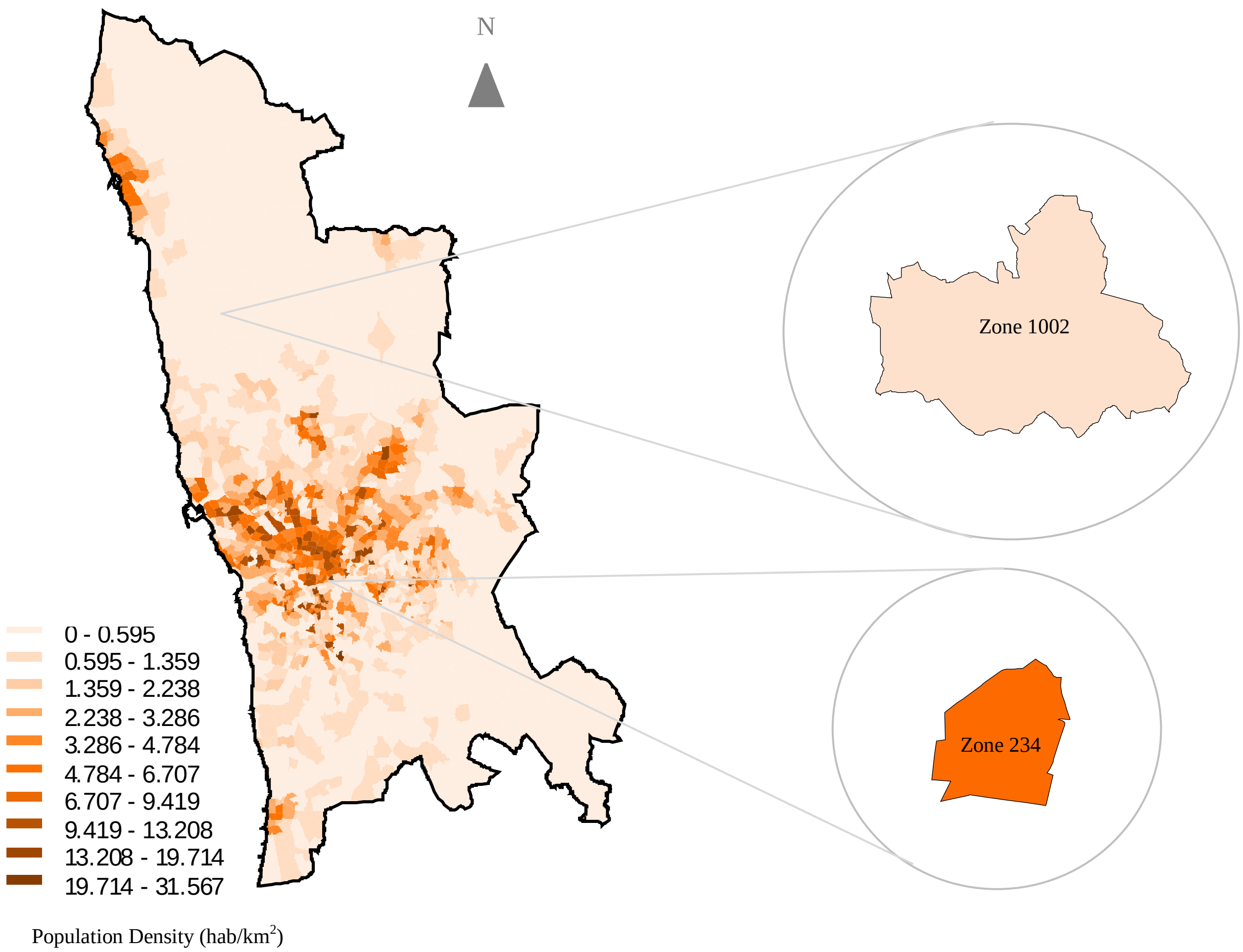

Figure 9: Differences in TAZ´s sizes.

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(11) TAZ´s are defined depending on geographical location and on the population density of the zones. Here are represented two typical zones. One in the centre of the city (zone coded as 234 more population density) and the other zone (zone coded as 1002 less population density).

3.2.4 Demand Matrices

In almost all transportation planning applications the input data which is the most difficult and expensive to obtain is the origin-destination demand matrix. Since the demand data cannot be observed directly, they must be collected by carrying out elaborate and expensive surveys, involving home or road based interviews or complicated number plate tagging schemes. Origin-destination (OD) matrix estimation, corresponding to the distribution phase of the four-stage process, consists in defining a two-entry table, called full demand matrix (OD matrix), whose rows and columns represent the zones of the study area. A cell of the matrix refers therefore to a particular origin-destination pair, and contains the total number of people accomplishing this journey.

The construction of the demand matrices used in these model are based on the transport survey done by the Portuguese National Institute of Statistics (INE) in 2001. This survey takes into account the entire home based trips (considering all purposes: education, work, religious, pleasure, etc.) that were done under the different modes of transport and are representative of typical week or weekend day.

Considering the base year of the survey (2001) it was necessary to adjust the demand matrices to a more actual and representative values. To accomplish this task several traffic counts were done to re-estimate the demand matrices. This re-estimation is done using a special macro language program that adjusts the modelled values to the observed values (traffic counts in several point of the metropolitan area in the year 2005) using the *steepest descent* [12] (also called gradient method) methodology (Spiess, 1990). This methodology proved to be very efficient and helped to calibrate and validate the transport demand matrices (according to the “British Guidelines – Department of Transport”, as showed in section 3.7) and is considered, for the base year definition, that the values are calibrated and validated to represent year 2005 base scenario.

[12] Steepest descent is an optimization algorithm. To find a local minimum of a function using gradient descent, one takes steps proportional to the negative of the gradient (or the approximate gradient) of the function at the current point.

3.2.5 Mode Choice Model

Discrete choice theory focus on the behaviour of an individual confronted with a choice and having a finite number of alternatives. In the context of logit models, observable characteristics are assumed to influence linearly the user's utility, and the unobservable ones, together with other sources of uncertainty, are gathered in a random term (Ben-Akiva and Lerman, 1985). The household survey (revelled preference data), used in Porto model, provides good enough data for the estimation of utility parameters, but it is insufficient to further segment demand by income. As different income groups and trip purposes are not equally represented across the region, it would obviously improve the model to include these levels of demand segmentation in the future. The other important factor is to obtain an accurate representation of the travel attributes of different alternatives. The utility function is linear-in-parameters and includes travel time, gas cost, toll cost for car mode and in-vehicle time, wait time, access time, cost of main mode, cost of access mode for transit modes.

The mode choice model implemented in the Porto Metropolitan Area is a typical multinomial logit model that can predict the probability of a journey taking place in the several modes that are available for each origin/destination pair. The output of a simple multinomial logit model is given by the probabilities of a mode choice between the individual transport and transit network. This is commonly used in transport studies and it can predict the decrease or increase in the individual transport demand depending on the conditions of evaluation.

3.3 Emission and Energy Consumption Model Selection

In the framework of an integrated modelling approach, emission models can be considered as tools allowing the calculation of pollutant emissions and fuel consumption from a traffic network by using the data obtained from travel demand models (link flows, capacities, and network geometry characteristics). Road assignment models and emission models represent two components of the combining modelling process. These components have been largely developed independently of one another, and Chapter 2 has revealed that there are plenty of models dealing with the calculation of exhaust emissions. Emission and Energy model choice can be a difficult task but the starting point should be the definition of different choice factors: a) emission and energy modelling objectives; b) available input data; c) appropriate resolution; d) sensitivity to variables; e) emission model and energy model accuracy; f) other factors.

a) Emission and Energy Consumption Modelling Objectives:

Verifying compliance with air quality standards, in a current or in future situations is one of the possible objectives in emission and energy consumption modelling. An important scale is the assessment of local air quality impacts (Nagendra *et al*.,2002) due to existing emission "hot spots" such as intersections, new transport projects (e.g. new roads environmental impact assessments) or the implementation of traffic management measures. A second objective is the development and evaluation of emission reduction policies through urban or national emission inventories, which are needed where environment problems have been identified or are needed to verify compliance with international agreements (e.g. greenhouse gas emissions). This objective requires prioritization of emission sources, evaluation of existing emission control strategies and the assessment of the effectiveness of alternative policy options.

b) Available Input Data:

The size of the study area and road network affects the availability of emission model input data. The demand for resources to generate and process input data for emission models from either travel demand model, field data or both, increases with network size. As a result, the extent and the level of detail of available input data are effectively reduced in practice when network size increases (Gipps, 1984). On the other hand, the amount and types of required input data are a function of emission model complexity, considering that a more complex model imposes a larger input data on the model user.

c) Appropriate Resolution:

Emission models can operate at different scales, which could vary from a national, regional, urban to local road networks, and that the actual study objective determines the size of the study area that needs to be considered. A hierarchy of emission models can be distinguished in terms of the minimum spatial and temporal resolution. The most complex emission models predict emissions at the highest spatial and temporal resolution of typically one second, whereas the least complex models operate at network level. The appropriate resolution for a particular study would clearly depend on the study objectives and the situation that is being investigated. For instance, when concentration levels at certain receptor points near an intersection are predicted, it seems appropriate to model at a high resolution. This would be necessary to account for the distribution of emissions along the roads near the intersection. However, for local air quality impact assessments of roads with relatively homogeneous traffic conditions, a higher resolution (e.g. link level) seems suitable. It is important to note that, although reasonable, decisions on the appropriate resolution are made in a rather arbitrary manner. This is because this decision ideally needs to be balanced using information on other aspects such as model accuracy. It is, for instance, not clear if it is actually possible to accurately predict emissions at very short time intervals, and there are indications that this might not be the case (TRL, 1999).

d) Sensitivity to Variables:

The basic components of emission modelling, is the amount of vehicle kilometres travelled by vehicle class and by the particular "traffic situation” that are of interest, should always be included emission modelling. Typically, one would like to use emission models that are "complete" (e.g. models that include all vehicle classes segmentation), since emissions from entire traffic streams are usually of interest. In some cases “incomplete models” may be used. For instance, the aim of a project may be to determine the effects of vehicle class specific measures on emissions. In addition to these basic constituents, emission models should be sensitive to the issues that are investigated in a particular study. Otherwise, these issues cannot be effectively assessed. The specific aim of a study determines which other variables are relevant and should be included in the model. In addition to these constituents, emission models should at least be sensitive to the issues that are investigated in a particular study. Otherwise, these issues cannot be effectively assessed. The specific aim of a study determines which other variables are relevant and should be included in the model. For instance, if emission models are used to assess the emission effects of implementation of different speed limits on highways, the emission model should (at least) be sensitive to the variable “speed limit”.

e) Emission Model and Energy Model Accuracy:

Because complex emission models are sensitive to many factors they would expected to be more accurate than less complex models. On the other hand, the sensitivity to many factors would also create additional uncertainty because more input data are needed, each with its own intrinsic uncertainty.

In addition, there are several other aspects of emission models that would affect model accuracy (and could thus be used as selection criteria) such as number of measurements (precision), the use of simplified or real world cycles (bias) and the use of up-to-date emissions test data, and perhaps several other factors such as the use of local emissions test data. In this respect, less complex models such as travel average speed based models may actually be more accurate than more complex emission models, because they use the largest empirical database, use real-world cycles and are regularly updated.

f) Other Factors:

It is noted that other factors such as the available budget and project planning (deadlines) for a particular study and cost-effectiveness of different options would also clearly affect the emission/energy model choice, but these are not considered or discussed during this dissertation.

The analysis of the described factor, and considering the models reviewed in Chapter 2, has induced the author to choose a model that will better fit the Porto Metropolitan Area travel demand model present reality and that can give a set of meaningful environmental indicators in an integrated transport and emission modelling framework (**emission and energy consumption modelling objectives**). For this purpose *COPERT IV* is considered adequate for calculating total emissions and fuel consumption (in the same modelling platform) for a relatively low spatial and temporal resolution. As a general rule *COPERT IV* can be used with a sufficient degree of certainty at a higher resolution in urban emission inventories with a spatial resolution of 1x1 km^2 and a temporal resolution of 1 hour (**appropriate resolution**), requires a relative low degree of input information considering the size of the modelled road network (**available input data**), and can deal with the data from a transport model and scenarios like the ones that are going to be tested (**sensitivity to variables**). *COPERT IV* (2006) is the fourth update of the emission calculation model and is continuously in revise, several improvements have been made since the previous releases and more updated test data is available in this model (**emission model and energy model accuracy**). The choice had also in consideration the applicability and capability of integrating in specific commercial software with licence limitation like *EMME/3* transport planning software, and the specific time line for this project dissertation (**other factors**).

3.4 Linkage Considerations with Travel Demand Models

To better understand the possibility of using *COPERT* emission model in a travel demand forecasting model, such as the one proposed, several model linking considerations should be accounted. Attention must be paid to the fact that travel demand models are an approximation of the reality and the output data still remains an estimation associated with uncertainty (despite all effort to calibrate the model). It is perhaps negligible for the objectives for which travel demand models have been initially built (analysis of congestion, multi-modal network, road network analysis, etc..) but for linking with emission models, is important to assess the degree of certainty needed for input data (average speed, trip distances, etc.) to get acceptable results.

In the case of models dealing with the number of passengers (for individual transport only), the model must be able to convert this value into the number of vehicles. In general, travel demand models cannot directly provide emission models with usable data. Adjustments and approximations are necessary to overcome some difficulties. Considering the emissions model data requirements, the main incomplete data for hot emission calculation are the number of vehicles per category, kilometres travelled per vehicle category on different road section types and average speed per road type taken into account or allocation of typical traffic situations to the road network with respect to different road section types. However travel demand models provide number of vehicles per mode on each O/D trip and the paths/route chosen; average speed of a representative vehicle in function of road link characteristics and in function of the flow on the link. Transport models can deliver several important outputs for emission model, and it is thus possible to infer for each O/D trip: the number of vehicles travelling per mode and the average speed from the origin to the destination (knowing the average speed on each link type travelled). Trip distance, number of kilometres travelled per time period can also be deduced from the input and output of the transport models. Matching problems between hot emission calculation and travel demand models remain in the calculation of kilometres driven per vehicle category and of kilometres driven per road type. First, travel demand models can only distinguish the share of kilometres driven by car, considering only the individual transport demand. In order to reconcile them with emission models, it is possible to overcome some linking difficulties considering that it is possible to refine mode choice models by splitting existing modes into sub-categories, for instance, by splitting the O/D matrices for cars into sub-matrices differentiating car sub-categories. On the other hand the use of statistical data on the car fleet and to weight the number of vehicles on each O/D pair per the share of the different vehicle categories including year per year considerations. This alternative can easily be operational but needs to assess the accuracy of the method. Second, differences are observed in the road typologies used for mobility and emission models. A homogenization and standardization will make the link easier between both models.

3.5 COPERT IV Calculation Methodology

COPERT IV is a software programme aiming at the calculation of air pollutant emissions from road transport. The model consists in several emission functions relating to the vehicle average speed that are obtained by plotting the individual emission measurements conducted over different cycles vs. the average speed of the cycle. The approach used in this model is based on aggregate emission information for various driving patterns, whereby the driving patterns are represented by their mean speeds alone. This information is managed according to vehicle technology, capacity class and model year and a speed dependent emission function is derived.

As mentioned in the literature review, the average speed approach is the most commonly used method for estimating emissions from road traffic (Ntzachristos and Samaras, 2000). For the individual transport *COPERT IV* methodology includes a total of 34 different classes of gasoline and diesel passenger cars. A given car belongs to one of three different ‘‘subsectors’’ depending on the cylinder volume (< 1.4 l, 1.4 - 2.0 l and > 2.0 l), and each subsector contains 10 - 12 different ‘‘technology classes’’, reflecting the various stages of the EU exhaust regulation (e.g. ECE 15/04, EURO 1, etc...). For diesel passenger cars there are two different subsectors (< 2.0 l and > 2.0 l), each containing six different technology classes.

Based on this distribution of classes, binomial regression analysis is applied to give the best correlation coefficients taken during the production of the emission factors included. An attempt to improve the correlation coefficients by distinguishing between different speed regions, which would potentially be described by different equations, has no effect except for CO_2 and fuel consumption.

3.5.1 Input Data Requirements

In order to consider the possible link between mobility models and emission models, it is important to firstly deem with the input data requirements by emission models in order to carry out the calculation of pollutant emission and fuel consumption values using the proposed methodology within a transport model.

The *COPERT IV* can be applied at different levels of resolution. As a general rule the methodology can be used with a sufficient degree of certainty at a higher resolution too (e.g. urban emission inventories with a spatial resolution of 1x1 km^2 and a temporal resolution of 1 hour). The main data required by emission models consists of the emission and consumption factors expressed in [g/km], in [g/h] or in [g/kg fuel]. In *COPERT IV*, these factors are provided by the model itself, and the way the emission factors are defined determines their conditions of application. In this dissertation only hot stabilized emissions and those which are defined in a speed-dependent form as is the case in the *COPERT* methodology are considered (fuel consumption/CO_2, CO, $NO_{x,}$ and VOCs). To better understand a possible link with a travel demand model, a detailed analysis of the input variables influencing emissions is described, and a list of the main input data of emissions models is given. These data, including information on the vehicles, their mechanical and operating conditions and the meteorological conditions, are:

- Number of vehicles;
- Vehicle mix (percentage of each legislative class);
- Vehicle age;
- Vehicle technology, engine size, and presence of catalytic converters;
- Vehicle average speed (for the average speed approach models).
- Vehicle speed-time profiles (emission modal models);
- Vehicle kilometres travelled (VKT);
- Trip distribution percentage by facility (urban, rural and freeway);

The distribution of listed data should be also known: distribution of length trips, and the temporal scale should be fine-grained and not annual based. These data, including information on the vehicles, their mechanical and operating conditions, are resumed in the next table considering the input data requirement and the availability of data in a perspective of linking with transport models.

Table 2 shows the input data required in order to calculate the emissions for a reference year with respect to the different emission types according to the *COPERT IV* Methodology:

Input data required	Availability of data	Output from Transport Model
· average speed-dependent emission factors in [g/km] for vehicle of category j	· available from the *COPERT* program for various pollutants and vehicle categories	
· speed-dependent consumption factors in [g/km] for vehicle of category j	· available from the *COPERT* program for various pollutants and vehicle categories	
· representative average speed or speed distribution for the three road types (urban, rural and highway)		· link average speed by road type defined in the transport model
· number of vehicles of category j [hj]	· exogenous input data available from national car fleet statistics ;	· divided demand by vehicle type
· average annual distance travelled per vehicle of category j [vj]	· unavailable as independent statistical data in many countries and has to be estimated ;	
· fleet composition	· exogenous input data available from national car fleet statistics ; possible link with traffic models.	· divided demand by vehicle type
· distance travelled by the different vehicle categories on the different road section types		. link average distance travelled by road type defined in the transport model

Adapted from: Gilson *et al*., 1997

Table 2: Emission input, available data and input from transport model

3.6 Integrating *COPERT IV* in *EMME/3*

For the estimation of environmental variables, the starting point is the abstraction of the urban transportation system in the form of modal networks. The *EMME/3* serves as a framework for this purpose (figure 10). The detailed coding and network representation capabilities enable an analyst to define links and vehicle types as showed in figure 11. From these, as a result of travel simulation and assignment outputs, fuel consumption and emissions can be calculated. During this project dissertation a simple but effective way to calculate environmental variables is elaborated with a special macro language that is given in the *EMME/3* software package.

The implementation of *COPERT IV* methodology must be concise with the Portuguese fleet distribution and so there must be several manipulations for the correct use of the built model.

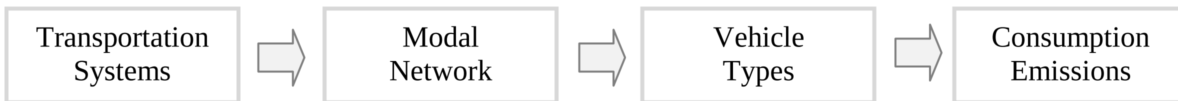

Figure 10: Conceptual representation of road emission estimation requirements

Figure 11: Conceptual representation of model functionality and outputs

The calculation of the individual transport road emissions and fuel consumption is done considering traffic volumes in the different emission legislative classes of the modelled car fleet. The *COPERT* methodology uses the information that was composed by André *et al*. (1999) for the Portuguese National fleet distribution for the year 2005 and postulated information for the years 2010, 2015 and 2020 (Table 14 in the Annex). Considering this information, fleet distribution is then divided in 34 different legislative classes which have their own equations to determine the pollutant emissions and fuel consumption.

The implementation of the *COPERT IV* methodology for road emissions (that consists mainly of linear equations in function of specific intervals of vehicle speeds) are coded in a special *EMME/3* macro language that is implemented in the travel demand model. This macro runs in a special set of iterations to obtain all the values demanded. To better understand the implementation of this macro it is important to explain in different and defined steps:

Step 1 – Background Traffic

The *EMME/3* assignment main outputs for a modelled network are: simulated vehicles/hour, riders/hour, link speeds and travel times. From these outputs, we can obtain average speed for links considering the volume delay functions (for links) and intersection delays (for intersection nodes).

As demonstrated in figure 12 the first step is to assign the initial demand to the network, obtaining the first values of road volumes and delays, which are going to be used in the following steps. This is important to have background traffic information and to be used in the following steps, considering that the main matrix is going to be subdivided in several other matrices that are also going to be singly assigned to the network.

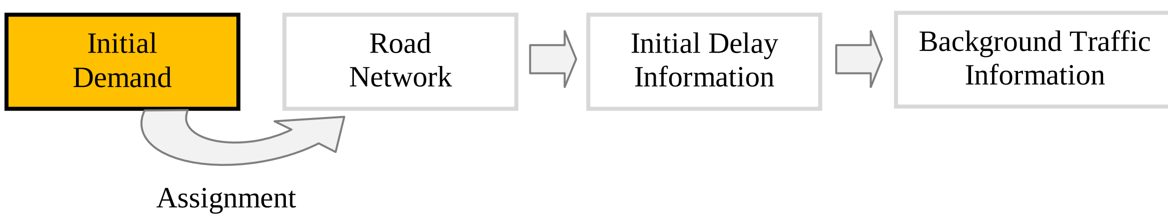

Figure 12: Conceptual implementation of the background traffic.

Step 2 – Legislative Emission Classes

The second step consists in the input of the information about the legislation classes in a special *EMME/3* matrix type called scalars (matrix scalars). This information is the percentage of each legislative emission classes that is taken from specialized literature (André *et al.*, 1999) considering different years. The matrices are coded with an individual number that identifies each one of them. After the introduction of these matrix scalars, each one is multiplied by the initial demand matrix resulting a new demand matrix that corresponds to the demand of a specific emission legislative class.

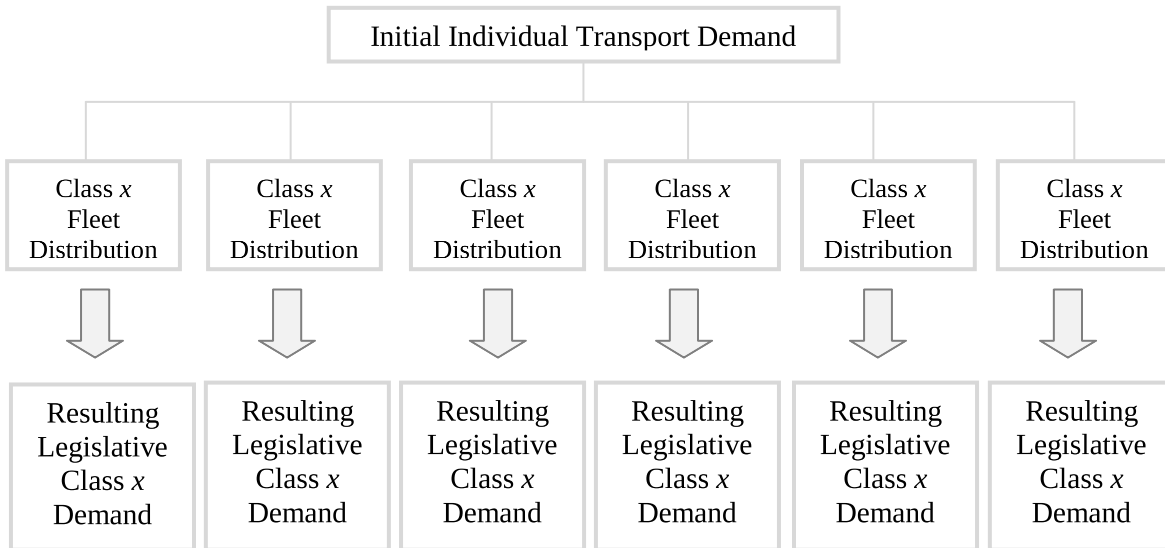

Figure 13: Legislative emission classes calculation process

Step 3 – COPERT IV Equations

The third step is to include all *COPERT IV* equations concerning the individual transport in attributes that can be evaluated by the following step. This is done by coding in the macro languages, and differentiated by the same code that recognizes the respective matrix scalar and legislative emission class, all the speed dependent *COPERT IV* equations for CO_2, NO_x, CO and VOCs, considering the speed restrictions.

Step 4 – Assignment and Results

The fourth step consists in doing several assignments of the 34 different matrices that were created in Step 2 and also using the extra attributes in the Step 3. It is possible with an extra option of auto assignment in *EMME/3* to save several matrices with the results expected using the matrices from Step 2 and the extra attributes from the Step 3. Despite all the modelling processes that are necessary to implement in a suitable way for evaluating a number of simple equations, is important to have in mind that this process needs to be extensively tested and it is necessary to have a very high confidence in the model that it is built on.

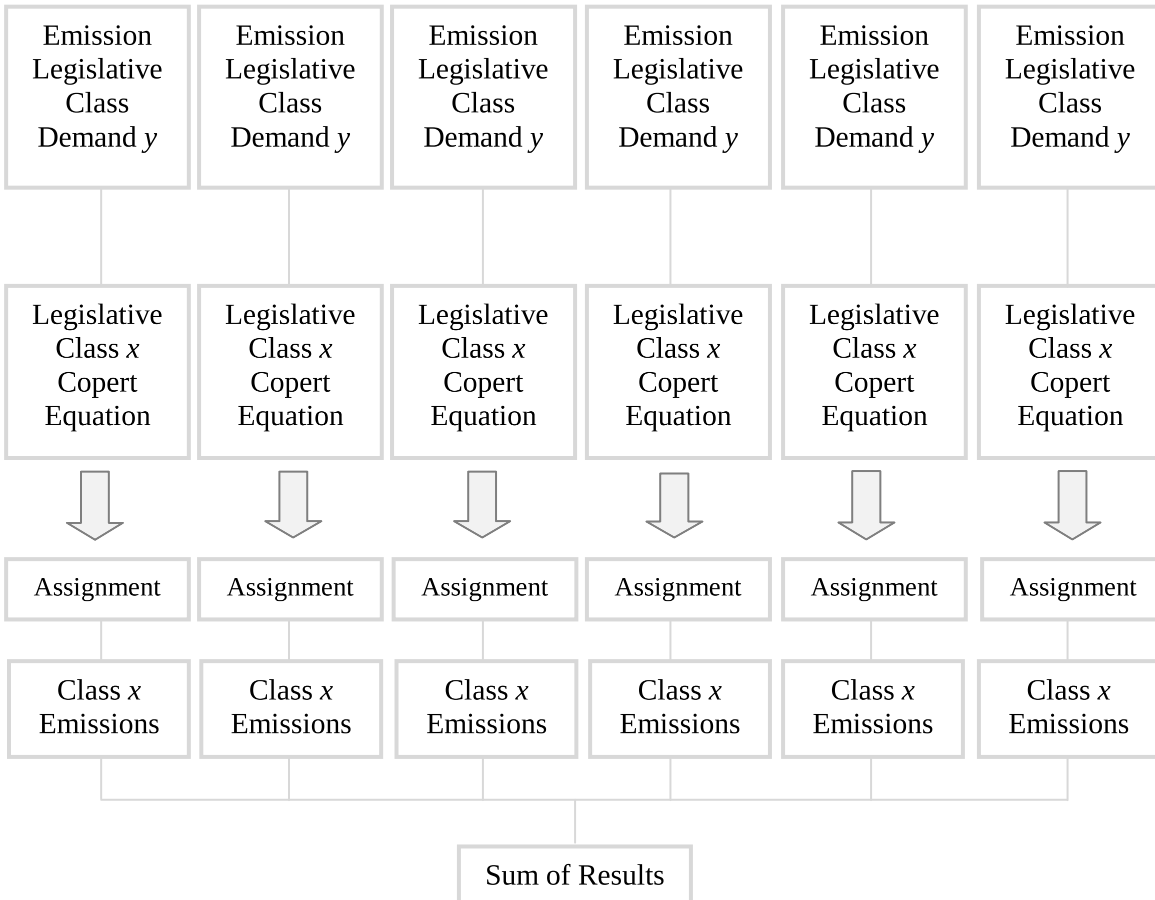

Figure 14: Assignment and sum of results

The results can be obtained by legislative emission class or all summed together during the evaluation of this macro. The end of this step encloses the calculation of the emissions and fuel consumption for the individual transport demand, and opens a new step that is fundamental in any modelling process called validation. This is done by comparing different scenarios and by obtaining real emissions values or fuel retail selling in the metropolitan area as explained in the next point.

3.7 Calibration and Validation

Calibrating and validating a model is always the final step of any modelling process. The calibration and validation of the emission models and transport models can have joint calibration process but values should be validated in separate ways with different data sets. Considering that the environmental models work with the outputs of the transport model, the calibration of the travel forecasting sub-models, such as the gravity model or the logit model, involves estimating the values of various constants and parameters in the transport model structure. Estimating model coefficients and constants was done by solving the model equation for the parameters of interest after supplying observed values of both the dependent and independent variables. As indicated previously, the estimation process is a trial and error effort that seeks the parameter values which have the greatest probability or maximum likelihood of being accurate within acceptable tolerance of error. During this project evaluation, a big effort of error scrutiny and calibration of the transport model was done by the team that is building it (PMA model belongs to TRENMO Engenharia, Lda). Once satisfactory estimates of the parameters for all sub-models have been obtained, the models where checked to assure that they adequately perform the functions for which they are intended, that is, to accurately estimate traffic volumes and roadways traffic. Verifying a calibrated model in this manner is commonly called "validation." The validation process establishes the credibility of the model by demonstrating its ability to replicate the reality. Validating the models requires comparing traffic estimated by the model to observed traffic on the roadway and transit systems and to compared emission and fuel consumption value with real data available. For the purpose of this dissertation the validation of the pollutant emission values for a specific metropolitan area can be difficult or impossible. Some partial emission model validation is possible and different methods are used in practice, such as tunnel studies, remote-sensing studies or “inverse dispersion modelling” (Reynolds, 2000). However, all these methods have their own drawbacks. A major issue is that all methods are restricted to specific locations with specific traffic conditions during relatively short time periods. Hence, validation data cannot be used to arrive at an overall emission model evaluation. Values of fuel retail sales are available from the local gas stations resellers and can be used as an indicator for fuel consumption numbers. Despite this fact, it is almost impossible to get disaggregated values for the A.M. Peak hour and so values cannot be compared with annual fuel retail sales. The calibration and validation parameters used in the model are according to the "British Guidelines - Department of Transport". These parameters are demonstrated in the following table:

Calibration and Validation Parameters	Suggested Criteria	Calibration (130 counting spots)	Validation (10 counting spots)
P85 = % Links $\begin{cases} \lvert Vm-Vo\rvert < 100 \text{ if } Vo \leq 700 \\ \lvert Vm-Vo\rvert / Vo<15\% \text{ if } 700 \leq Vo \leq 2700 \\ \lvert Vm-Vo\rvert <400 \text{ if } Vo>2700 \end{cases}$	≥ 85%	82.6%	86%
GEHM= GEH (for 85% of the links)	≤ 2	1.59	1.7
GEH5=% Links with traffic counts with GEH ≤ 5	≥ 85%	84%	83%

Vm = Values modelled

Vo= Values observed

GEH= The GEH Statistic is a formula used in traffic engineering, traffic forecasting, and traffic modelling to compare two sets of traffic volumes.

GEHM = Average GEH

Table 3: Calibration and validation parameters for PMA model according to the "British Guidelines - Department of Transport".

CHAPTER 4

CASE STUDY RESULTS AND ANALYSIS

4.1 Introduction

A successful integrated transport and environmental model system must be responsive to the interest of the stakeholders. This requires at least sufficient output indicator that satisfies the policy interests of those who focus on the key global dimension of urban management efficiency, equity and environmental sustainability. Each should have a set of practical translators of performance including indicators of emission and energy variables, transport accessibility and mobility in the same decision platform. An integrated modelling system offers more than forecast and outcomes, it is an important support system for planners and decision makers who often want to get a feel for implication of the “what if …?” questions.

In order to complement the theoretical analysis of transport modelling for environmental impact assessment, conducted in Chapter 2, the general objective of this dissertation is to present the PMA results using the methodology proposed in Chapter 3. Before the case study results analysis is presented, the definition of the scenarios constitutes the tool for evaluation of different transport policies that are intended to be studied and presented in this dissertation.

4.2 Scenario Simulations

The structured development of energy and environment scenarios allows a range of public policies to be examined within the context of alternative assumptions about the future. Scenarios are stories, not predictions or recommendations, about how the future might unfold (Nijkamp and Castells, 2001). They are useful for organizing scientific insight, gauging emerging trends, and considering alternatives. In this dissertation four primary scenarios are proposed: a business-as-usual (BAU) forecast and three alternative policy cases for the future years of 2010, 2015 and 2020. The BAU scenario assumes a continuation of current energy and environmental policies and a steady transport demand progress. In contrast, the year evolutions scenarios are defined by policies that are consistent with increasing levels of individual transport demand and the normal evolution of vehicle fleet renovation. After the primary scenarios evaluation, a group of secondary scenarios are proposed to evaluate transport policies. Three types of transport policies are going to be evaluated, and they can be separated in travel cost scenarios, time changes and combined scenarios. The travel cost scenarios are: increase of inner-city parking charges; reduce public transport fares; increase public transport fares. The travel time scenarios are: making public transport faster (25%); reduce headways (50%) and make cars slower (20%). Combination scenarios are: promotion of public transport scenarios and reduction of mobility scenarios.

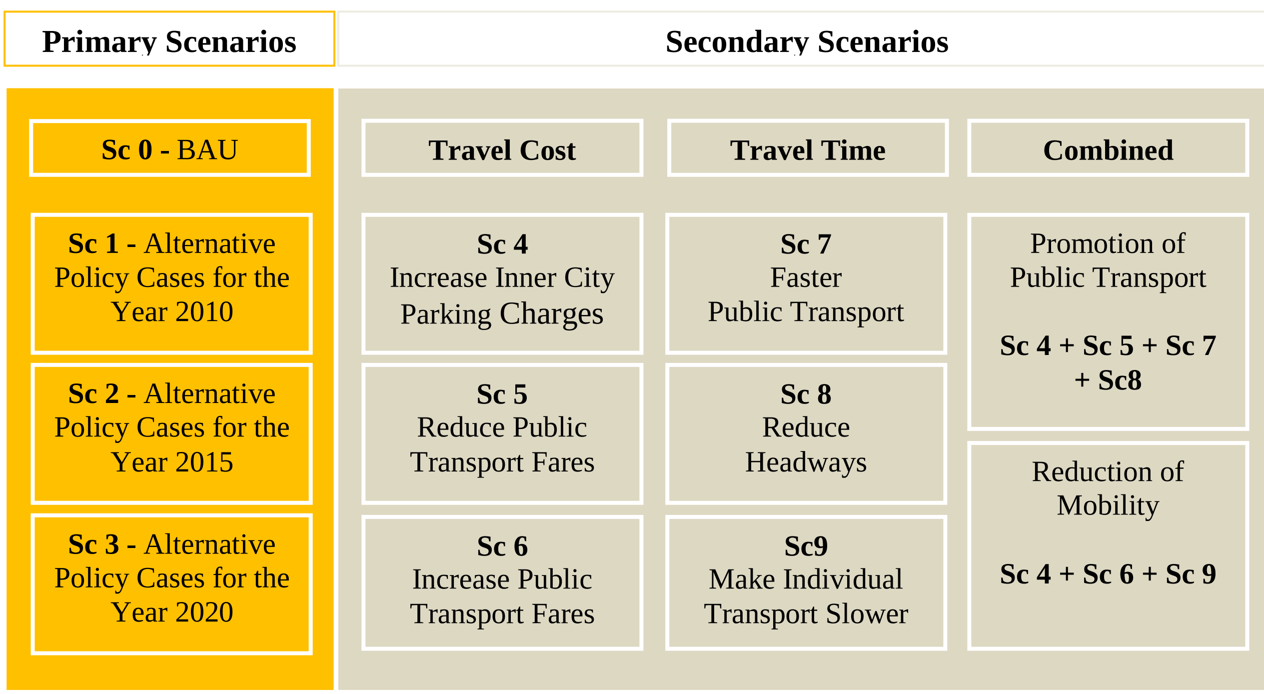

Figure 15: Definition of primary and secondary scenarios

4.3 Primary Scenarios

In the primary scenarios a more detailed set of outputs are delivered, considering that a good characterization of emission and energy values can contribute to a better understanding of the environmental variables and as well as sending warning signals on what instruments detract from environmental progress. The characterization of the PMA results examines the usefulness of various measures of travel patterns as environmental indicators of vehicle emissions and energy use. If certain measures of travel patterns were reasonable proxies for vehicle emissions and energy use, and could be collected relatively easily without complex measurement or calculation, they are useful for environmental monitoring, assessment and development of transport policies.

4.3.1 Scenario 0 - Business as Usual

In this scenario a base year was established to be used for evaluating a business-as-usual, which examines the consequences of continuing current trends in population, economy, technology and human behaviour.

In this scenario it will be presented the pollution emissions (CO_2, NO_x, CO and VOCs) and vehicle fuel consumption, considering the typical traffic scheme in the study area region for the time interval that the model is calibrated and validated to work in. The private car transportation has been modelled according to the origin-destination matrix for the morning peak hour (7:30 h - 9:30 h) on an average day of the year 2005. The traffic intensity volumes (number of vehicles), average time and speed for each link are calculated as a result of traffic assignment with *EMME/3* assessment module. During this scenario evaluation, a special attention was derived to the characterization of the emission values considering the mobility patterns, vehicle emission figures for each journey and aggregated figures of energy consumption and emissions per habitant. In this scenario, results are also split considering origin and destination values of the transport demand, and division can be establish between emission values that are geographically representative of the modelled region and values that represent outside demand that as origin or destination in the PMA. A characterization of the PMA individual municipalities is also given considering the actual geographic representation and the individual municipality generated values.

Table 4 resumes the aggregated results in CO_2, CO, VOCs and NO_x for the PMA. Results are represented as total emissions in ton/h in the morning peak for all the spatial transport activity that is made inside the metropolitan area perimeter, aggregated results in the considered pollutant emission from all the trips that are attracted to and from the metropolitan area (these results have in consideration the trips that have origin or destination outside of the metropolitan area perimeter, especially from the main district centres), and the absolute difference between inside PMA and generated emissions by PMA results (these values represent the total pollutant emissions that PMA causes outside the metropolitan area perimeter).

Scenario 0 – Business as Usual

	Energy Consumption (GJ/h)	CO_2 (ton/h)	CO (ton/h)	VOCs (ton/h)	NO_x (ton/h)
Total Emissions inside PMA	2505.2	176.1	2.178	1.150	0.817
Total Emissions generated by PMA	6248.2	439.0	4.872	2.202	1.572
Difference between inside and generated by PMA Emissions	3729.0	262.9	1.994	1.052	0.741

Table 4: Total pollutant emissions (GJ/h and tons/h in the morning peak).

Having calculated energy consumption and vehicle emission for each journey, aggregated figures of energy consumption and emissions per inhabitant were calculated. The following table (Table 5) represents several sets of environmental indicators for the region considered using the emission calculation methodology proposed. Values are also separated by its spatial emission location (inside PMA perimeter and generated by PMA) and correlations are delivered by inhabitant and by trip considering all environment and energy outputs.

Scenario 0 – Business as Usual

	Inside PMA	Generated by PMA
Habitants	1759958	-
Number of Trips	138524	184378
Number of Car Passenger	23453	34567
Travelled Model Avg. Trip Distance (km)	12	40
Avg. Model Vehicle Speed (km/h)	34	43
Avg. Vehicle Occupancy	1.17	1.20
CO_2 Emission (ton) / Trip	$1.2*10^{-3}$	$6.8*10^{-2}$
CO_2 Emission (ton) / Habitant	$1.0*10^{-4}$	-
CO Emission (ton) / Trip	$5*10^{-5}$	$2.6*10^{-5}$
CO Emission (ton) / Habitant	$1.2*10^{-6}$	-
NO_x Emission (ton) / Trip	$5.89*10^{-6}$	$8.52*10^{-6}$
NO_x Emission (ton) / Habitant	$4.72*10^{-7}$	-
VOCs Emission (ton) / Trip	$8.30*10^{-6}$	$1.19*10^{-5}$
VOCs Emission (ton) / Habitant	$6.53*10^{-7}$	-
Total Energy Consumption (MJ)	2553604	6366345
Energy Consumption / Trip (MJ)	18.43	34.53
Fuel Consumption (Litres)	73379	182941
Fuel Consumption / Trip (Litres)	0.52	0.99

Table 5: Scenario 0 – Business as Usual values per hour in the morning peak.

Tables 6 and 7 represent desegregated emissions values for each of the metropolitan area municipalities including Trofa, considering inside and generated by PMA values. Table 8 and 9 represents aggregated and desegregated information for PMA environment values. Graphics 1 and 2 represent the displacement of the emissions by legislative classes inside the perimeter of the metropolitan area in several types of emission and energy indicators. Then, in figures 16, a graphical representation of CO_2 emissions aggregated by its origin zone are given and spatial relation between mobility and emissions can be easily analysed. Figures 17 and 18 represent link flow CO emissions and a more local environment assessment can be accomplished.

Scenario 0 – Business as Usual

2005	CO_2	% Total	CO	% Total	VOCs	% Total	NO_x	% Total
Porto	41.7	24%	0.54	25%	0.27	24%	0.24	25%
Matosinhos	19.9	11%	0.24	11%	0.13	11%	0.09	11%
Gaia	27.5	16%	0.34	15%	0.18	16%	0.14	16%
Valongo	15.5	9%	0.20	9%	0.10	9%	0.06	9%
Gondomar	16.0	9%	0.19	8%	0.10	9%	0.06	9%
Espinho	6.2	4%	0.08	4%	0.04	4%	0.007	4%
Maia	18.9	11%	0.23	11%	0.12	11%	0.08	11%
Vila do Conde	11.0	6%	0.13	6%	0.07	6%	0.03	6%
Póvoa do Varzim	8.4	5%	0.10	5%	0.05	5%	0.03	5%
Trofa	10.4	6%	0.12	6%	0.06	6%	0.03	6%

Table 6: Total emissions inside each municipality (tons/h in the morning peak) and its weight in percentage of the total emission value.

Scenario 0 – Business as Usual

2005	CO_2	Ins/Gen	CO	Ins/Gen	VOCs	Ins/Gen	NO_x	Ins/Gen
Porto	10.4	9.48	0.65	2.12	0.08	10.93	0.06	14.13
Matosinhos	20.8	0.96	1.20	0.20	0.12	1.11	0.08	1.12
Gaia	16.3	1.69	0.94	0.36	0.09	1.97	0.06	2.23
Valongo	13.1	1.18	0.76	0.26	0.07	1.36	0.05	1.19
Gondomar	13.9	1.15	0.80	0.24	0.08	1.28	0.05	1.12
Espinho	17.1	0.36	0.99	0.08	0.10	0.42	0.07	0.11
Maia	23.3	0.81	1.35	0.17	0.13	0.92	0.09	0.89
Vila do Conde	15.9	0.69	0.92	0.14	0.09	0.78	0.06	0.49
Póvoa do Varzim	11.6	0.72	0.67	0.15	0.07	0.77	0.04	0.67
Trofa	39.3	0.26	2.28	0.05	0.22	0.27	0.15	0.20

Table 7: Total emissions generated by each municipality (tons/h in the morning peak) and the relation between inside and generated values by PMA.

Scenario 0 – Business as Usual – Porto Metropolitan Area Environment Matrix

	Porto	Matosinhos	Gaia	Valongo	Gondomar	Espinho	Maia	Vila do Conde	Póvoa do Varzim	Trofa
Porto	0.7	0.73	0.69	0.41	0.56	0.48	0.29	0.53	0.50	0.28
Matosinhos	0.64	0.31	2.13	3.00	2.10	3.38	1.05	0.41	3.88	3.93
Gaia	0.65	1.47	1.49	3.63	1.34	0.56	1.07	0.61	0.37	5.18
Valongo	0.39	1.85	3.59	1.65	0.75	0.38	0.19	0.98	0.30	3.08
Gondomar	0.52	0.91	1.49	0.92	0.60	1.89	1.00	1.72	2.14	2.73
Espinho	0.43	2.82	0.52	0.47	1.71	0.36	0.74	5.56	0.50	4.03
Maia	0.24	7.27	0.93	1.85	8.10	0.72	0.49	1.11	0.33	2.27
Vila do Conde	0.40	0.41	5.39	1.00	1.82	0.63	1.16	1.27	0.57	3.26
Póvoa do Varzim	0.37	3.12	0.30	0.36	1.89	0.05	0.03	0.57	0.19	4.79
Trofa	0.32	4.54	6.20	4.03	3.95	5.10	2.76	4.78	5.73	1.90

Table 8: Total CO_2 Emissions generated by each municipality to the correspondent destination municipality (tons/h in the morning peak hour).

Porto Metropolitan Area Environment Matrix (CO_2) is represented in a spider web diagram in the Annexes of this dissertation.

Scenario 0 – Business as Usual

Mode	Fuel Type	Engine Size	Energy Consumption (MJ/vehic.km)	Energy Consumption (MJ/pass.km)*	Emission per vehic.kilometer (g/vehic.km)				Emission per pass.kilometer* (g/pass.km)			
					CO_2	CO	VOC	NO_x	CO_2	CO	VOC	NO_x
Car	Gasoline	Small	2.16	1.10	75	5	1.31	1.05	36	3	0.5	0.4
Car	Gasoline	Medium	2.30	1.14	94	9	0.71	1.32	43	4	0.3	0.5
Car	Gasoline	Large	2.60	1.34	110	10	0.34	1.83	55	5	0.15	0.7
Car	Diesel	Small	2.08	1.02	69	0.21	0.03	0.26	32	0.11	0.01	0.1
Car	Diesel	Medium	2.11	1.06	71	0.20	0.04	0.37	33	0.12	0.02	0.15
Car	Diesel	Large	2.26	1.09	96	0.23	0.05	0.57	44	0.20	0.03	0.25
Car	LPG	All Sizes	1.65	0.80	68	5	1.4	1.0	34	2	0.2	0.3

Small Engine Size = 1.4 l or smaller; Medium Engine Size = 1.4 – 2.0 l; Large Engine Size = Larger Than 2.0 l
* Passengers of individual transport

Table 9 : Scenario 0 – Business as Usual desegregated result by mode, fuel type and engine size (values inside PMA).

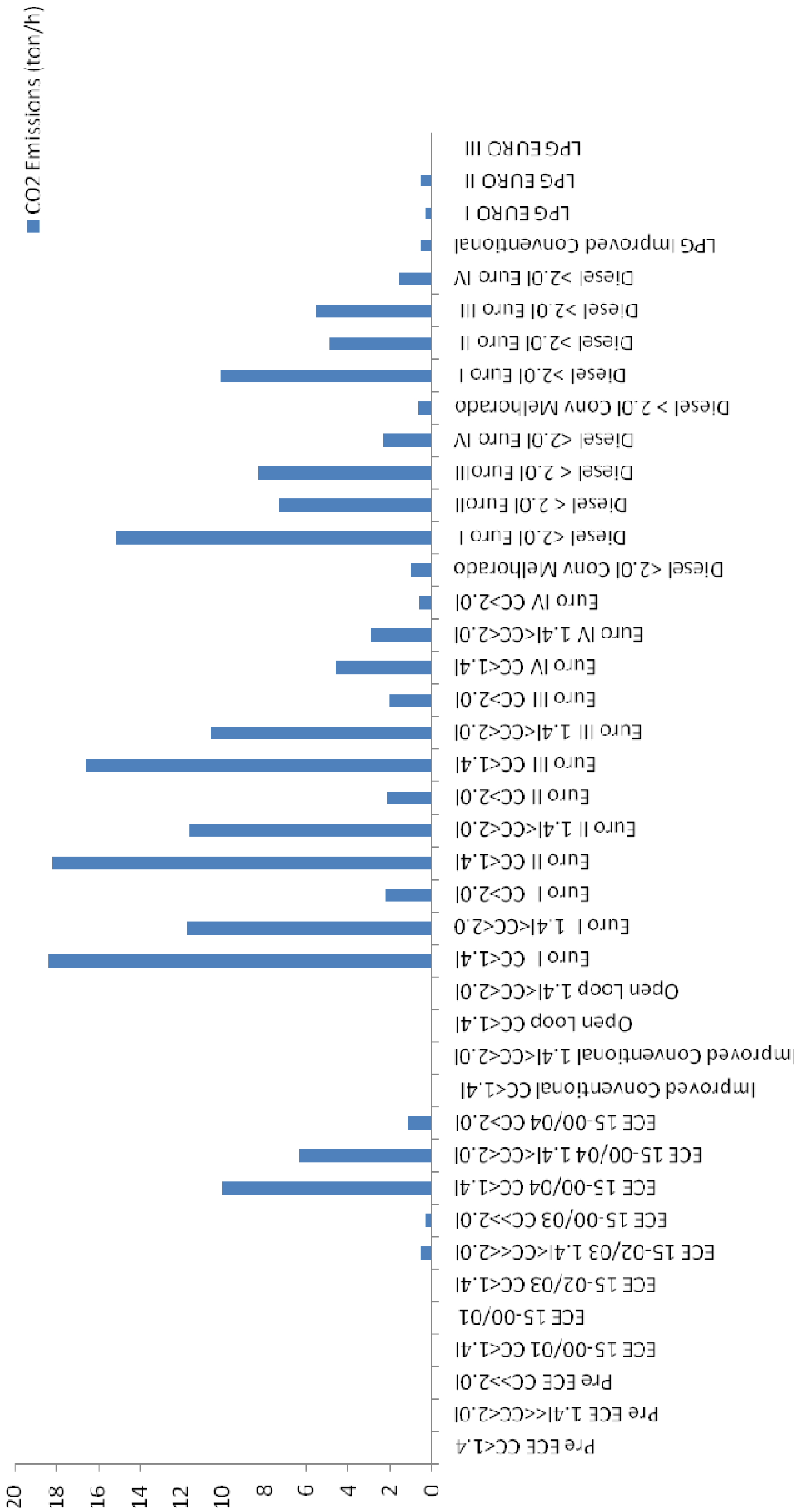

Figure 16: Representation of the CO_2 Emission (ton/h) values depending on the emission legislative class (values inside PMA perimeter).

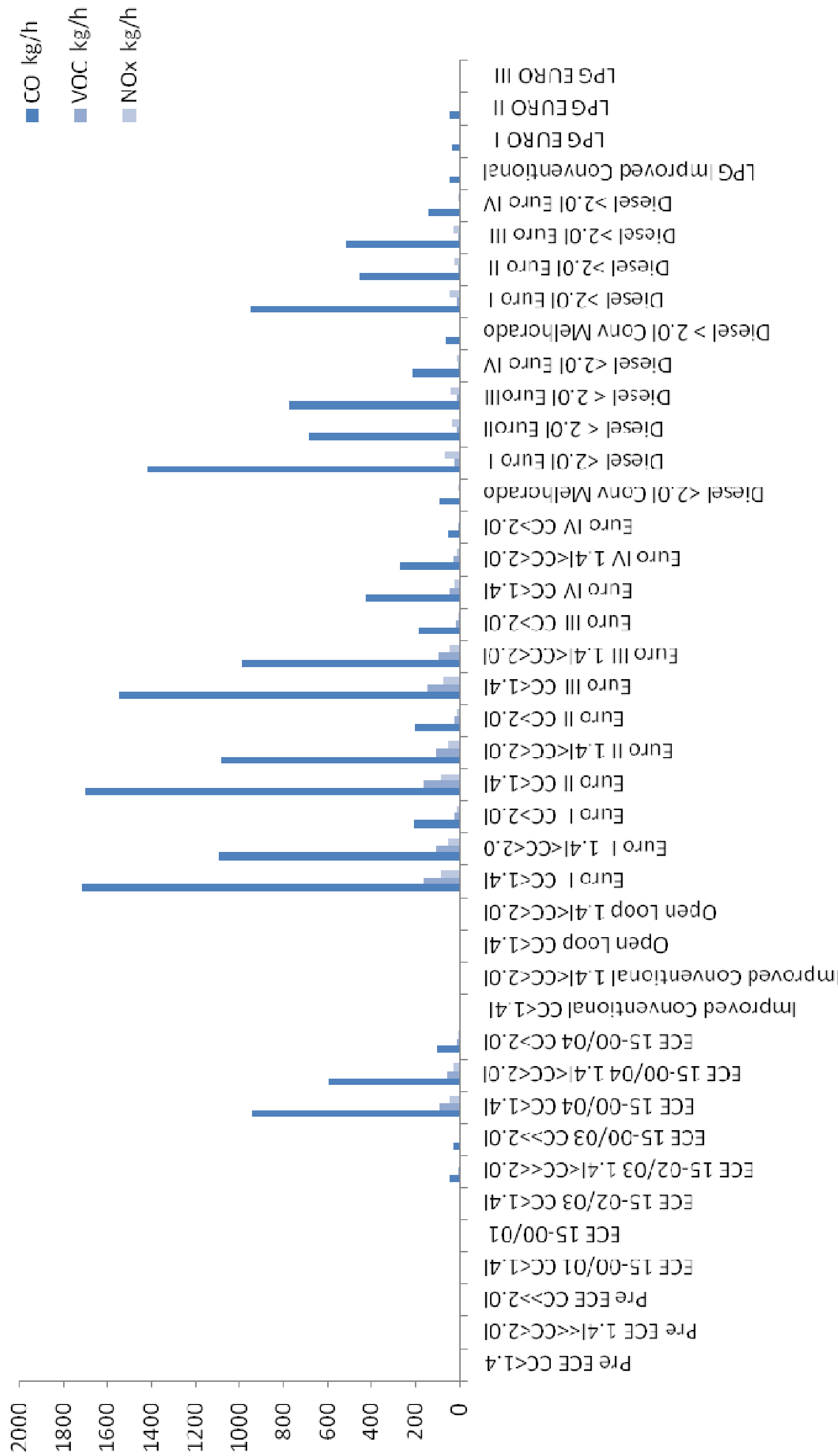

Figure 17: Representation of the CO, VOC and NO_x Emission values (in kg/h) depending on the emission legislative class (values inside PMA perimeter).

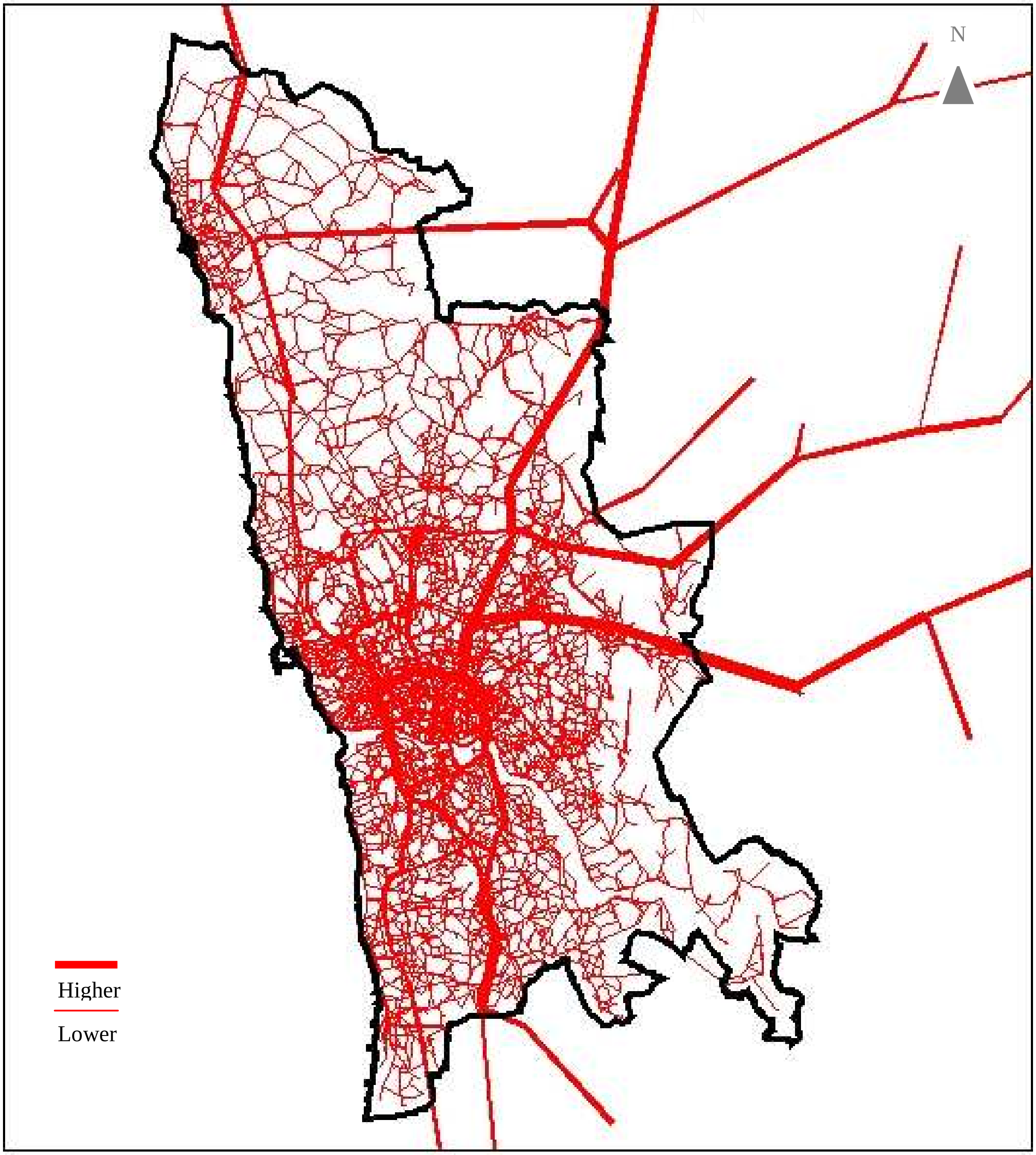

Figure 18: CO Emission’s representation in the road network in the PMA (+ Trofa).

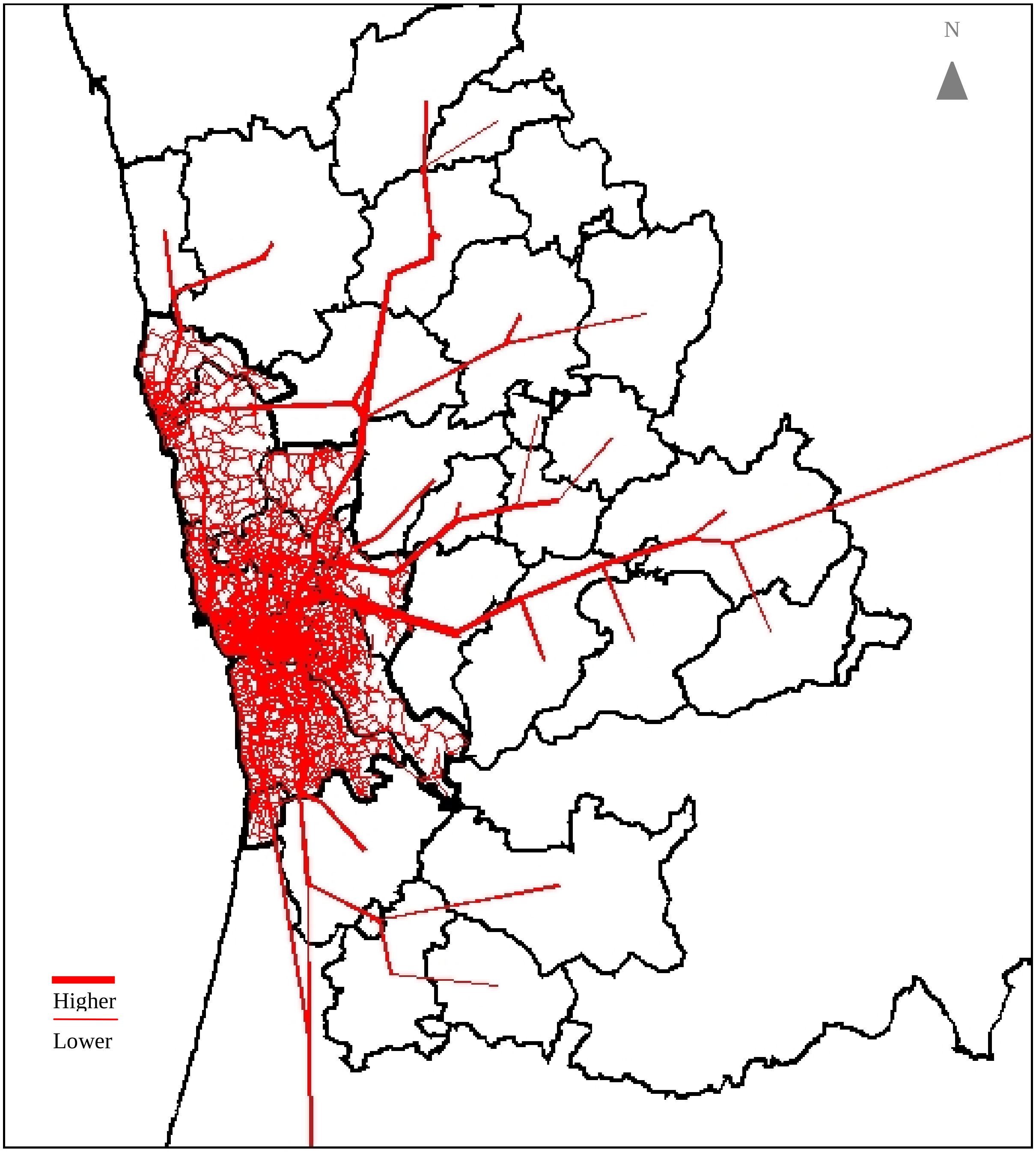

Figure 19: CO Emission's representation in the road networks in the PMA (+Trofa) and its relations with the outside municipalities.

4.3.2 Scenario 1, 2 and 3 - Alternative Policy Cases 2010/2015/2020

The definition of alternative policy cases will lead to future scenarios of the year 2010, 2015 and 2020. In these scenarios the expected evolution of the transport demand and the evolution of the individual transportation fleet will be tested. The future scenarios are evaluated considering the different average distribution of the Portuguese fleet in future years. This is done by considering literature values (André, 1999) based in the year 2010, 2015 and 2020 of the distribution of the Portuguese vehicle emission legislative classes. The year differences between the distributions of the vehicle fleet are achieved mainly by substitution of older legislative emissions classes; this can be done by government incentives or by natural fleet renewal over the years. Considering the information available and by using the methodology proposed, three alternative policy cases scenarios are built for the year 2010 (Scenario 1), for the year 2015 (Scenario 2) and for the year 2020 (Scenario 3). For these scenarios the individual demand matrix must be different from the one that is used for Scenario 0, since this one is based in the year of 2005. To overcome this problem it is assumed a 1.675 % growth (this number is the year difference in percentage between the original demand matrix, year 2001 survey, and the matrix re-estimation that was carried out with the traffic count for the year 2005) in the individual transport demand matrix each year, which corresponds to an increase of 6.7% for 2010, 15.0% for the year 2015 and 25% for the year 2020 (these numbers are based on the notion that individual transport demand is expected to continue to grow, considering several growth indicators such as the local rate of motorization [12]). This approach can give a better estimate of the transport emissions and fuel consumption for future scenarios where a big number of variables are difficult to obtain or estimate. The results for each of these scenarios are for the same time period (7:30 h to 9:30 h, morning peak period, considering hourly average values) and are presented in pollutant emissions (CO, VOCs, NO_x) and fuel consumption (then expressed in CO_2).

[12] Information from the Portuguese Institute of National Statistic - PMA Mobility Report (INE, 2001).

Scenario 0, 1 , 2 and 3 - Comparison of future scenarios values inside PMA

Year	Energy Consumption (GJ/h)	CO_2 (ton/h)	CO (ton/h)	VOCs (ton/h)	NO_x (ton/h)
2005	2553.6	176.1	2.178	1.151	0.817
2010	2758.1	190.2	0.848	0.442	0.312
2015	3050.1	210.3	0.706	0.363	0.256
2020	3402.6	234.6	0.608	0.282	0.198

Table 10: Scenario 1, 2 and 3 – Alternative Policy Cases - Total energy consumption and pollutant emission inside PMA.

Scenario 0, 1 , 2 and 3 - Comparison of future scenarios values generated by PMA

Year	Energy Consumption (GJ/h)	CO_2 (ton/h)	CO (ton/h)	VOCs (ton/h)	NO_x (ton/h)
2005	6366.3	439.0	4.172	1.863	1.579
2010	6788.1	468.1	1.614	0.720	0.614
2015	7556.4	521.1	1.559	0.692	0.589
2020	7545.5	530.3	1.461	0.654	0.554

Table 11: Scenario 1, 2 and 3 – Alternative Policy Cases - Total energy consumption and pollutant emission generated by PMA.

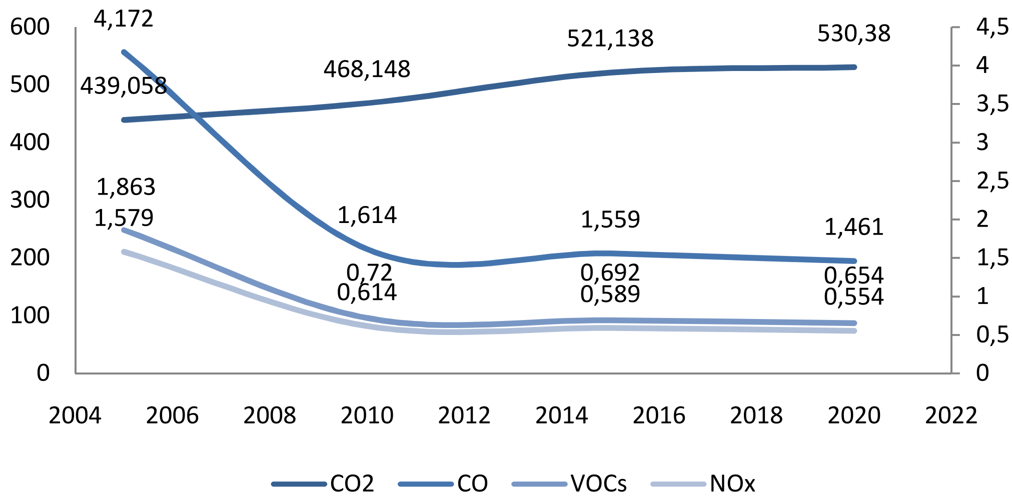

Figure 20: Result Presentation of the Future Scenario generated by PMA (tons/h).

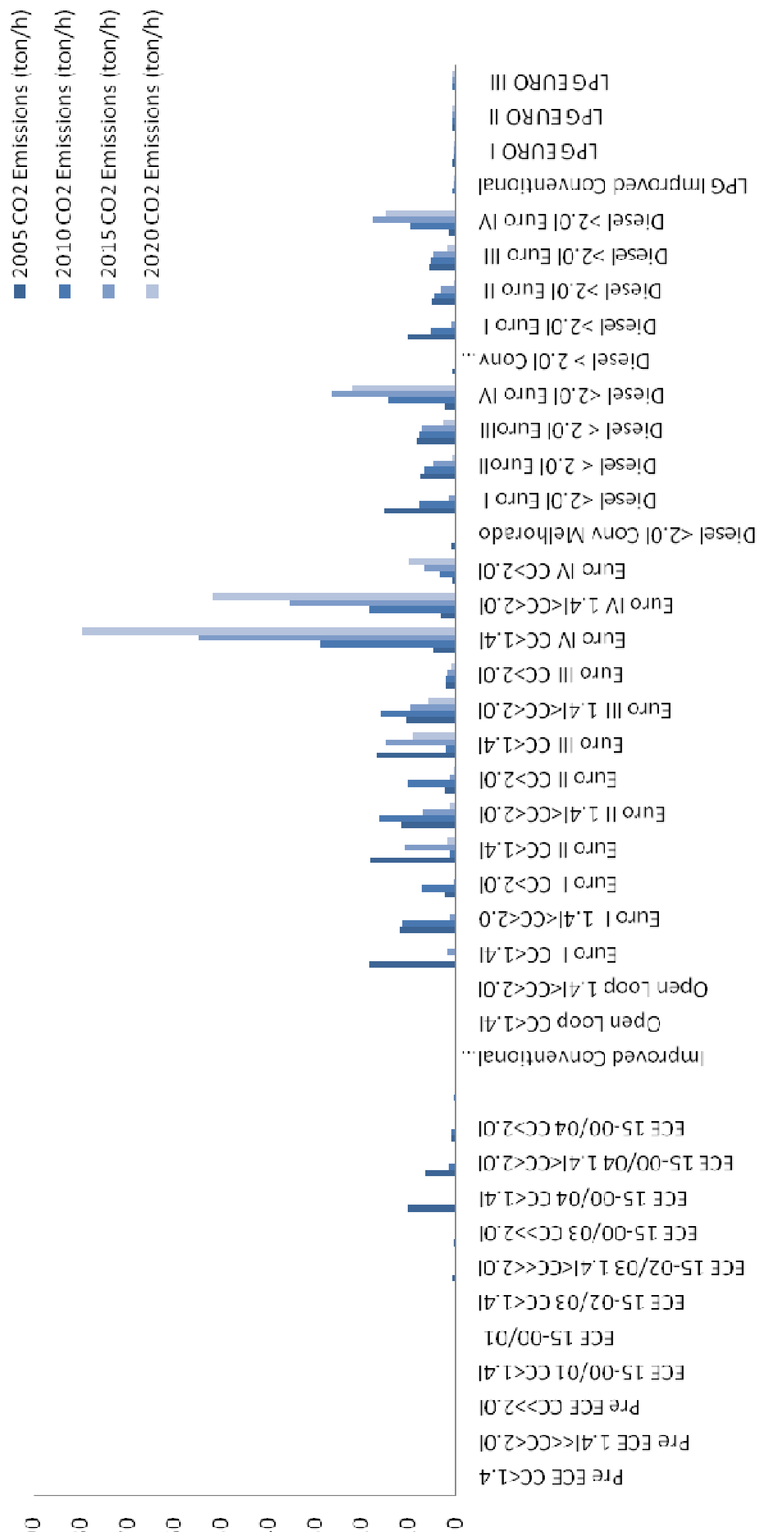

Figure 21: Representation of CO_2 emission values (ton/h) depending on the legislative emission class.

4.4 Secondary Scenarios

In the secondary scenarios attention is derived to a set of policies instruments to determine environmental impact variations while questions can be raised about the nature and scale of the changes required to achieve a more sustainable mobility. Though models are no more than an incentive to debate these planning issues, they do define a setting within which, as a minimum, it can be appreciated where the big gains in policy and investments are most likely to be achieved in respect of positive impacts in transport policies changes on the environment.

4.4.1 Scenario 4-Increase of Inner Cities Parking Charges

The parking problems culminate in the inner city residential and mixed use areas close to the centre of the big cities. In the Porto city centre parking supply is sufficient thanks to large extensions built during the last past years. Parking problems in Porto city centre are less severe, not only because of good parking provisions, but also because of the high quality of public transport within the city centre and the low density of residents. Despite the described facts, the increase of parking charges can have a big effect in the mode choice that is going to be chosen for the specific centre areas, especially for A.M time periods. The choice of public transport is then more attractive and a reduction of individual transport vehicles is obtainable and so an expectable emission and energy consumption reduction can be obtained from the diminishing individual transport demand.

4.4.2 Scenarios 5 and 6-Reduce and Increase Public Transport Fares

An alternative policy to achieve reductions in individual transport emissions is to encourage switches to public transport. These scenarios consider the impact of this policy on overall of transportation emissions and energy values. The policy chosen to model in these scenarios is to change fares on all modelled public transport modes (rail, light rail metro and local bus services). Such a reduction/increase would increase/reduce demand for all these services in line with the values of their own-price elasticity's from the transport model, but it would also reduce/increase the demand for individual transport travel via the relevant cross-price elasticity's between the particular public transport fare and the overall demand for individual transport travel. Hence total emissions could either rise or fall considering different fare schemes.

4.4.3 Scenarios 7 and 8-Faster Public Transport and Reduced Headways

The attractiveness of public transport can be improved by faster travel times or increased quality of service reducing headways. Some individual transport trips will be switched to public transport, but a new public transport demand will be generated by the improvements and more public transport vehicle will be needed to satisfy the demand. The overall effect of the policy then depends on the relative size of the reduction in individual transport use and the increase in public transport use. Despite these facts evaluation in these scenarios is considered only in the individual transport side due to the lack of valid information to consider public transport increase vehicle demand. During these scenarios evaluation a variation of 25% in the speed of public transport system and a 50% headway reduction are to be tested.

4.4.4 Scenario 9 - Make Individual Transport Slower

During this scenario evaluation an individual transport speed reduction is simulated to test the environmental sensibilities in the modelled scenario. The proposed evaluation intends to reduce all the individual transport travel speed by 20% in residential zones and to reduce speed by 10% in the main highways. The emission variation will have different outcomes, considering that less attractive individual travel times will lead more journeys to the public transport (especially the ones that are not affected by traffic) and a significant impact can be expected from the increase of the traffic congestion modelled road network.

The following table and graphic represent the secondary scenarios pollutant emission results, inside the metropolitan area perimeter, in relation with the BAU primary scenario.

Secondary Scenarios

	CO_2	CO	VOCs	NO_x
Sc 4 - Increase of Inner Cities Parking Charges	-1.69 %	-4.13 %	-3.12 %	-3.13 %
Sc 5 - Reduce Public Transport Fares	-3.39 %	-6.2 %	-5.21 %	-4.2 %
Sc 6- Increase Public Transport Fares	1.57 %	1.6 %	1.40 %	0.9 %
Sc 7 - Faster Public Transport (25%)	-3.45 %	-5.31 %	-3.42 %	-3.62 %
Sc 8 - Reduced Headways (50%)	-2.58 %	-5.32 %	-4.20 %	-4.2 %
Sc 9 - Make Individual Transport Slower (10% and 20 %)	4.16 %	6.22 %	5.21 %	6.0 %

Table 12: Vehicle emission variation percentages for the proposed transport policies scenarios.

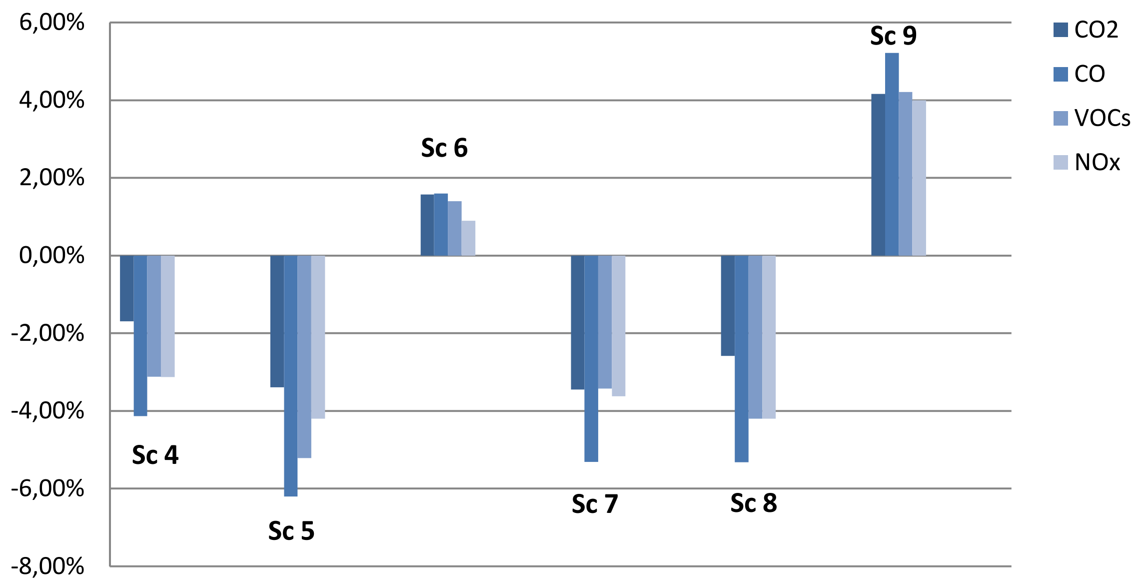

Figure 22: Secondary scenarios difference in percentage with BAU scenario.

4.5 Combined Scenarios

The overriding goal of transport policy is to improve accessibility, while at the same time fulfilling such goals as sustainability, efficiency, equity and safety. There is a growing recognition that many traditional transport policy instruments are relatively blunt over a range that is politically acceptable and within tolerable budgetary limits in respect of delivering environmental outputs. Policy instruments can have the most significant abatement in emission and energy values and these are difficult to measure and by consequence analysed.

To better understand the influence on the environment variables of political changes, and considering that the methodology proposed can give suitable and measurable environmental outputs, a set of combined scenarios is proposed and evaluated in two political transport demand changes: promotion of public transport and reduction of mobility. These scenarios intend to study the variation in pollutant emission and energy consumption considering two political macro scenarios for transport demand management. The following table represents the emission values inside the metropolitan area perimeter for the proposed combined scenarios.

Combined Scenarios

	CO_2	CO	VOCs	NO_x
Promotion of Public Transport Sc 4 + Sc 5 + Sc 7 + Sc8	-9.69 %	-10.13 %	-8.11 %	-8.43 %
Reduction of Mobility Sc 4 + Sc 6 + Sc 9	2.69 %	3.13 %	2.12 %	2.13 %

Table 13: Vehicle emission results for the transport policies combined scenarios

CHAPTER 5

CRITICAL FINDINGS AND CONCLUSIONS

5.1 Critical Findings

This dissertation has investigated the role of transport modelling in urban road network in helping the process of transport environment impact assessment for the Porto Metropolitan Area. In particular, it has tried to address the following question:

How and to what extent do travel demand models can be used in a joined way to predict emissions over urban road networks?

Transport pollutant emission modelling is a multidisciplinary exercise since it combines the results from transport modelling with emission models. Because both fields have largely been developed independently from each other, answering the research question can be a complex task, and requires a systematic approach.

A comprehensive literature review indicates that various methodologies of different complexity can be used for estimating the travel-related environmental variables. Actual research effort seems to concern intensively in the input data required by the emissions models or transport models and less in the possibility of using an integrated methodology. In the ideal situation, models that predict vehicle modal activity on detailed networks can be integrated with modal emissions, so that the two operations are performed simultaneously. Some research and relative applications have been presented to understand the possible approaches followed to improve the actual estimation of emissions. The analysis of these efforts shows that an integrated approach is still far and is considered as an "integrated problem". Each researcher tends to improve some particular aspects, as the activity based framework, the assignment phase and the disaggregation of transport data.

Several emission models were identified from the literature and they differ in the extent to which the different aspects of vehicle emissions (e.g. type of emission, vehicle categories) have been incorporated into the model. They also have a different input requirement, which in practice affects the interface with travel demand models and affects their temporal and spatial resolution. Since an increase in network size often reduces the level of detail in the output data from traffic models, a “scale effect” is visible in transport pollutant emission modelling (trade-off between network size and emission model complexity). The size of the study area affects input data availability, which subsequently determines the possibility of application of different emission model types. This is because the level of complexity of an emission model is reflected in the extent and level of detail of input data it requires to run. The more complex a model is the more input data it generally needs. However, traffic models are also subject to different levels of complexity and traffic field data are subject to different levels of availability. The spatial resolution of link level is considered to be an "expected" minimum resolution for the estimation of travel demand effects on emissions, since major differences in minimum road capacity (e.g. differences in intersection layout and signal settings) are not taken into account in a microscopic way and because capacities at different points along a link would be relatively constant.

More complex traffic models generate more comprehensive output data. For instance, the microscopic simulation model can provide data that are sufficient to run all emission model types. However, more complex traffic models require more comprehensive input data themselves, which, in practice, leads to a reduction in the size of the modelled network in order to keep use of resources within practical and manageable limits (TRB, 1997). Thus, the demand for resources (recourses, labour, computer runtime, etc.) to generate and process input data to emission models from either traffic models, field data or both, increases with network size. As a consequence, the extent and the level of detail of available input data are effectively reduced when network size increases (Gipps, 1986). In simple terms, complex models can only be applied at small networks and large networks require less complex models.

Considering the presented case study, the methodology proposed and spatial resolution of the built travel demand model (PMA model), the use of emissions and energy consumption models in a joint way with this specific travel demand model, as a significant number of factors that should be taken into account to reduce the number of inaccuracies that can be produced. Indeed the combination of models with different detail requires some simplifications and standard transport data are used (cold start, vehicle-mix and vehicle-age characteristics). A better quantification of the emissions impacts will require a methodology that accounts for or solves the significant imperfections of existing mobile source emission models and travel demand models. The emission models that use average speed cannot accurately estimate the effect of traffic flow improvements on trip emissions because they do not take into account the speed profiles of vehicles. Depending on the purpose of the study (e.g. to compare different future scenarios) it may be sufficient to apply less complex emission models, which have the advantage of requiring less input data than more complex emission models. However, when differences between models are substantial, for instance in case of absolute emission predictions (e.g. total emission load in the peak hour) or relative emission predictions between models of the same type, a choice needs to be made.

The presented findings can be considered restricted by the fact that they follow from one travel demand urban network model with particular characteristics (demand matrices, link length, free-flow speeds, delay information) and application of a particular emission models (*COPERT IV*) in a specific commercial transport model software (*EMME/3*). Considering several of the pointed critical finding, the next points intend to resume some of the problems that transport data and emission data can have when used in a joint way considering the travel demand model and the methodology proposed.

5.1.1 Modelling Limitations

The transport modelling step can give a set of transport activity data used in the subsequent emissions modelling steps in an integrated transport and emissions framework. Basically this means that the accuracy of estimated emissions and environmental impacts can be no better than the accuracy of the underlying transport model information. As seen before, the limitation of this chain is that the travel demand model, represented by traditional four-step process, is more focused on simulating flow volumes than on realism in behavioural choices. The most persisting problems in the methodology proposed are revealed in the following points.

5.1.2 Transport Data Limitations

This project dissertation demonstrated a simple but effective way to use emission and transport models in an integrated way. However several aspects must be considered to get better estimates using the joint methodology calculation. The methodology proposed in this dissertation requires linkable input data that is currently given from the travel demand model and uses a set of evaluated simplifications. Despite this fact, it is useful to analyse outcomes and some problems existing in the methodology proposed.

5.1.2.1 Characteristics of the Vehicle

The most evident outcome is that the transport data derived from the travel demand model does not give the output classified by type of vehicle, in particular about the volume, speed and distance travelled. This is the greatest difficulty to be solved, because the alternative (used in this dissertation) is to utilize default values derived from statistics at national level and this can cause greater errors. The emission rates vary according to the characteristics of a vehicle: in particular the size and weight of the vehicle, the type of fuel used and the age. So, the information required on vehicle mix is: the class; the age and distance accumulation rate; the fuel type used; the usage levels. Travel demand models do not give these data and the sources for the emission models are the national/area statistics and the counts/surveys. Indeed there can be considerable differences between the classes of vehicles required by the models and the data available and so some conversion factors are needed. In fact traffic counts do not give the vehicle classifications required and are not usually located on minor roads. There is also little information on temporal or seasonal variation in vehicle characteristics on the roads.

5.1.2.2 Operating Modes

The operating modes of a vehicle can be broadly classified in two categories: engine warming-up phase and thermally stabilised modes. Transport models do not provide information on these operating modes. This information should be made available by location within an urban area and by functional classification of roadway. Also the percentage accumulated in cold-start, hot-start and hot-stabilised modes is required. An accurate determination of the operating mode requires measurements of the engine temperature, difficult to obtain. For that very often default values are used. More accurate predictions of trips by trip purpose can be derived through the travel modelling procedure. Work trips can be estimated fairly accurately while non-work trips have generally been poorly estimated, given the complexity of the trips and the few updated O/D data.

In addition it can be useful to determine trip ends for different periods of the day (e.g. for evaporative emission purpose); although there is no temporal resolution built into the travel forecasting models, it is possible, through manipulation, to determine trip ends by time of day, location and trip purpose. However this requires a significant departure from standard practice in time-of-day treatment in travel forecasting procedures. Standard procedure is to split trips by time of day immediately before assignment. But applying time-of-day factors just before assignment results in inconsistencies and errors in the transport forecasts and make it difficult to estimate trip ends by time of day (André, 1999).

5.1.2.3 Vehicle Kilometres Travelled (VKT)

The vehicles distance travelled is a principal requirement for forecasts of mobile source emissions. The VKT can be calculated from the conventional travel forecasting process in the traffic assignment stage, using an equilibrium assignment procedure. The link length multiplies the volume obtained on each link and the VKT is given. The aggregate estimates produced from the transport models should be made consistent with the estimates of national statistics available in each nation for Europe (André, 1999). Estimates of local roads also represent a problem; in fact inter-zone travel that occurs on local roads is difficult to represent (much of it assigned to arterial system). In addition intra-zone trips are not assigned to the network and so they are ignored. This is the biggest problem in considering the effects of cold starts, particularly for the A.M peak period, when much cold-start operation takes place on local streets and intra-zone trips normally operate mainly in the cold-start mode. Moreover it is critical to provide estimates of travel for different periods of the day; there are four basic approaches to this: directly factoring the output of traffic assignment, trip table factoring, trip end factoring and direct generation. But there is not a lot of information on the accuracy of these techniques. Temporal resolution is important because measures to reduce emissions tend to have the greatest proportional effect during the peak periods, when the emissions are higher. No reflection of seasonal variation can be considered in the travel forecasting models, generally set up to represent travel on a midweek spring or fall day. Thus, seasonal adjustment factors are also required (Chatterjee, 1997).

5.1.2.4 Queue

In travel demand models flow rate is commonly used, which can exceed the physical capacity of a road (queue formation). Direct use of travel demand flow rate in emission predictions may lead to incorrect prediction and incorrect allocation of emissions in congested situations in the network. The queue is formed when demand exceeds the capacity for a period or arrival-time headway is less than the service time at a specific location. This phenomenon occurs at intersections, bottlenecks and accident sites. The input requirements for queuing analysis include mean arrival value (in vehicles per hour or seconds per vehicle), the arrival distribution, the mean service value, the service distribution and the queue discipline; in addition information on intersection characteristics (geometric attributes and traffic operations) is needed. The traffic simulation models have to be employed, for these detailed studies, to replicate the behaviour of pollutant emissions estimation in transport models traffic under certain conditions. The accuracy of these predictions depends on the data required as input for the models as well as the methodology employed by the model themselves. The information should be validated with empirical observations.

5.1.3 Emission and Energy Data Limitations

There are several aspects of emission and energy models that can affect model accuracy such as number of measurements, the use of simplified or real world cycles and the use of up-to-date emissions test data, and perhaps several other factors such as the use of local emissions test data. In this respect, the choice of a less complex emissions model such as travel average speed models (*COPERT IV*) may actually be more accurate than more complex emission models, because they use the largest empirical database, use real-world cycles and are regularly updated. Considering the resolution of the transport model, the methodology proposed can give a good and representative set of outputs. Despite these facts Matzoros and Vliet (1992) stated that emissions and fuel consumption are higher near junctions than at mid-links. Considering this, a more detailed methodology should be used in modelled signalized and unsignalized intersections even considering the macro level that the model is built in. The use of instantaneous emission approaches (modal modelling) is recommended when emissions have to be estimated in situations where driving behaviour and dynamics are of major interest. Standard average speed models are not appropriated for such tasks.

5.2 Potential Improvements

Considering the presented methodology and the travel demand model that is presented in this dissertation, a number of potential improvements should be listed to reduce inaccuracies that can be produced and to obtain better estimate results in transports and emission modelling using the proposed model.

1- Using disaggregate and activity-based travel demand emerging modelling approaches focus on the individual, household, vehicle and trip rather than aggregate groups of households or area wide traditional approaches. A strong evolution is been accomplished and travel demand analyses incorporate estimates of the level, type, and age of vehicles owned by a household. Non-motorised modes of travel (bicycling and walking) are being better integrated into urban area travel demand analyses so that the full range of smaller trips can be distinguish. Trip information is derived from the demand for individual activities. Activity-based travel analyses simulate individual daily activity patterns and, ultimately, will include activities that do not involve actual travel.

2- Household travel surveys containing stated as well as revealed preference data. New household travel surveys can be designed to include additional emissions-related information, especially with respect to vehicle characteristics. Possible air quality extensions for these surveys are the inclusion of information for trips in different seasons, additional vehicle data and information on weekend trips. Another important detail is the class of vehicle used for each trip.

Another extension to current household survey practice is to include stated preference questions regarding traffic control mechanisms (TCM) and policies that cannot be modelled through revealed preferences data. Techniques have been successfully introduced in recent years that reduce error and overestimation bias of stated preference surveys and also integrate stated and revealed preference survey data. An additional improvement in household surveys is the use of panel surveys. While each of these modules exists individually today, they have not yet been fully integrated into a production oriented transport analysis system. Further, some of these modules still are in the relatively early stages of research and deployment, especially activity-based travelling demand modelling. The immediate strategies to improve the transport models capabilities, to analyse the effects of TCM and intelligent transport systems (ITS) are based on selective enhancements to the current “four-step” set of planning and analysis tools.

3 - The estimated values for link speeds obtained from travel demand models can vary substantially, depending on the procedure used. To improve speed estimation, reliable information on traffic volumes and roadway characteristics are necessary considering that traditional planning models are not calibrated to produce accurate speed estimates. Free-flow speeds and a speed-flow curve are input into those models and adjusted as necessary to obtain calibrated volume estimates. Typically, the reasonableness of the final travel speeds is not checked once reliable volume forecasts have been achieved. A post-processor[13] methodology that can be applied at the end of a typical planning model forecast process to improve the estimates of travel speeds output by a planning model. The post-processor methodology uses an improved speed-flow curve and queuing analysis to obtain travel speed estimates that more closely approximate the average speeds estimated by typical operations models.

The typical application of a post-processor to a network considers links as individual entities, which is adequate for free-flow conditions, however, when volumes on a single link exceed capacity; repercussions develop on other links in the network that go unaccounted for by post-processor. The post-processor significantly improved the original planning model estimates of average speed and delay (Dowling, 1992).

4 - Some studies are focused on the improvement of assignment phase of travel demand model. Venigalla *et al.* *(*1994) aimed to build a specialized equilibrium assignment algorithm for air quality modelling. In fact, the conventional traffic assignment algorithms generally account for a single purpose assignment, that is, assignment of total vehicle trips on to network links. On the new perspective of emissions forecasting it will be necessary to assign multiple classes of trips to network links, preferably in a simultaneous fashion.

In the past some authors proposed a multiple user class assignment model for different purposes. The research conducted by Venigalla (1994) is focused on the use of traffic assignment for deriving operating mode fractions, technique still in its conceptual stage. The study presents a specialised equilibrium assignment algorithm for tracking vehicle trips in various modes of operation.

In order to determine the proportion of vehicles operating in different modes on a roadway, it is essential to know the start mode as well as the elapsed time since the start.

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[13]Several post-processing techniques have been developed to improve the prediction of standard travel demand models estimated speeds (Dowling, 1992); to disaggregate daily (or time-period) link volumes into hourly volumes (Quint *et al.*, 1994; Niemeier *et al.*, 1999); to adjust daily volumes into season-specific volumes (Quint *et al.,* 1994; Benson *et al.,* 1994);

Venigalla (1994) established that the FTP mode mix, which was derived based on a small sample of trips several years ago, does not provide a true representation of present day general driving patterns of the population. In addition, the operating mode fraction values should be developed for varying situations (stratified by functional class of highway and geographic location).

An accurate determination of the operating mode of a vehicle engine requires measurements of the engine temperature, but it is difficult and expensive. An indirect approach can be the utilisation of the travel time from a trip origin. This can be estimated either by interviewing drivers or by modelling (less expensive). This last approach is followed in the research, which wants to address the gaps in multiple user class assignment models for air quality analysis. An algorithm is used; it is aimed to minimise the objective function governed only by the total trips that is a superset of trips of all operating modes.

5 – The road intersections underline a number of factors that can have great influence in the emission and energy consumption final values. The use of an integrated modal model to calculate the influence of factors such as acceleration and deceleration near sign junctions could help to desegregate information and include more detailed input and output values. Different methodologies (such as the VSP model, on-board emission approach) can be incorporated in the future as modular models (standard intersection situations) for specific intersections (such as the work developed by Coelho *et al*., 2006), and potentially improvement in emission estimation can be obtained where *COPERT IV* fails to deliver in low speed situations. This methodology can also incorporate several other set of scenario outputs including traffic management policies and its impacts in congested urban network.

5.3 Conclusions

This dissertation has investigated the importance of urban network modelling for environmental impact assessment and possible linking with emission models, by applying *COPERT IV* methodology emission models to a urban road network in Portugal (Porto Metropolitan Area) using the *EMME/3* software. It was also possible to overview the role that integrated emission and transport models systems can play in aiding the environment impact assessment of transport related policy instruments. While the literature is extensive, a set of well-defined perspective on modelling, data, and software architecture are evolving highlighting the features of integrated model systems that add substantial value to policy debates.

The results applying the proposed methodology have been modelled considering several scenarios differentiated in a specific time line (A.M Peak Period) in order to contrast network congestion levels and differentiated in space to examine different scenarios effects. Given the large number of emission models techniques that exist, general conclusions that would apply to the current calculation methodology model can logically not be made from this work. Also, the extent of differences that could potentially exist between the results from this dissertation and outcomes from studies conducted in a similar fashion, but based on other urban networks with different characteristics (fleet composition, network configuration, etc.) cannot be assessed here. With these limitations in mind, the results of this dissertation suggest that:

1- Transport emission and energy consumption can be evaluated in a joint way with the present travel demand model and the emissions/energy consumption calculation methodology, as demonstrated in Chapter 3, considering also the temporal and spatial resolution of the PMA model. This dissertation has identified the main pollutant emissions and energy consumption from the transport activity (individual transport), their recent impacts and future trends in the PMA. Several transport environmental indicators are extracted and the region mobility patterns environmental impact can be evaluated.

2- Several emission and energy consumption models were identified from the literature review and they differ manly in the extent to which the different aspects of the vehicle have been incorporated into the model. They also have a different input requirement, which, in practice affects the interface with travel demand models and their temporal and spatial resolution. The trade-off between emission model complexity and network size and its consequences for model choice at any spatial resolution should be carefully considered. In practical applications, complex emission models are effectively applied to small networks only and large road networks require less complex travel demand and emission models due to reduced data availability.

3- Travel demand models were developed as a tool for planning the location and size of new transport facilities. Some structural and theoretical aspects of travel demand models exclude a thorough analysis of TCM and ITS. In particular, assumptions of perfect knowledge of the system, presumed equilibrium condition and lack of variation complicate the application of the conventional travel demand models to TCM and ITS deployment evaluations. On the other hand the emission models that use average speed (*COPERT IV*) cannot accurately estimate the effect of traffic flow improvements on trip emissions because they do not take into account the speed profiles of the vehicles. For evaluating TCM and ITS and their specific application field which is to evaluate the impact of slight changes in driving patterns on emissions or to take into account the kinematic component of the driving behaviour with high accuracy a different integrated transport and emissions modelling methodology should be implemented as future work.

5.4 Dissertation Contributions

This dissertation used an integrated transport and environment planning tool in an application developed in *EMME/3*. This tool overcomes the drawbacks of the traditional transport planning tools, which are by nature not suitable to evaluate planning strategies that involve explicit environment modelling. Therefore, this integrated transport planning tool was able to capture the different scenarios more accurately to evaluate the transport policies and its implications in the environment. Moreover, this tool can be used to analyse day-to-day travel patterns, within-day behaviour of travellers, and in the same way be responsive to the environment variables. The results for the PMA scenarios show that predictive transport and environment modelling can be effective. Modelled values (even aggregated ones) are extracted and constitute a good representation of the environment impact of transport in the scenarios evaluated.

5.5 Further Work

In terms of further work and new directions, the following comments can be made:

- A reduction in model complexity is accompanied by a reduction in spatial and temporal resolution. Now the question arises: what is the appropriate spatial and temporal resolution in the modelling of the emissions and energy consumption in urban networks?
- Considering the increasing importance of traffic congestion, namely in specific interruptions like signalized and unsignalized intersections. It seems vital to extend current transport and emission and energy consumption models with algorithms that enable the prediction of the full impacts of traffic congestion on pollutant emissions for all dimensions.
- Additional investigation in using different emissions and energy consumption models and transport models in a joint way considering their differences and further research into the relative importance of the various factors that contribute to emission model accuracy.

- Incorporate the calculation of PM emissions, since is one of the pollutants that cause problems or air pollution within the cities, with consequences in human health.
- Considering the distribution of travel speeds within a traffic stream (links) in emission estimation may lead to different (and more accurate) predictions. This investigation of the relationship between level of congestion and the distributions of travel speeds would precede further investigation into this matter.
- Knowing the difficulties associated with evaluating emission model accuracy, it seems important to employ different techniques (e.g., laboratory measurements, on-board measurements, remote-sensing) in the process of emissions model validation, where each technique has its own strengths and weaknesses, and not to assess overall model accuracy with one particular methodology.
- Add a layer of air pollution modelling, in order to calculate the pollutants concentrations in PMA along a typical weekday, according with the evolution of hourly traffic volume.

ANNEX

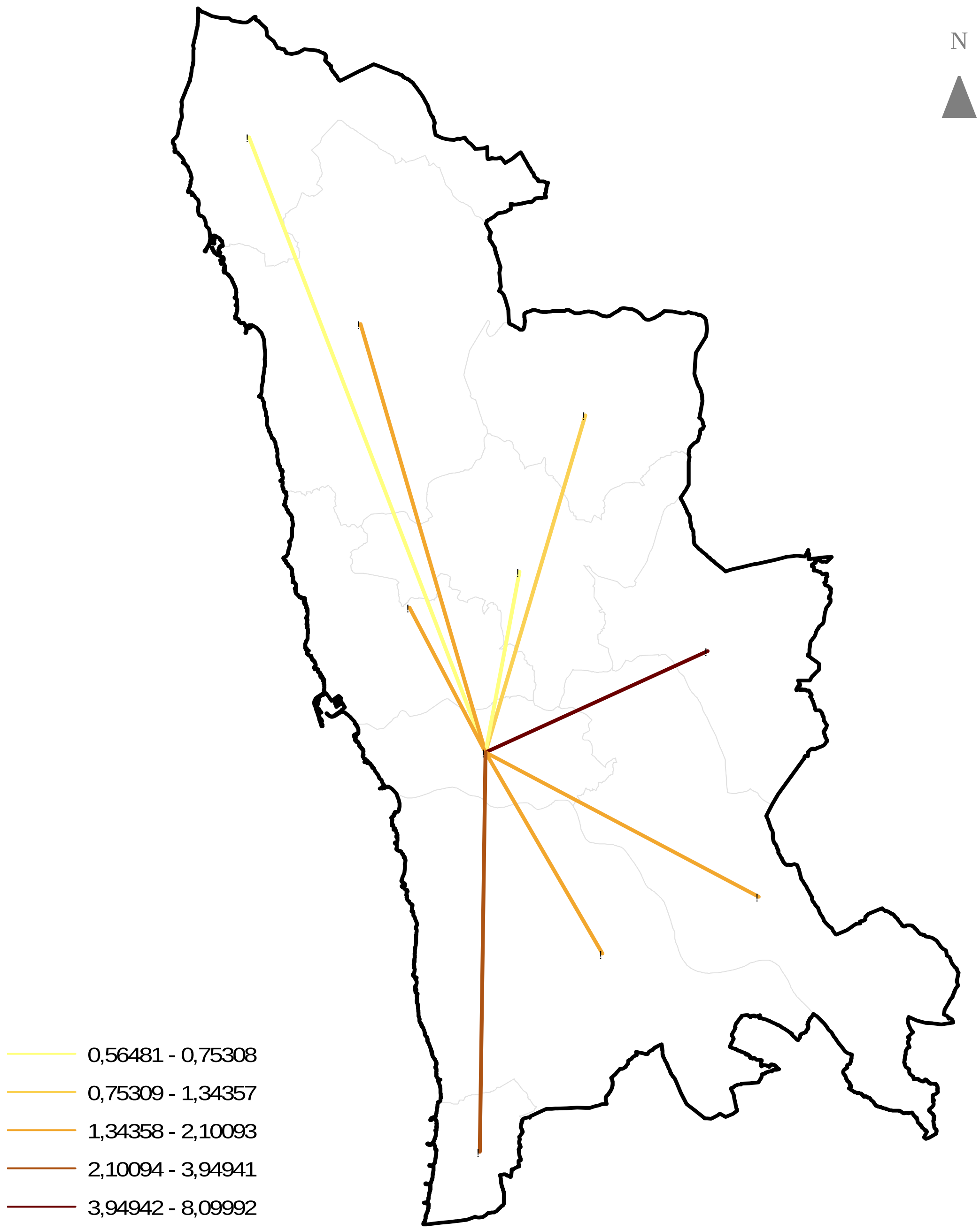

Figure 23: Porto municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

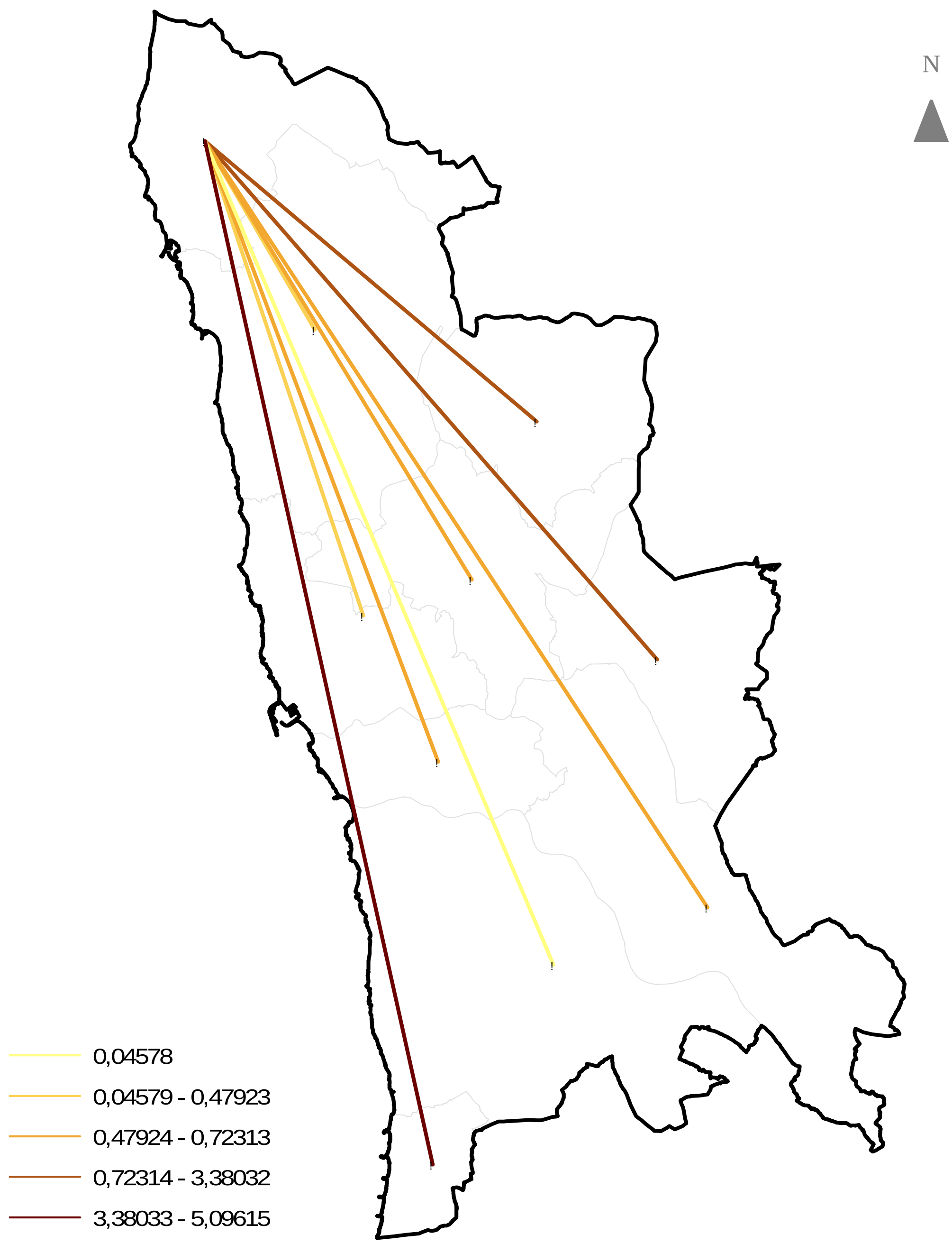

Figure 24: Póvoa do Varzim municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

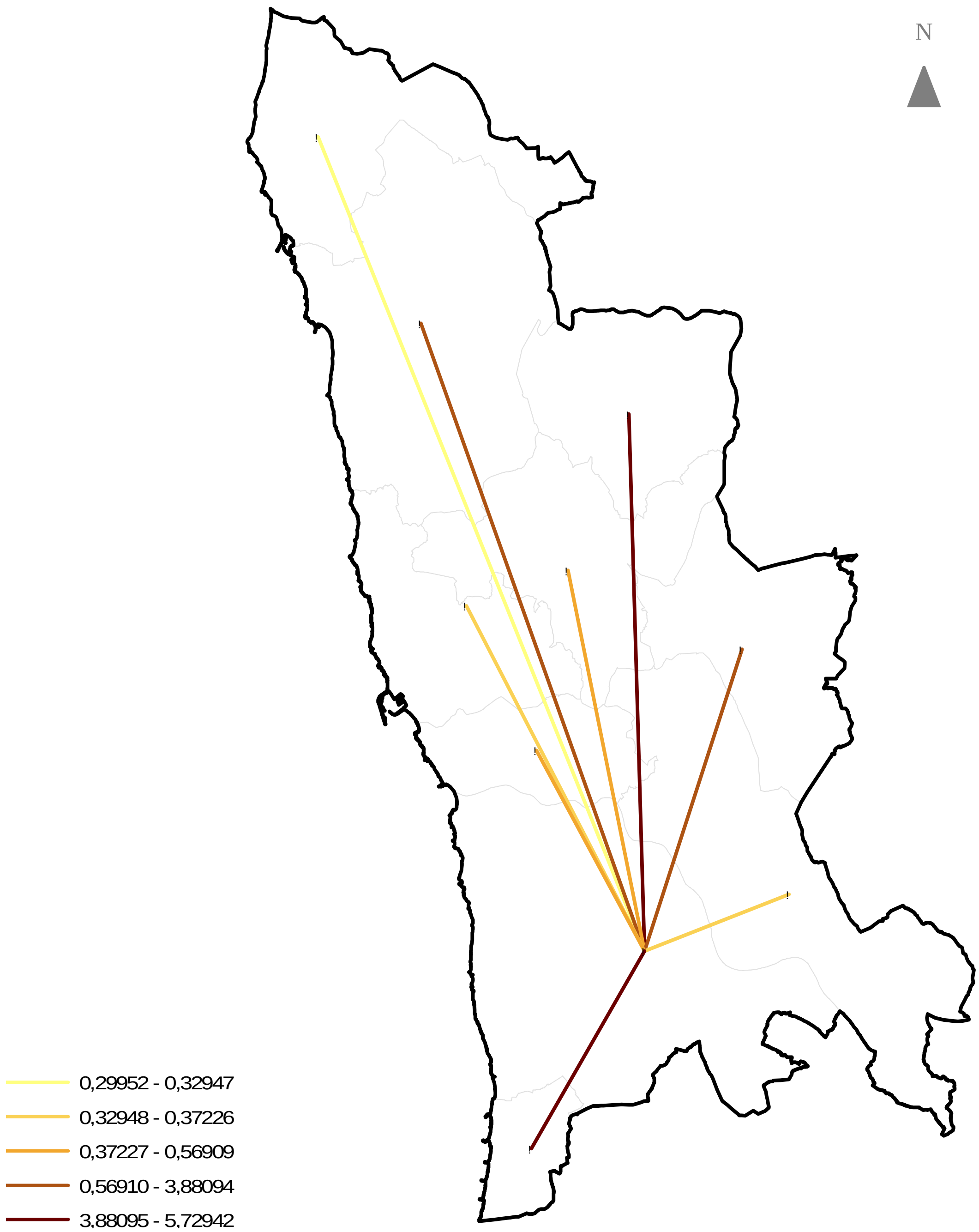

Figure 25: Gaia municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

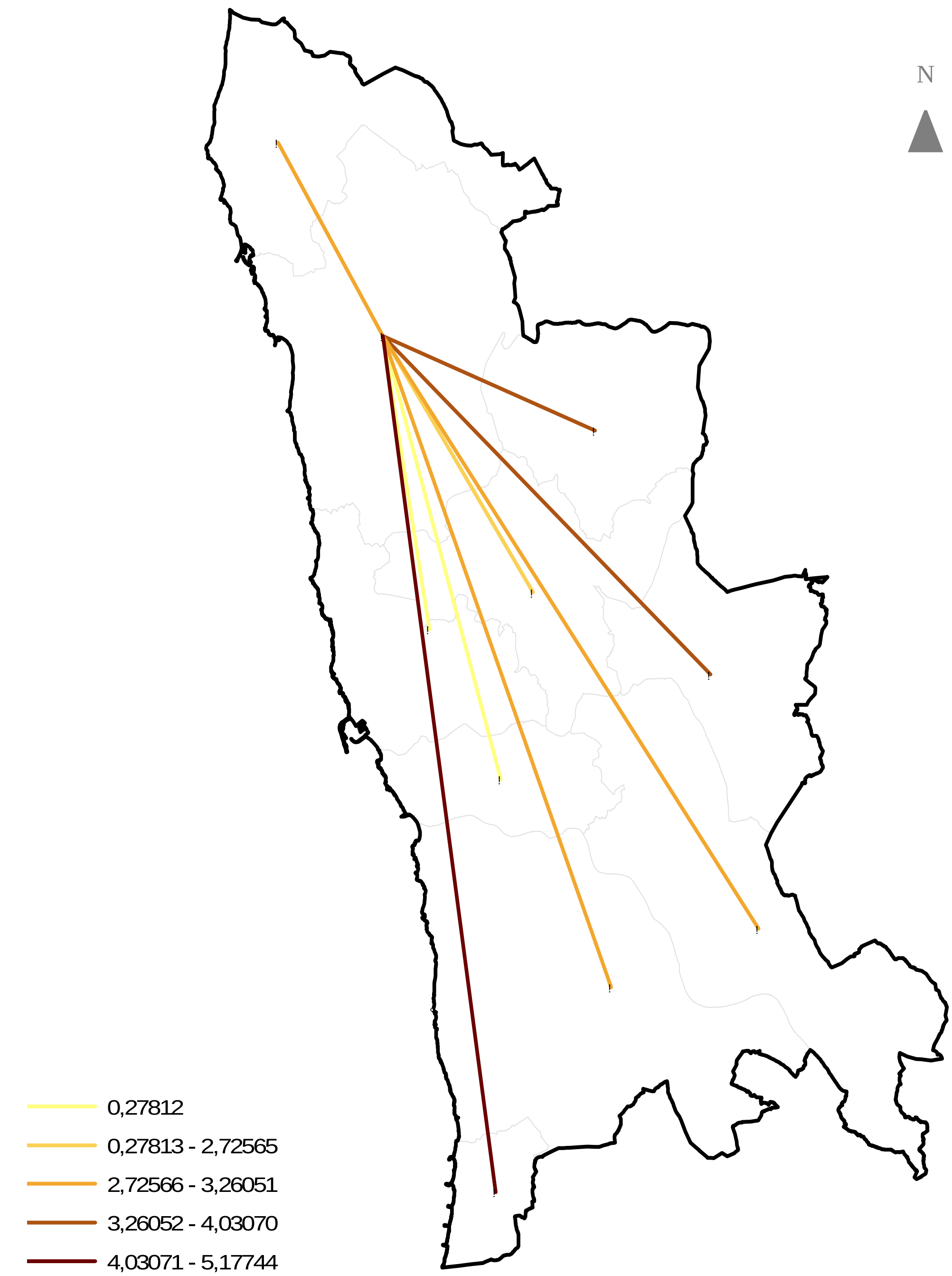

Figure 26: Vila do Conde municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

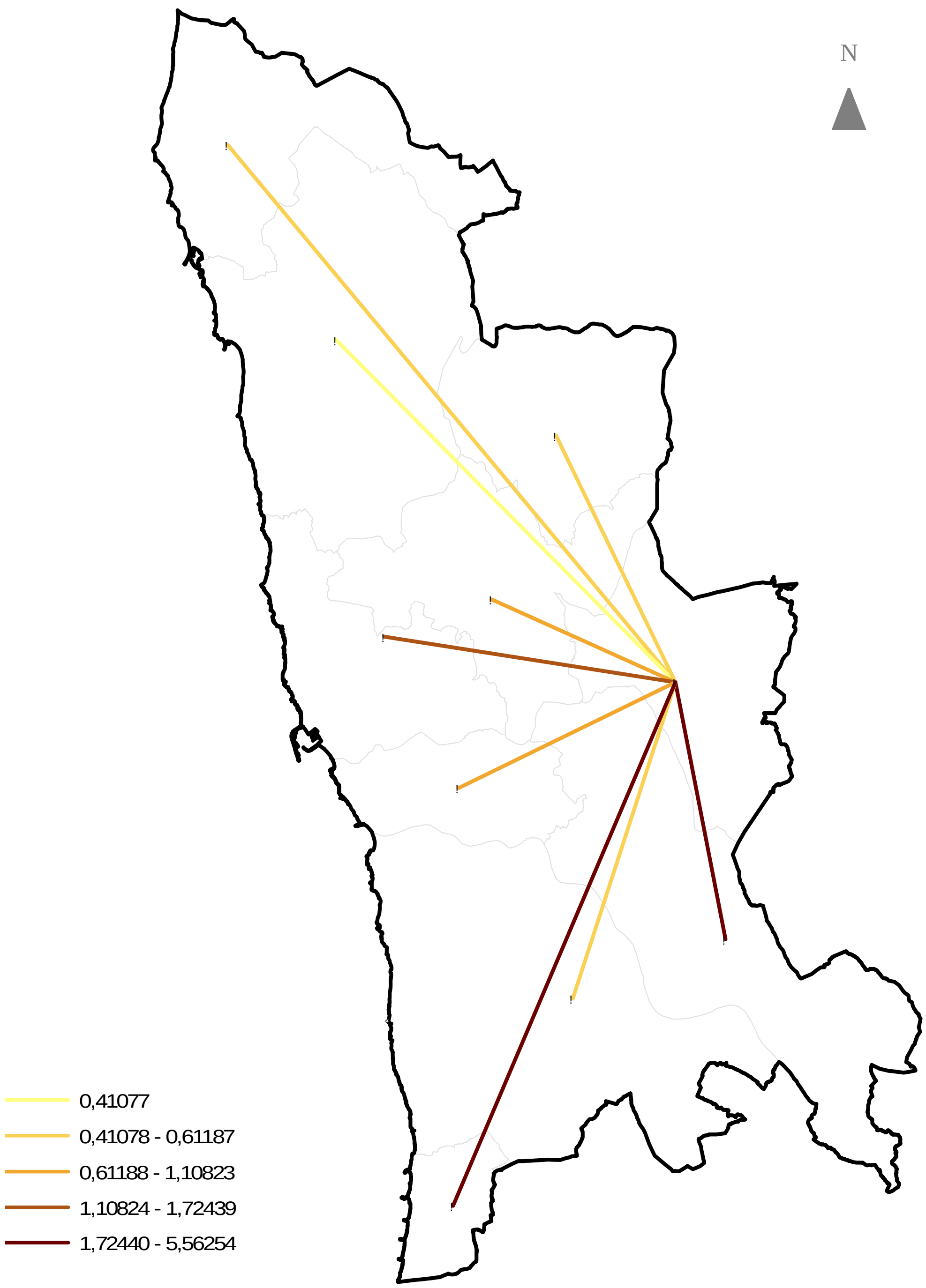

Figure 27: Valongo municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

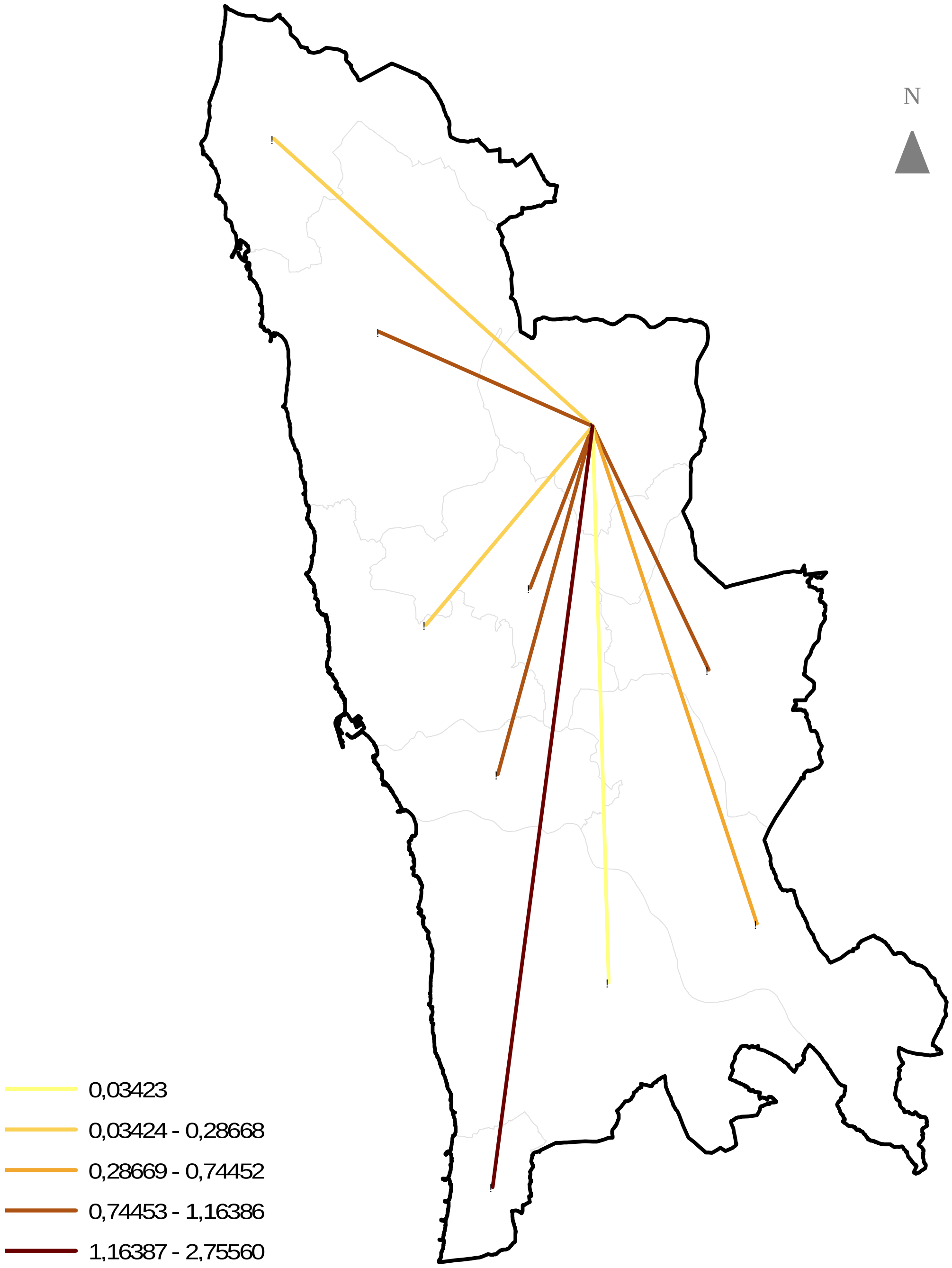

Figure 28: Trofa municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

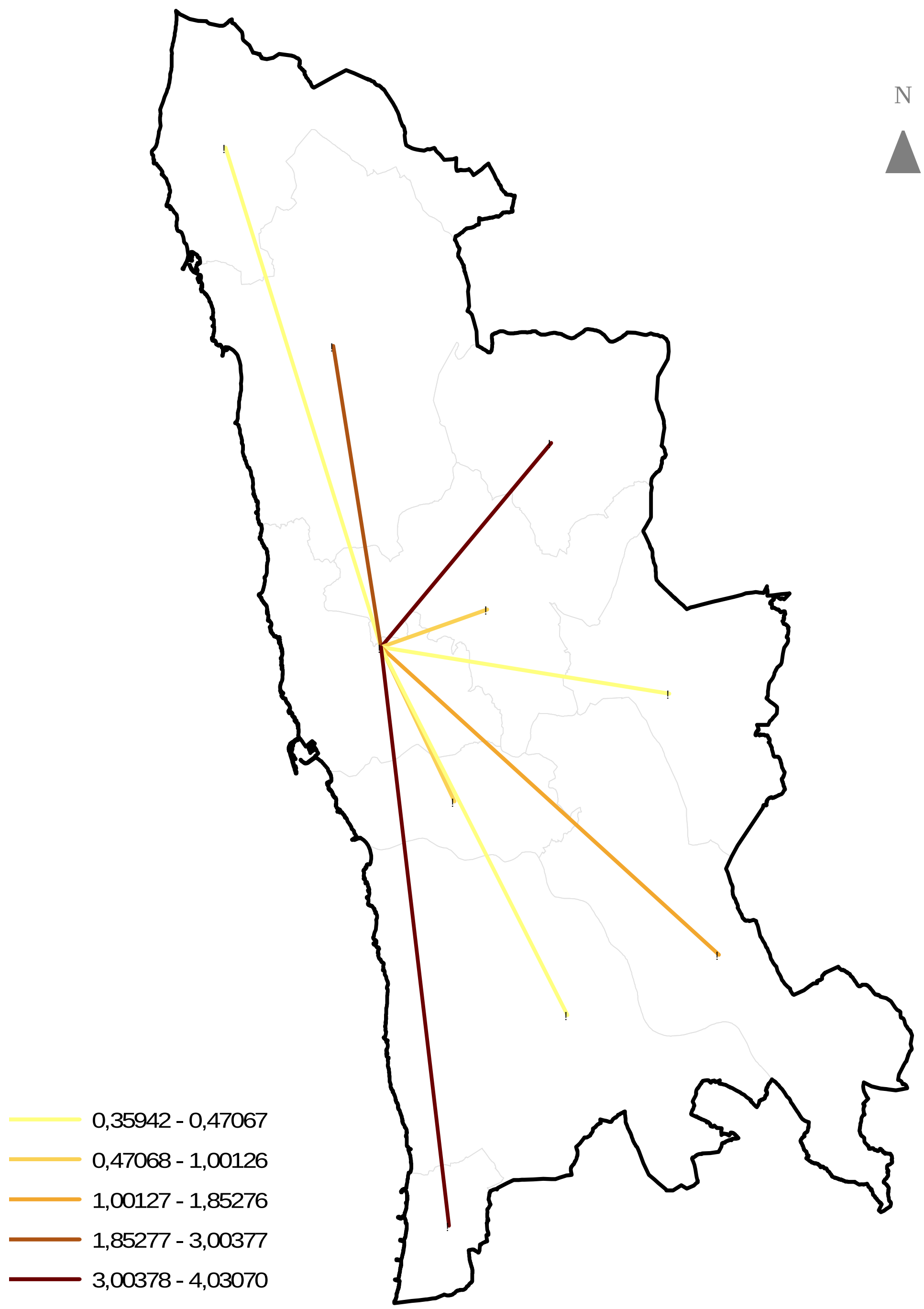

Figure 29: Matosinhos municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

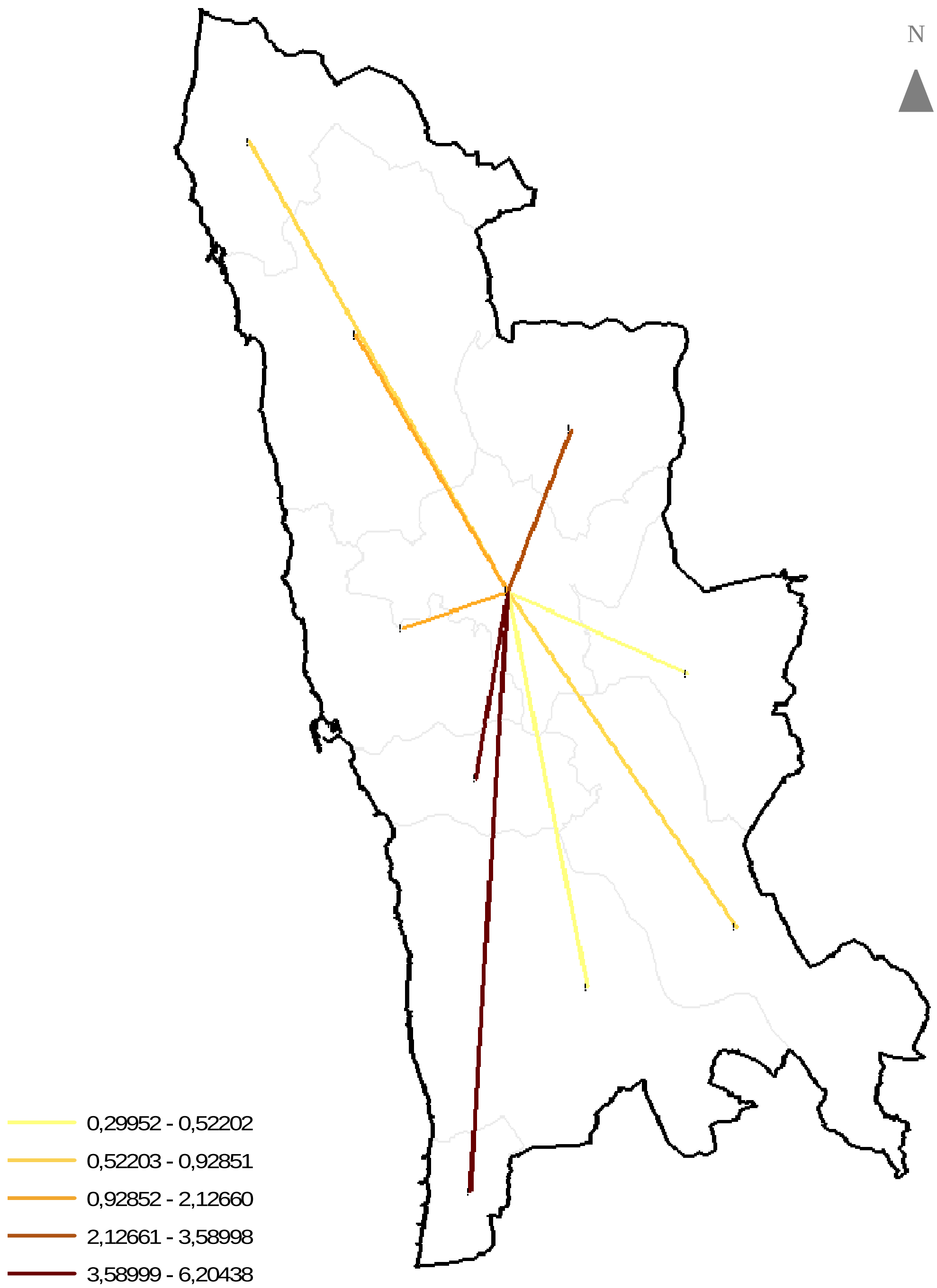

Figure 30: Maia municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

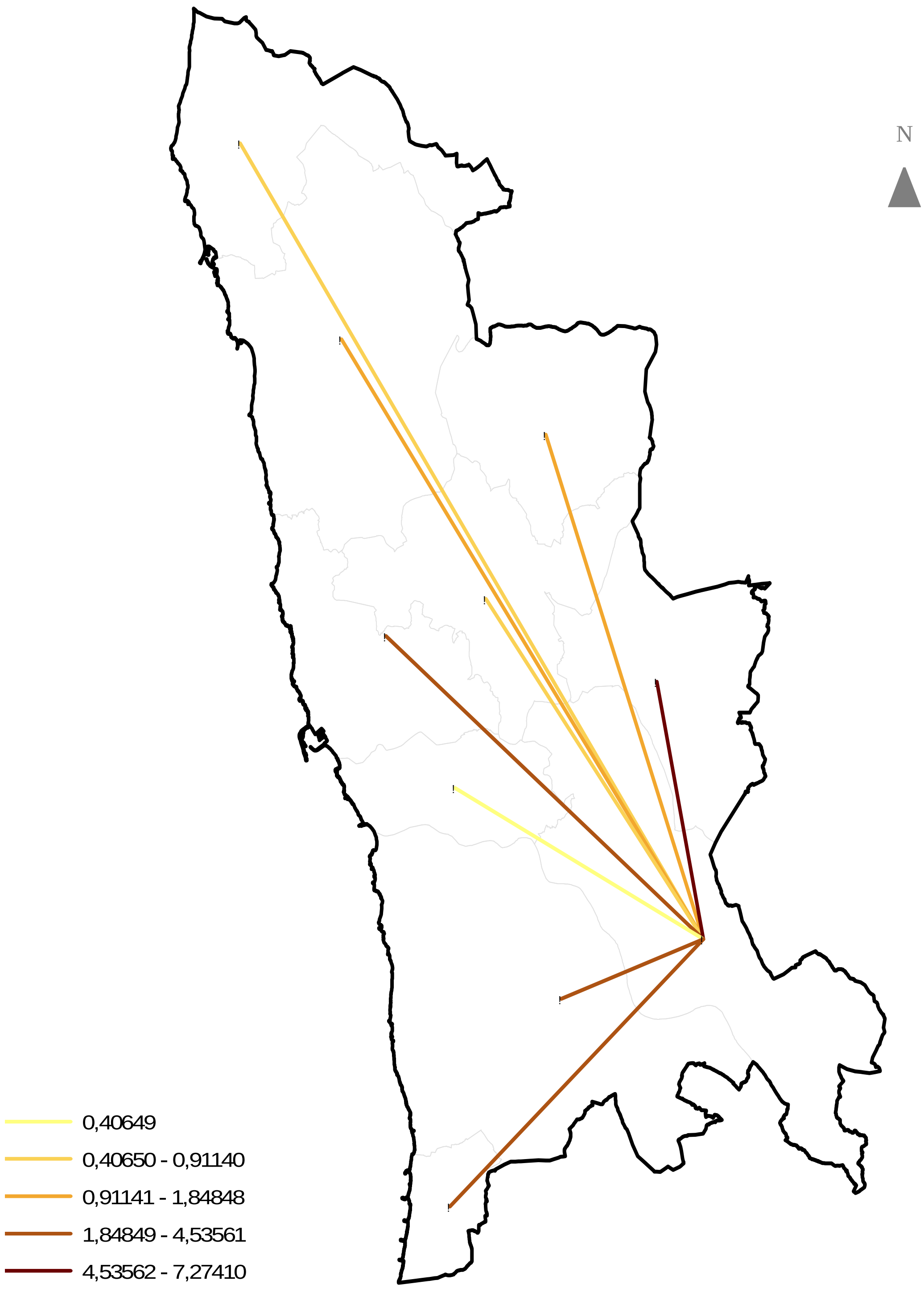

Figure 31: Gondomar municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

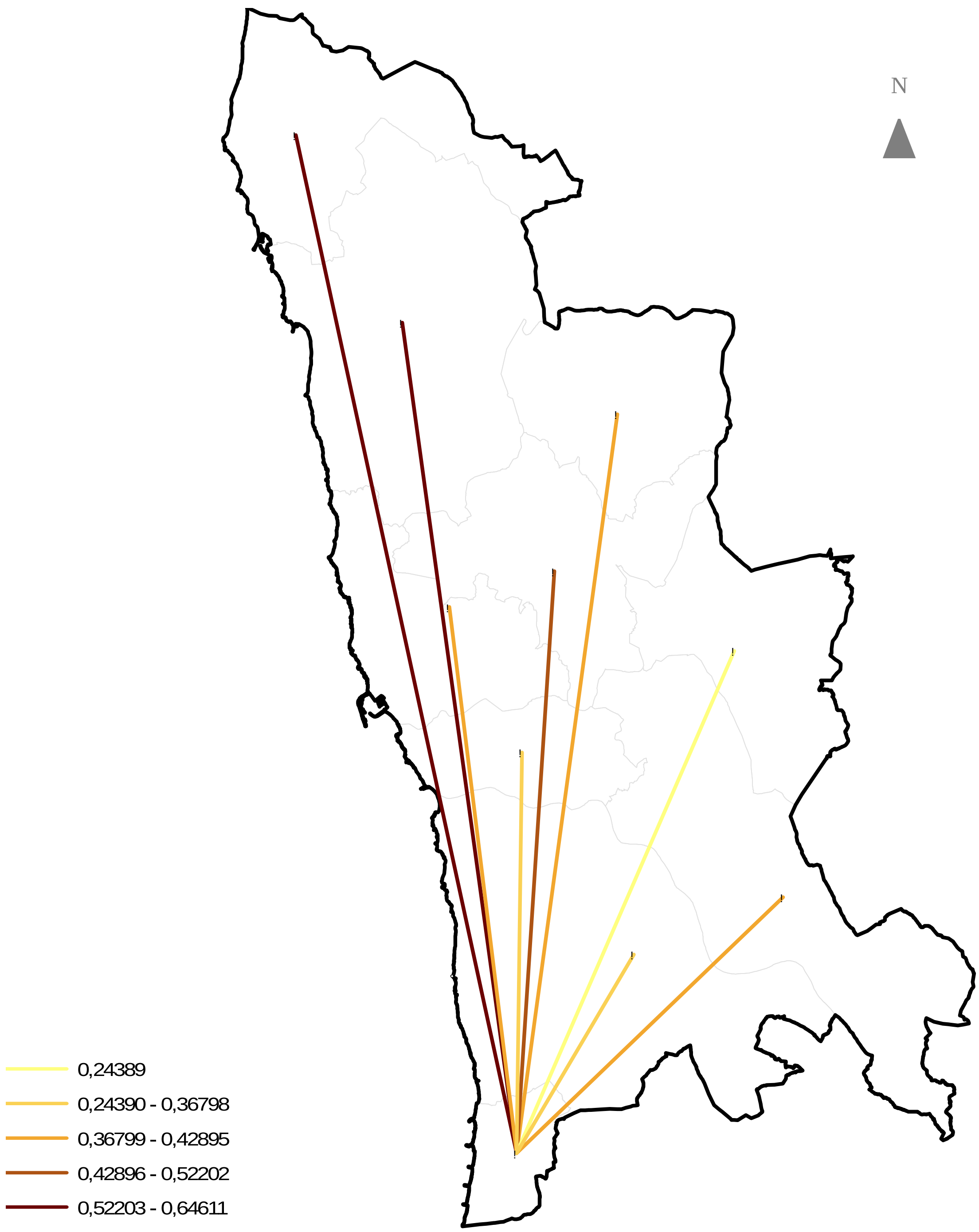

Figure 32: Espinho municipality CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

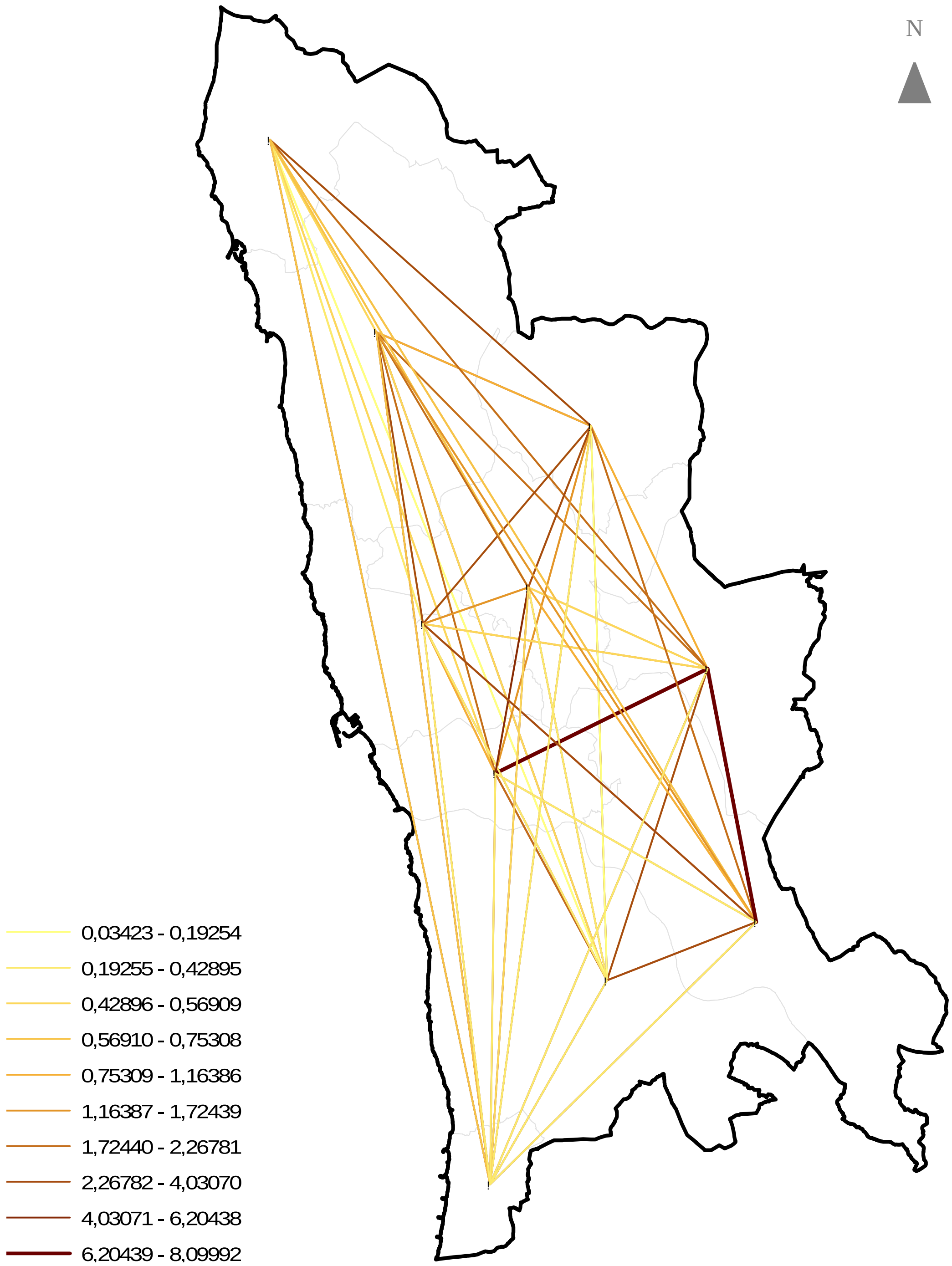

Figure 33: CO_2 (ton/h) emissions by origin and its spatial relation with the other PMA municipality´s in the morning peak period.

Fuel	Engine Size	Technology	For 2005	For 2010	For 2015	For 2020
Diesel	<2.0 l	Improved Conventional	0,53	0,01	0,00	0,00
Diesel	<2.0 l	EURO I	8,30	3,98	0,68	0,01
Diesel	<2.0 l	EURO II	4,00	3,37	2,09	0,36
Diesel	<2.0 l	EURO III	4,53	3,98	3,28	1,87
Diesel	<2.0 l	EURO IV	1,25	7,27	12,19	16,45
Diesel	>2.0 l	Improved Conventional	0,36	0,00	0,00	0,00
Diesel	>2.0 l	EURO I	5,53	2,65	0,45	0,00
Diesel	>2.0 l	EURO II	2,67	2,25	1,39	0,24
Diesel	>2.0 l	EURO III	3,02	2,65	2,19	1,25
Diesel	>2.0 l	EURO IV	0,83	4,85	8,13	10,97
Gasoline	<1.4 l	pré-ECE	0,00	0,00	0,00	0,00
Gasoline	<1.4 l	ECE 15-00/01	0,00	0,00	0,00	0,00
Gasoline	<1.4 l	ECE 15-02	0,00	0,00	0,00	0,00
Gasoline	<1.4 l	ECE 15-03	0,25	0,00	0,00	0,00
Gasoline	<1.4 l	ECE 15-04	6,09	0,84	0,00	0,00
Gasoline	<1.4 l	Improved Conventional	0,00	0,00	0,00	0,00
Gasoline	<1.4 l	Open loop	0,00	0,00	0,00	0,00
Gasoline	<1.4 l	EURO I	11,19	6,33	0,90	0,00
Gasoline	<1.4 l	EURO II	11,08	9,12	5,38	0,79
Gasoline	<1.4 l	EURO III	10,09	8,80	7,44	4,07
Gasoline	<1.4 l	EURO IV	2,78	16,09	27,69	35,75
Gasoline	1.4-2.0 l	pré-ECE	0,00	0,00	0,00	0,00
Gasoline	1.4-2.0 l	ECE 15-00/01	0,00	0,00	0,00	0,00
Gasoline	1.4-2.0 l	ECE 15-02	0,00	0,00	0,00	0,00
Gasoline	1.4-2.0 l	ECE 15-03	0,13	0,00	0,00	0,00
Gasoline	1.4-2.0 l	ECE 15-04	3,27	0,45	0,00	0,00
Gasoline	1.4-2.0 l	Improved Conventional	0,00	0,00	0,00	0,00
Gasoline	1.4-2.0 l	Open loop	0,00	0,00	0,00	0,00
Gasoline	1.4-2.0 l	EURO I	6,01	3,40	0,48	0,00
Gasoline	1.4-2.0 l	EURO II	5,95	4,90	2,89	0,42
Gasoline	1.4-2.0 l	EURO III	5,42	4,73	4,00	2,19
Gasoline	1.4-2.0 l	EURO IV	1,49	8,65	14,88	19,21
Gasoline	>2.0 l	pré-ECE	0,00	0,00	0,00	0,00
Gasoline	>2.0 l	ECE 15-00/01	0,00	0,00	0,00	0,00
Gasoline	>2.0 l	ECE 15-02	0,00	0,00	0,00	0,00
Gasoline	>2.0 l	ECE 15-03	0,02	0,00	0,00	0,00
Gasoline	>2.0 l	ECE 15-04	0,52	0,07	0,00	0,00
Gasoline	>2.0 l	EURO I	0,96	0,54	0,08	0,00
Gasoline	>2.0 l	EURO II	0,95	0,78	0,46	0,07
Gasoline	>2.0 l	EURO III	0,87	0,76	0,64	0,35
Gasoline	>2.0 l	EURO IV	0,24	1,38	2,38	3,08
LPG	All	Improved Conventional	0,57	0,45	0,37	0,28
LPG	All	EURO I	0,67	0,57	0,53	0,47
LPG	All	EURO II	0,43	0,75	0,70	0,64
LPG	All	EURO III	0,00	0,38	0,78	1,54
LPG	All	EURO IV	0,00	0,00	0,00	0,00

Table 14: Emission legislative class distribution in percentage, André *et al*. (1999).

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