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METHODOLOGY FOR AIR POLLUTION IMPACT ASSESSMENT OF LOW EMISSION ZONES IN URBAN AREAS OF BRAZIL - THE CASE STUDY OF FORTALEZA

FORTALEZA
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Orientador: Prof. Dr. Bruno Vieira Bertoncini.
Coorientador: Prof. Dr. Rivelino Martins Cavalcante.

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Thesis presented to Post-Graduation Program in Transportation Engineering of Federal University of Ceará, as a partial fulfillment to obtainment of doctorate degree in Transportation Engineering. Area of concentration: Planning and Operation of Transportation Systems.

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To my mother.

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“All knowledge which ends in words will die as quickly as it came to life, with the exception of the written word: which is its mechanical part.” (Leonardo da Vinci 1452 – 1519)

RESUMO

O principal tema desta pesquisa é o desenvolvimento de uma metodologia para avaliação do impacto da poluição do ar de Zonas de Baixa Emissão em áreas urbanas brasileiras, utilizando o município de Fortaleza como cidade de estudo. Zonas de Baixa Emissão são áreas geograficamente definidas onde os veículos mais poluentes são restritos, a fim de reduzir a concentração de poluentes de fontes móveis. Para isso, os métodos de concentração da poluição do ar na coleta de dados reais em nível das ruas foram adaptados e desenvolvidos. Além disso, o sistema de modelagem da poluição do ar THOR-AirPAS foi ajustado às condições meteorológicas e de tráfego de Fortaleza. Neste trabalho, os detalhes dos experimentos para análise de sistemas de coleta e modelagem de dados reais de poluição do ar utilizando os resultados de um modelo de demanda de viagens são apresentados, TRANUS, Modelo de Transporte e Uso do Solo. O sistema de avaliação da poluição atmosférica THOR-AirPAS com o IFS, o pré-processador meteorológico OML-Highway, o UBM e o OSPM foram ajustados e validados para o desenvolvimento da metodologia. O experimento realizado nesta pesquisa mostrou que, devido ao atraso tecnológico da frota brasileira de veículos, as Zonas de Baixa Emissão apresentam um potencial significativo na redução da poluição atmosférica, especialmente relacionada ao NO_2, poluente fortemente ligado a veículos pesados (ônibus e caminhões, em maioria). O experimento simulado de dados de poluição do ar mostrou erros aceitáveis em comparação com dados reais coletados na área analisada, no entanto, as concentrações a níveis regionais e urbanos da coleta de dados reais poderiam reduzir as subestimações e superestimações simuladas e observadas. Sete diferentes cenários sugeridos na literatura foram propostos para a Zona de Baixa Emissão de Fortaleza, com cenário UZBE apresentando potencial significativamente maior na redução da poluição do ar, atingindo 9,525 $\mu g/m^3$ de reduções de NO_2 (9,22%), 2,201 $\mu g/m^3$ de Reduções de PM_{10} (9,94%) e 0,630 $\mu g/m^3$ de reduções de PM_{10} (69,25%) para fatores de emissão da CETESB, no entanto, a viabilidade das medidas de restrição na realidade econômica de Fortaleza sugere a implantação do cenário de ônibus, que traz reduções significativas na poluição do ar, com menores impactos nos aspectos econômicos e sociais da região observada.

Palavras-chave: Poluição do Ar, Modelagem da Qualidade do Ar, Zona de Baixa Emissão, THOR-AirPAS

ABSTRACT

The main topic of this research is the development of a methodology for air pollution impact assessment of Low Emission Zones in Brazilian urban areas, using Fortaleza municipality as study city. Low Emission Zones are geographically defined areas where the most polluting vehicles are restricted, in order to reduce the pollutant concentration from mobile sources. For this, methods of air pollution concentrations real data collection in street levels have been adapted and developed. In addition, THOR-AirPAS air pollution modelling system has been adjusted to Fortaleza traffic and meteorological conditions. In this work, the details of experiments for analysis of air pollution real data collection and modelling system using a travel demand model outputs are presented, in this research, TRANUS land use and Transport Model. THOR-AirPAS air pollution assessment system with IFS, OML-Highway meteorological pre-processor, UBM and OSPM have been adjusted and validated, in order to develop the methodology. The experiment carried out in this research showed that, due to delayed technologies in Brazilian vehicle fleet, Low Emission Zones presents significant potential in air pollution reduction in street levels, especially related to NO_2, pollutant strongly connected to heavy-duty vehicles (buses and trucks, in majority). The experiment simulated air pollution data showed acceptable errors in comparison with real data collected in analyzed area, however, regional and urban background concentrations real data collection could reduce the observed simulated under and overestimations. Seven different scenarios from state-of-art literature have been proposed to Fortaleza Low Emission Zone, with ULEZ scenario presenting significantly higher potential in air pollution reduction, reaching 9.525 $\mu g/m^3$ of NO_2 reductions (9.22%), 2.201 $\mu g/m^3$ of global PM_{10} reductions (9.94%) and 0.630 $\mu g/m^3$ of Exhaust PM_{10} reductions (69.25%) for CETESB emission factors, however, feasibility in restriction measures in Fortaleza economic reality suggest the implementation of buses scenario, which brings significant reductions in air pollution, with minor impacts in economic and social aspects of observed region.

Keywords: Air Pollution, Air Quality Modelling, Low Emission Zone, THOR-AirPAS

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1 INTRODUCTION

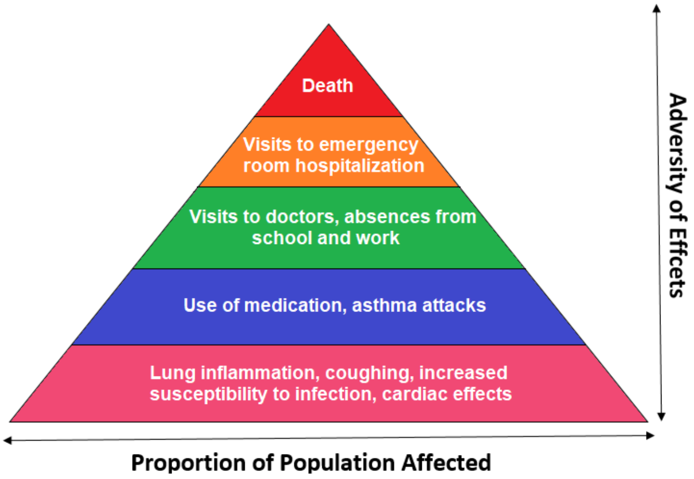
Understanding the several challenges of big cities, especially in developing countries, in terms of accessibility and mobility, the distribution of people and goods in urban areas can be highlighted as one of the most complex in terms of urban planning. Fast population growth, complexity and high competitiveness in service delivery are associated with the freight transportation within urban areas, causing problems such as air pollution, accidents, noise, congestion and potential risks to human health. As a result, air quality action plans are applied which have a strong emphasis on traffic regulation and involve policies such as stimulation of public transportation usage, ring road utilization, traffic flow improvement, speed limit reduction, among others (PANTELIADIS *et al.*, 2014).

The problems to urban mobility in Brazilian cities are related, among others, to the accelerated and unplanned city growth, to the spatial activities distribution, the expressive growth of private transportation associated with a deficient public transportation system, and to the occurrence of negative impacts related to freight transportation (SANCHES JÚNIOR, 2008), whose impacts caused by traffic have significant proportions, especially in social and environmental aspect (i.e. energy consumption and air pollution, in particular).

Concerning environmental issues, air pollution has impacting consequences to society, with urban transport representing more than half of all air pollution. More than 80% of people living in urban areas that monitor air pollution are exposed to air quality levels that exceed the World Health Organization (WHO) limits (WHO, 2013). While all regions of the world are affected, populations in low-income cities are the most impacted. According to the latest air quality database, 97% of cities in low- and middle income countries with more than 100 000 inhabitants do not meet WHO air quality guidelines.

However, in high-income countries, that percentage decreases to 49% (WHO, 2018). According to EPA (2012), health effects from air pollution, specifically from PM, can be represented by Figure 1, which represents that how much harmful air pollution is, less people are affected, however, the potential of population affected by air pollution is high for lower health impacts, which can be increased with high concentrations of gases and particulates in the atmosphere. PM_{10} is particulate matter 10 micrometers or less in diameter, $PM_{2.5}$ is particulate matter 2.5 micrometers or less in diameter. $PM_{2.5}$ is generally described as fine particles. By way of comparison, a human hair is about 100 micrometres, so roughly 40 fine particles could be placed on its width.

Figure 1 - Pyramid of Health Effects from Air Pollution ($PM_{2.5}$ and PM_{10})

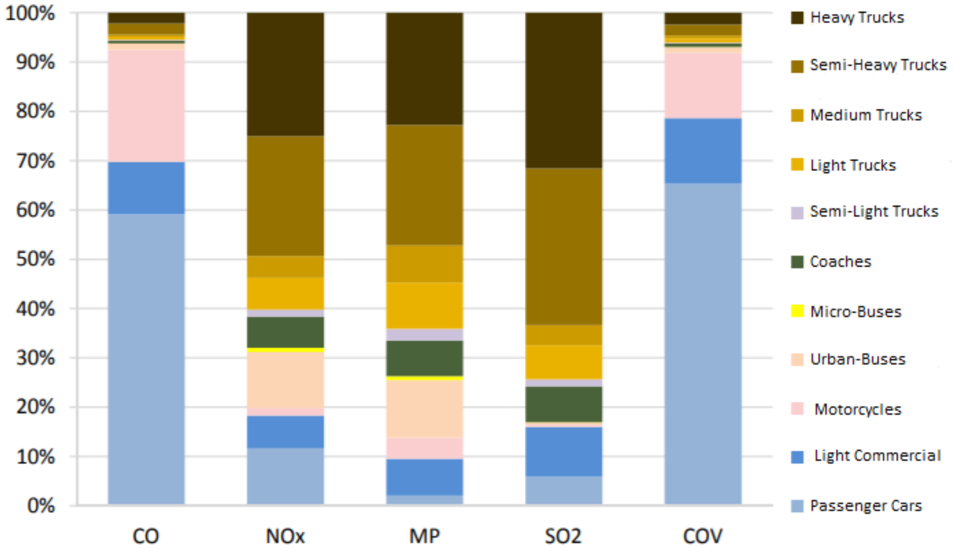


Source: EPA (2012)

In Brazilian case, in the city of Rio de Janeiro, for example, this index reaches 77% (COELHO, 2006). Thus, when planning for improvements in urban mobility, not only indicators that result in improved "trafficability" should be observed, but also those that impact on human health, especially those related to air quality. European studies includes several countries aiming to reduce the air pollution, Italy, for example, motorized road traffic is the source of 44% of the NO_2 and 26% of the PM_{10} emissions in Italy. In the city of Rome, these percentages raise to 80% and 52%, respectively (TAURINO *et al.*, 2009). In addition, São Paulo city, with only 5% HDV (High Duty Vehicles) on vehicle fleet, represents 40% and 47% of benzene and black carbon atmospheric concentration, respectively, showing how harmful diesel vehicles are in urban areas (BRITO *et al.*, 2018).

Regarding the direct impacts to population in urban areas, epidemiological studies have consistently reported effects of air pollution on respiratory and cardiovascular health (BRUNEKREEF and HOLGATE, 2002; DOCKERY *et al.*, 1993; COHEN *et al.*, 2004; POPE and DOCKERY, 2006), where traffic-related air pollution is considered to be of particular importance, due to the proportion emitted by mobile sources (BRUNEKREEF *et al.*, 2009; JERRETT *et al.*, 2009; ZUURBIER *et al.*, 2011).The distribution of Brazilian vehicle fleet indicates several fuel consumption technologies and different configuration in terms of dimensions, engine and efficiency, among other parameters, which directly impacts the emissions of each category. CETESB (2017a) shows the specificities in the pollutants emitted by the different vehicle categories of the Brazilian fleet, shown in Figure 2:

Figure 2 - Relative mobile pollutant emissions per vehicle type – 2016



Source: CETESB (2017a)

Considering the negative impacts related to air pollution caused by vehicle traffic in urban areas, some restrictive measures may be taken, depending on the characteristics of the observed traffic zone. There are five main categories of mitigation measures to reduce the emission of vehicular pollutants: (i) Economic-fiscal and financial measures; (ii) Technological measures; (iii) Information and communication measures; (iv) Urban and design planning measures; (v) Regulatory measures (BARCZAK and DUARTE, 2012).

The main economic-fiscal and financial measures applied to urban mobility follow two aspects: (i) those that penalize the user of individual motorized transport; and (ii) those that encourage the user of non-motorized transportation or public transportation. Among the measures that penalize individual motorized vehicles are taxes or levies on fuel, vehicle registration and licensing fees, traffic taxes, road taxation (such as urban toll), congestion charges and on public parking lots. Between the measures that encourage the use of public transport are subsidies or financial incentives for infrastructure and services, or measures such as emission certificates (BREITHAUPT, 2006; DALKMANN and BRANNIGAN, 2007; LITMAN, 2007; RIBEIRO *et al.*, 2007; SCHWAAB and THIELMANN, 2001; VTPI, 2009; WBCSD, 2001).

Technological measures aim to improve vehicle efficiency in order to reduce emissions directly from exhaustion. As an example, technological improvements in these systems include the use of low-emission refrigerant gases, efficient control of internal airflow, the installation of solar panels in vehicles in order to reduce the demand for electrical energy by internal components and the use of reflective layers in vehicle windshields (IEA, 2005, 2006; WBCSD, 2004).

Information and communication measures can be defined as actions that will be shared with the population to keep it informed and generate a process of awareness that will lead to a gradual change of behavior and democratic society participation in the discussion of traffic problems (ANTP, 2003). Communication, information and education measures therefore act directly on changing people's habits and behavior, aiding in the effectiveness of other, stricter measures, aimed at mitigating problems related to current mobility patterns (WRIGHT, 2006).

Measures of urban and design planning are related to growth and distribution of land use in urban areas, besides being able to be integrated to regulatory measures. The intensive, and often uncontrolled, occupation of urban areas has increased the pressure on demand for natural and material resources, exerting increasing pressure on the surrounding natural physical environment (JABAREEN, 2006). Some authors point out that what is to be sought is a pattern of sustainable urban development, which would imply in the "ecological reordering of the territory, the revision of the forms of settlement, the modes of production and the patterns of consumption" (LEFF, 2001); or "spatial redistribution of technical pressure of populations and activities on the basis of urban environmental resources" (ACSELRAD, 2001).

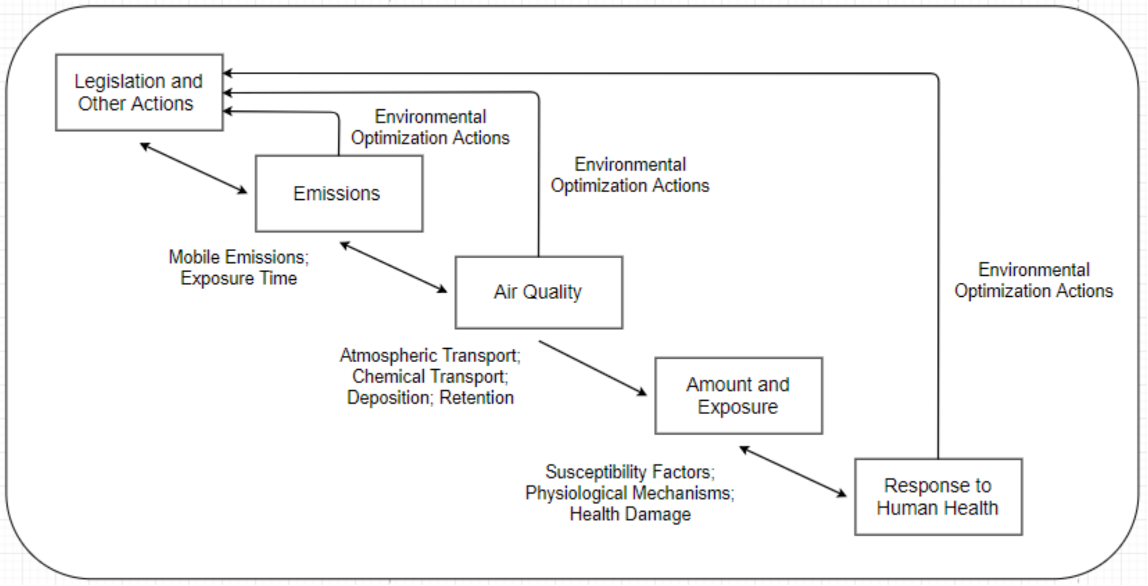
In addition do urban and design planning measures, regulatory measures can be also be added, which follow the command-and-control policy approach, with the objective of determining specifications, norms and standards, aiming to regulate or restrict potentially polluting activities (BREITHAUPT, 2006; LUSTOSA *et al.*, 2003). Another measure, of physical restriction, for example, vary in schedule time, duration and severity in regulation, from temporary bans on motorized traffic, such as car rotation operations, to the definitive impediment of access to central areas by automobiles (*Car-free Zones*) (DALKMANN and BRANNIGAN, 2007; WBCSD, 2002). And as environmental measure, Low Emission Zone (known as *LEZ*), which restricts the circulation of freight transportation and buses (among other vehicles) with dimensions and/or specifications above an established limit, aiming to reduce the concentration of these pollutants in the defined region (WEINMANN, 2014).

1.1 Research Problem and Questions

To optimize performance in transportation networks, supply and demand should be in equilibrium, however, due to indiscriminate growth of urban areas, transportation supply and demand tends to change and be unbalanced. A chaotic situation can be generated by the imbalance between supply and demand, resulting in constant congestion, difficulties in the movement of people and goods, which leads to environmental impacts, among other negative impacts (SOUSA, 2016). The impacts can be quantified by data collections in vehicles with emission factors database and air pollutant concentrations in area and/or streets impacted by vehicle traffic. Considering the resulting impacts from transportation supply and demand imbalance, travel demand modelling could be applied to understand the current situation, in addition to offer prognostics to the problem (CASCETTA, 2009), especially with lack of not only emissions and air pollution data, but also with no reliable traffic database in Brazilian urban areas.

Although improvements have been observed in reducing the concentration of atmospheric pollutants in the methodologies for construction of Low Emission Zones, the limits of size or emissions are usually the only ones observed in the implementation of the restrictive measure, not being analyzed the pollutant behavior in the environment to which they are emitted. Measures that seek to reduce the impacts of air pollutants can be used to implement actions to improve air quality. For the sake of clarity, the atmospheric pollution cycle flow chart from mobile sources is presented in Figure 3:

Figure 3 - Atmospheric Pollution Cycle Assessment Flowchart from Mobile Sources



Source: Adapted from HEI (2011)

In order to achieve improvements of the mentioned measures, mechanisms of monitoring the vehicle emission behavior are necessary. Due to the impossibility of local monitoring in each vehicle and road of the transport network, air quality and pollutant emission models can be used as tools to estimate the emissions and pollutant concentrations impacted by vehicles (among other sources) present in the network, providing emission factors and air pollution generated by mobile sources (FENSTERER *et al*., 2014). The amount and exposure can be measured or estimated by modelling, which can lead to health damage estimations. The response to human health can be observed, in order to suggest environmental optimization actions by updating the legislation and other actions.

In this sense, the pollutant emission modelling can be used to make such surveys, especially with their integration into travel demand models and later analysis of the emission behavior in the atmosphere, through air quality modelling, provided that they are calibrated by data collection in the field (CAPPIELLO, 2002), which can be a way of analyzing/implementing LEZ's in a more accurate way, aiming significant reductions in emissions and lower impacts on the traffic and system of activities, consequently, on people's life quality.

The state-of-art literature shows that research to improve efficiency in the implementation of LEZ is significantly more advanced when compared to Brazilian european countries (HOLMAN *et al*., 2015), where environmental criteria are widely considered in the construction stages of transportation networks, being possible to adapt LEZ's to Brazilian urban areas, considering the particularities and differences of the observed scenarios. Considering this, an air pollutant concentration data collection is required, followed by a mobile source atmospheric air pollution modelling in urban areas, which can be realized by the use of mathematical models capable of explaining/replicating the effects of emissions and air pollutant concentrations. For this purpose, some research questions are listed below:

- How the latest strategies of Low Emission Zone implementation can be adapted for urban Brazilian reality?
- How is the spatial and temporal variation of traffic and air pollutants in the area of a potential Low Emission Zone?
- How to use spatial and temporal information about traffic and air pollution in determination of control measures of Low Emission Zones?
- What methodology is suitable for collection of vehicle emissions and air pollutant concentrations for assessment of Low Emission Zones?
- Which methodology of travel demand estimation is appropriate to Low Emission Zone road network modelling?
- How can an air quality tool be validated to pollutant concentrations estimation in Low Emission Zones, considering the particularities of Brazilian cities?

1.2 Objectives

The objective of this research is to propose a method capable of representing the pollution impact of mobile sources with a view to the implementation of Low Emission Zones in urban areas, not only considering the exhaustion of the vehicles, but the behavior of the emissions and air pollutant dispersion on analyzed area . To meet this general objective, the following specific objectives are defined, arranged in chronological order of execution:

- To explore state-of-art strategies of Low Emission Zones implementation, and how this strategy can be adapted to Brazilian reality;
- Analyze the spatial and temporal variation of different air pollutants in the selected area for Low Emission Zone;
- Evaluate criteria to define different scenarios for Low Emission Zone regulation and model the impact to emissions and air quality with simulations.
- Evaluate emission factors and air quality modelling parameters for Low Emission Zones assessment;
- To analyze methodology parameters for estimation of travel demand on a road network applicable for air quality modelling;
- Validate air pollution dispersion model against air quality measurements, and calibrate model if necessary;

1.3 Work Justification

Urban transportation of people and goods is important, because it directly influences the efficiency of an economy, plays a fundamental role in maintaining industrial and commercial activities, generates jobs and contributes to the competitiveness of local industries. Despite this, it has negative effects in the social and environmental sphere in the urban environment (BESTUFS, 2007). Understanding the economic importance of the transportation activity in urban areas and its environmental impacts becomes necessary strategies of restrictive measures that seek to incorporate improvements to the population that consider the traffic and environmental effects, specially air pollution.

According to Brazilian Traffic Code (CTB, 1997), in its sixth chapter, paragraph one, it says that the National Transit System aims to: establish guidelines of the National Traffic Policy, with a view to safety, fluidity, comfort, environmental protection and traffic education, and supervise the compliance.

Considering the directives of Brazilian Traffic Code, Low Emission Zones could be used as restrictive measure to aid in environmental protection, especially in air pollution reduction, with Nitrogen Dioxides (NO_2) and Particulate Matter (PM) (> 10µm), the potential most affected air pollutants reduced by this measure in urban areas (TRANSPORT FOR LONDON, 2017).

Brazilian efforts are still in the beginning to build air quality monitoring networks, such as the “Relatório da Qualidade do Ar Grande Vitória”, 2016, carried out by IEMA (2018), which Fortaleza municipality is not covered. Efforts related to Low Emission Zone implementations are still not developed in Brazil. Curitiba – PR have implemented in 2016 an area called “Area Calma” where there is a restriction in vehicle speed but not for vehicle emissions specifically.

The PROCONVE (Programa de Controle da Poluição do Ar por Veículos Automotores), was the beginning of limitations in the Brazilian vehicular emissions, however, the limits of pollutant concentrations were not adjusted over the years, not following the technological evolution in terms of energy efficiency (MMA, 2018).

In order to change urban planning scenario of vehicle traffic with a view to the inclusion of environmental issues related to emissions, therefore the concentration of pollutants from these vehicles, through an optimized strategy of implementation of LEZ the content of this study is justified. For instance, Fortaleza wind directions and speeds must be considered in studies, in addition to high population density and particularities of vehicle fleet. It is known that pollutant levels must be obtained through monitoring, but the reality of many municipalities does not allow such action, so the use of data sampling collection strategies and mathematical models may be an alternative, as recommended in Resolution Sema N^{o}. 54/2006 (SEMA, 2006). However, there are no efforts in Brazil regarding the use of these techniques, and may be an alternative to sustainable strategies for vehicle traffic in urban areas.

1.4 Thesis Structure

The research is organized into six chapters, beginning with this introduction. In this chapter, the stages of problem definition, proposition of the research questions and objectives to be investigated, according to the methodological proposal, are performed.

The theoretical revision has the function of supporting the development of the objectives and, in the particular case of this work, seeks to fill a gap in the state of the art. Thus, the composition of the theoretical framework was fragmented into two stages: Chapter

2 - literature review on Low Emission Zones, seeking to present the particularities of the implementation process of the restrictive measure; Chapter 3 - collection of air pollutant data, emission modelling and dispersion of pollutants, also presenting the step-by-step process in sequential sections to execute modelling.

Chapter 4 presents the methodology proposal elaborated to meet the established objectives, divided in three steps: (i) Area definition; (ii) Field Data Collection; (iii) LEZ Modelling. In addition, Chapter 5, the experiment will be presented, with the description of the calculations of the three steps described in Chapter 4. Finally, Chapter 6 will bring the final results and discussions carried out through the research schedule.

2 LOW EMISSION ZONES (LEZ)

The Low Emission Zone (LEZ) is a geographically defined area where the most polluting vehicles are restricted, dissuaded or discouraged from access and use, in order to reduce the pollutant concentration from mobile sources, especially nitrogen oxides (NO_x) and Particulate Matter (PM) (ECOD, 2011). The Low Emission Zones have been successfully applied and implemented for many years in several countries, for example, Sweden, Japan, Netherlands and, in the United Kingdom, London, among others. The implementation considers feasible traffic and parking restrictions on public roads, and the planning conditions for controlling vehicle use and parking on private places as the basis for creating a LEZ (SCOTISH GOVERNMENT, 2015).

The Low Emission Zones are mainly designed to reduce emissions of Particulate Matter, although in many cases also aim to reduce NO_x. These NO_x emissions are significantly higher in diesel vehicles when compared to gasoline vehicles (assuming, for NO_x, a three-way catalyst). Buses and trucks, which are almost all diesel-powered in Europe, as well as the Brazilian fleet, have the highest emissions per kilometer for each vehicle. For example, Wang *et al*. (2010), suggests that in an urban area in Copenhagen trucks and buses emit about 30 times more $PM_{2.5}$ and 26 times more NO_x than light gasoline vehicles. Therefore, many LEZs restrict these vehicles.

The first Low Emission Zones were established in Sweden in 1996. Today there are over 216 LEZs operating or planning in 12 countries. Each country, in some cities of each country, has defined its own criteria for its LEZ. Recognizing the advantages of deployment, several countries and regions have coordinated and standardized LEZ implementation criteria in their territory. Sweden, Germany and Denmark have national legal and technical structures for Low Emission Zones (AIRUSE, 2015).

The Netherlands has coordinated its LEZ through a National Pact signed by government, municipalities and other stakeholders. The Czech Republic and Austria have national Low Emission Zone frameworks based on the German model, the Czech Republic and Germany are discussing mutual recognition of their vehicles. The UK is considering establishing a national LEZ system. Although Italy does not have a National Low Emission Zone, several regions of Italy have coordinated the LEZ within their regions, including Valle d'Aosta, Bolzano, Emilia Romagna and Lombardy (GÖTEBORG STAD *et al*., 2009).

In Germany, for example, a LEZ is a defined area (usually located in urban centers) where the vehicles have to meet certain emissions standards. For entering the LEZ all vehicles have to be identified by color coded windscreen badges which are directly linked to the corresponding stages of European emission standards (Euro 2: red; Euro 3: yellow; Euro 4: green). In addition, gasoline-driven vehicles equipped with a catalytic converter are assigned to the Euro 4 class and will be entitled to a green badge. In the first stage of operation all vehicles with a badge (red, yellow or green) are allowed to enter the LEZ. In stage 2, the LEZ can be accessed by vehicles displaying a yellow or green badge, whereas stage 3 of the LEZ allows access only to vehicles with a green badge, following one principle of LEZ, the implementation in stages (FENSTERER *et al.*, 2014).

The European Mobility Plan identified and create an inventory of effective integrated air quality improvement policies (ETC/ACM, 2011). Measures identified include plans related to:

- Industries;
- Building emissions;
- Improved traffic technology and infrastructure;
- Campaigns and educational measures;
- Agriculture;

Integrated traffic measures:

- Creation of Low Emission Zones (LEZs);
- Improvement of public transportation;
- Incentive to use non-motorized transport; improvement in traffic;
- Changes in speed limits;
- Investment in public transportation emission reduction technologies.

The main measure of the restrictions imposed by the Low Emission Zone is to regulate the access of most pollutant vehicles that do not fit a previously established emission limit, in order to encourage the use of vehicles with more efficient technologies of fuel consumption and emissions, or use of old vehicles with rectification in engine with to improve efficiency (retrofit, for example).

The Low Emission Zone essentially introduces a gradual change in the normal fleet to the activity system, resulting in lower emissions than without its implementation. Over time, fleet emissions will become similar to transport networks that do not opt for their imposition, for that reason, to observe benefits more efficiently, it is necessary to periodically monitor the regime's criteria, together with vehicle technologies (HOLMAN *et al.*, 2015).

The effort to implement Low Emission Zones has shown improvements in the emission indexes in the cities that adopted the method, however, the LEZ implementation criteria commonly only observe the emission limits of the restricted vehicles, not paying attention to the behavior of the pollutants over space/time in areas restricted by the system, and can reduce the efficiency of urban freight transportation or public transportation by using more vehicles of smaller dimensions, considering that the restriction is usually imposed 24 hours, every day of the week.

According to Sadler Consultants Ltd. (2014), most Low Emission Zones are permanent and apply restrictions 24 hours a day, seven days a week. Some, however, apply only on weekdays (LEZ's of Athens and Budapest, for example) and the Lisbon LEZ only applies for 12 hours a day from Monday to Saturday. Some Italian LEZs restrict only passenger cars in the winter, but restrict 2-stroke motorcycles and scooters and diesel public transportation (buses) all year round (in Brazil, for example, the motorcycle fleet practically no longer presents this technology) (DETRAN, 2016).

The Athens Low Emission Zone applies the restrictions from September to July each year, with different needs within the city center and the rest of Athens. Vehicles up to 2.2 tons are allowed to enter the city center on alternate days depending on the last digit of the license plate (integrated restrictive measures) throughout the territory of Athens. Vehicles with more than 2.2 tons produced before January 1º 1991 were banned from circulation, with an annual increase in ban each year. To briefly understand the restrictions imposed by Low Emission Zones, Table 1 presents the most important restrictions around Europe.

Table 1 - Comparison of Low Emission Zone restrictions in Europe

(to be continued)

Vehicle Type	**LEZ**	**Current Emission Standards (data for 2014)**	**Future Emission Standards**
Lorries Only	Netherlands	Euro 4	-
	Austria (Motorway A12)	Euro 2/3	-
	Austria (Steiermark and Graz)	Euro 3	-
	France/Italy (Mont Blanc Tunnel)	Euro 3	-
	Czech Republic (Prague)	Euro 2	-
	Hungary (Budapest)	Differential parking charges	-

Table 1 - Comparison of Low Emission Zone restrictions in Europe

(conclusion)

Vehicle Type	**LEZ**	**Current Emission Standards (data for 2014)**	**Future Emission Standards**
Heavy duty Vehicles	United Kingdom (London)	Euro 4 (PM)	-
	Denmark	Fit Filter if less than Euro 4 (retrofit)	-
	Sweden	8 years old/Euro 3	-
Vehicles with 4+ wheels	Germany	Euro 3/4 (PM) and Euro 1 gasoline	Euro 4 (PM) and Euro 1 gasoline
	Portugal (Lisbon)	Euro 1 or 2	Planned: Euro 3 all (date not specified)
	Greece (Athens) Netherlands	Euro 1/Euro 4 (respectively)	Utrecht from 1/1/2015. Must be first registered after 1/1/2001
All Vehicles	Italy	Euro 1 – 4/ no 2-stroke motorcycle	Euro 2-4 / no 2-stroke motorcycles
	Slovenia (Maribor)	Euro 0 and Euro 1	Continuing with LEZ if the test phase is successful
Local buses under agreements	United Kingdom (Norwich)	Euro 3 (NO_x)	-
	United Kingdom (Oxford and Brighton)	Euro 5	-
Vans	United Kingdom (London)	Euro 3 (PM)	-
	Germany	Euro 2-4 (PM) and Euro 1 gasoline	Euro 3-4 (PM) and Euro 1 gasoline
	Italy	Euro 1-4 / no 2-stroke motorcycles	Euro 2-4 / no 2-stroke motorcycle
	Netherlands		Utrecht from 1/1/2015. Must be first registered after 1/1/2001

Source: Adapted from Holman *et al*. (2015)

The restrictions imposed by european countries presented in Table 1 shows high restricted technologies, due to advances in Low Emission Zones development and updated vehicle technologies, however, in Brazilian reality, the restrictions in vehicle technology must start in older technologies, such as Euro 2 (equivalent) vehicles, according to old technologies present in Brazilian vehicle fleet, in addition to economic and social reasons, due to delayed vehicle fleet technology.

Understanding that the imposition of the restrictive measure still does not present a consensus and solidity in the construction method, this research suggests behavior analysis of the emitted pollutants, through air quality study in pollutant concentration levels, seeking a better understanding of the negative impacts resulting from all vehicles, especially observing heavy duty vehicles air pollution (buses and trucks), and may suggest interventions at certain times and/or in more efficiently planned areas, in relation to Low Emission Zones. This strategy is aimed to be adjusted to Fortaleza reality, that differs significantly from European cities, due to: (i) different driver behavior; (ii) significant different meteorology conditions; (iii) land use; (iv) vehicle technologies, among others.

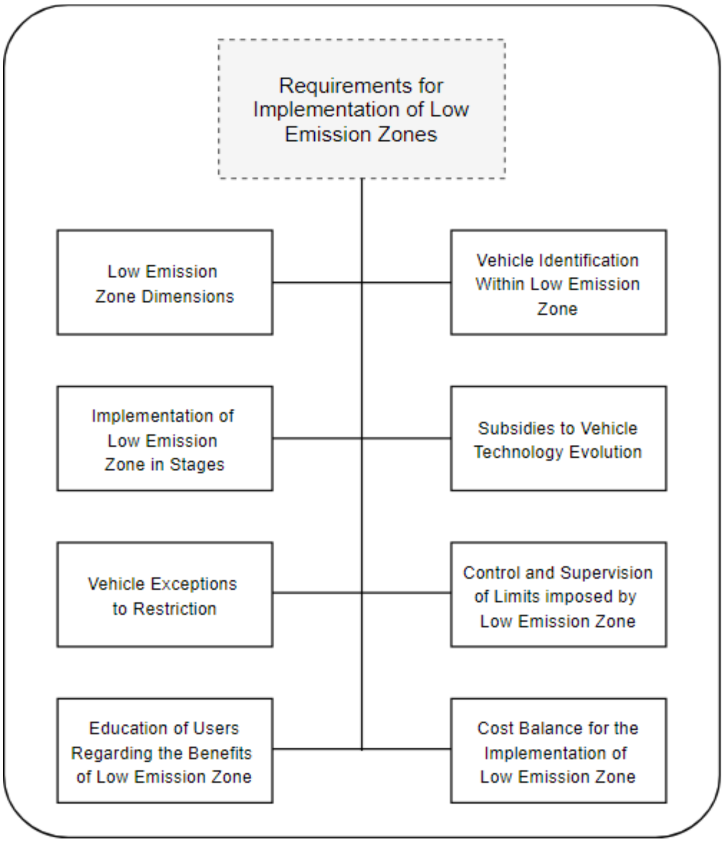
In order to do this, the application feasibility of emission and air quality modelling tools in the analyzes were assessed, seeking to observe pollutant behavior, especially with their integration with travel demand modelling tools, together with fixed pollutant data collecting in the field.

2.1 Requirements for Implementation of Low Emission Zones

As discussed earlier, Low Emission Zones establish traffic patterns that incorporate measures against atmospheric pollution, thus excluding more polluting light duty vehicles from city. If the imposition criteria are sufficiently rigorous, considering the current technologies on used fleet, the scheme will trigger accelerated changes in the network vehicles (in terms of size and technology) and thus reduce emissions, hence the concentration of air pollutants. If standards are not followed strictly, the fleet will not experience the desired change, and the expected reductions will not occur.

According to BUND (2017), for an efficient construction of the restrictive measure, some criteria must be met, seeking to reduce the impacts to traffic and pollutant concentrations in the analyzed region. A brief presentation of the implementation requirements for Low Emission Zones will be presented Figure 4 and describe in the next items.

Figure 4 - Requirements for Implementation of Low Emission Zones



Source: Adapted from BUND (2017)

2.1.1 Low Emission Zone Dimensions

If the LEZ project is too small or does not include the city region with intense vehicle traffic which emits higher pollution levels, it can be circumvented, using new route options, reducing the effect of minimizing pollutant concentrations. In the case of oversizing the LEZ project, such as the city of Berlin, impacts on fleet of external regions close to their limits could be observed, reducing the traffic level of service. The region perimeter should consider the land use and seek to meet the concentration pollutant limits imposed by the Ministry of Health (VCD, 2017). However, there is no specific size for LEZ implementation, which makes necessary to understand the particularities of each city observed.

2.1.2 Vehicle Identification within Low Emission Zone

In order to allow the delimited region control in the project, vehicle verification mechanisms that have traffic permission are necessary. As an example, the German Low Emission Zone imposes the use of reflective adhesives on vehicles, identifying the EURO standard which the vehicle was produced (equivalent to PROCONVE standards), where its “trafficability” can be observed. The stickers must be official, granted by the transit regulating agency. In addition to the adhesives, plate codes can be adapted to identify the manufacture year, granting permission to enter the Low Emission Zone.

2.1.3 Implementation of Low Emission Zone in Stages

Despite the proven effectiveness in improving air quality due to the imposition of strict requirements in traffic restriction measures, changing the fleet and adapting driver behavior demands time and resources to achieve LEZ success. Because of this, it is necessary to carry out the imposing process of the measure in stages, to enable the adaptation of fleet and user behavior. For example, in cases of vehicle traffic prohibition previously built under the PROCONVE VII standards, the vehicle reduction of technologies manufactured in stage PROCONVE IV should be initially established, subsequently gradually adjusting to the desired limits.

2.1.4 Subsidies to Vehicle Technology Evolution

The costs of adapting the fleet may be high for traffic network users under imposition of the restrictive measure, as a result, public incentives can be considered through subsidies. For example, the municipality of Fortaleza grants tax subsidies for the renewal of public transportation fleet by bus, allowing the vehicle traffic with a maximum 5 years of manufacturing, reducing fuel consumption and pollutant gas emissions (SINDIÔNIBUS, 2017).

Another efficient measure regarding the release of subsidies to enable the fleet renewal for users is the Retrofit, which consists of adding new technologies in vehicle combustion system that do not meet the standards, such as catalysts, filters and improvements in the ignition system, for example (DALLMANN *et al*., 2011). While the environmental performance of engines is constantly improving, new emissions standards only apply to new engines. However, because diesel is truly the workhorse of Brazilian economy - with engines often lasting hundreds of thousands of kilometers or running for hundreds of thousands of hours - a sizable fleet of equipment manufactured over two to three decades ago is still in operation. Fortunately, many of the same advances used to improve new engines can be applied to this existing fleet.

The term “retrofit” covers many technologies and activities to reduce emissions from older engines, vehicles and equipment and has typically been defined broadly. While the term is frequently used as a label describing various exhaust emissions control devices such as the diesel oxidation catalysts and particulate filters, it can also encompass a broader range of options to reduce emissions, including re-powering, rebuilding and in some instances replacing existing equipment.

Retrofit brings direct and indirect benefits, such as: (i) vehicle appreciation in case of resale/renewal; (ii) fuel consumption reduction; (iii) lower risk of damage to vehicle system; (iv) reduction in emissions of air pollutants, making it possible to comply with the limits established by legislation; among others.

2.1.5 Vehicle Exceptions to Restriction

Even with the efficiency reduction of the restrictive measure imposition, exceptions to the traffic of some type vehicles are necessary, such as: (i) emergency vehicles (ambulances, police vehicles, fire brigade, among others); (ii) large vehicles used by people with disabilities or difficult mobility; (iii) freight transportation with a minimum size above those permitted in LEZ; among others.

Exceptions should be temporary, since project efficiency may be compromised in case of high exposure to vehicles with the highest pollutant emissions authorized by the exceptions (VCD, 2017).

2.1.6 Control and supervision of limits imposed by Low Emission Zone

Understand the importance of imposing the restrictions and penalties provided by the measure, however, even more crucial is the control and enforcement of compliance.

Punishments through fines should be imposed, with their values high enough to discourage users from violating established laws. Classic fines are financial penalties, but points can also be imposed on a database, preventing vehicle traffic by reaching a previously established score limit. Parking spots and intersections are examples of locations that facilitate enforcement of the measure.

2.1.7 Education of Users Regarding the Benefits of Low Emission Zone

Similar to any other restrictive measure, informing users about the direct and indirect benefits brought by the imposition of the Low Emission Zone is fundamental to achieving the project objectives. Not only had an understanding on benefits brought by the measure, but an easier acceptance in complying with the legislation it imposed. In addition, widespread disclosure of the benefits of the measure accelerates fleet adequacy and user behavior.

In addition to the disclosure of reductions imposed on vehicles, public authorities should include companies and industries in emission reductions foreseen in the Low Emission Zone, as these sources generate strong impacts on the efficiency of the measure.

2.1.8 Cost Balance for the Implementation of Low Emission Zone

The education of users represents a straight connection with the observation of LEZ implementation costs, because despite the fleet adequacy initial financial costs, as for the users, besides the public power costs with signaling and limits identification and compliance with the measure, Low Emission Zones can be considered self-sufficient, due to reduced costs with medical care with the reduction of diseases caused by air pollution within the defined area.

Costs should incorporate possible changes in the LEZ road geometry, but consist essentially in restrictions identification and enforcement to comply with the measures, as well as the educational costs for compliance (VCD, 2017).

2.2 Major Reduced Pollutants in the Implementation of Low Emission Zones

In metropolitan areas, the problem of air pollution has been one of the most serious threats to the quality of life of its inhabitants. Emissions from vehicles carry a variety of toxic substances which, in contact with the respiratory system, can have a number of negative health effects. This emission is composed of gases such as: carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), sulfur oxides (SO_x), particulate matter (PM), non methanic hydrocarbons (NMHC), among others (CETESB, 2017b).

The Low Emission Zones are specifically aimed at reducing pollution from vehicle traffic in urban areas, especially buses and urban freight transportation. Because of this, the main pollutants are generated by the incomplete combustion of diesel engines (considering that Brazilian heavy duty fleet consists in this engine fuel technology). A brief exposition of the reduced pollutants with the imposition of Low Emission Zones will be presented in the next items, with emphasis on most emitted pollutants Particulate Matter (PM) and Nitrogen Oxides (NO_x).

2.2.1 Particulate Matter (PM)

According to WBCSD (2004), particulate matter is a generic term for all particles suspended in the air, including suspended dust, smoke and liquid droplets. According to CONAMA Resolution No. 382 of December 26, 2006, particulate matter is any and all solid or liquid material, in a gas mixture, which is maintained in this state at the temperature of the filter media, established by the method adopted (MMA, 2006).

Such particles originate mainly from diesel and consist of a solid core of elemental carbon, which large variety of organic compounds and oxides, such as sulfates adhere. When comparing emissions of particulate matter from Otto cycle vehicles, diesel cycle vehicles can reach the order of 50 to 100 times higher rates of particulate matter release due to fuel incomplete combustion. Higher particulate emissions result from the incomplete combustion of liquid fuel droplets near the fuel injection system. Although most of the particles are burned in the cylinder before leaving the engine, some continue and leave the engine exhaust as small particles (0.1-100 μm in diameter) (WBCSD, 2004).

According to EPA (2018), human upper respiratory tract is capable of filtering particles above 10 μm with 100% efficiency, and the Total Suspended Particles - TSP (<100 μm) may be considered less direct risk to human health, but it is still harmful to infrastructure, fauna and flora. The efficiency, however, decreases with particle size reduction and is close to zero for particles about 1 μm, which can easily enter the human pulmonary system. These particles behave as gases in atmosphere during the dispersal process in street levels and, over time, tend to agglomerate into larger particles. Various compounds may be present in the atmosphere in the form of particulate materials, as summarized in Table 2.

Table 2 - Main compounds present in Particulate Matter and their impacts

PM Compound	**Impact to Human Health and Environment**
Sulfur Dioxide (SO_2)	Formation of acid rain; Atmosphere visibility reduction.
Carbon Monoxide (CO)	Cardiovascular diseases; Respiratory/Breathing problems.
Ozone (O_3)	Photochemical Mist; Damage on vegetation structure to ozone near the ground.
Volatile Organic Compounds (VOC's)	Aldehydes may be carcinogenic; also contributes to the formation of smog.
Nitrogen Oxides (NO_x)	Contributes to formation of ozone; May cause respiratory problems.

Source: EPA (2018)

Still according to EPA (2012), it is important to communicate information about Particle Pollution to the Public due to:

• Exposure to particle pollution is a public health hazard;

• When inhaled, particle pollution can travel deep into the lungs and cause or aggravate heart and lung diseases;

• Exposure to particle pollution causes increases in: (i) doctor and emergency room visits; (ii) hospital admissions; (iii) use of prescript medication; (iv) absences from work and school.

People are exposed to particle pollution when they breathe:

• Effects of short-term (acute) exposure: (i) coughing; (ii) shortness of breath; (iii) tightness of the chest; (iv) irritation of the eyes.

• Effects of long-term (chronic) exposure: (i) reduced lung function; (ii) development of respiratory diseases in children; (iii) aggravation of existing lung diseases; (iv) premature death of people with lung disease.

Considering most emitted PM from mobile sources, $PM_{2.5}$ and PM_{10} are usually the most harmful. PM_{10} irritates human respiratory system, especially among asthmatics and the elderly. They make your eyes burn and throat dry. Public health experts, however, are less concerned about these larger forms of particulate matter because your body's defenses are reasonably effective against them. Tiny hairs along the respiratory tract block a portion of PM_{10}. Fortunately, you can also cough and sneeze some of it out. And your throat's mucus elevator ejects some of it back out of your mouth or harmlessly into your digestive tract. In addition, PM_{10} particles can stay in the air for minutes, perhaps up to a couple of hours, while $PM_{2.5}$ particles can linger for days or (weather permiting) up to weeks. As a result, even though levels of both $PM_{2.5}$ and PM_{10} are under constant surveillance, experts believe that $PM_{2.5}$ is the more harmful of the two (LI *et al.*, 2017).

Particulate Matter emissions from vehicle traffic are a main source to ambient concentrations, especially in urban areas of dense city environments. Vehicle traffic PM emissions can be simplified into three main groups: (i) direct exhaust emissions; (ii) direct emissions other than exhaust (e.g. from brakes and clutches); and (iii) indirect or re-suspended PM emissions from the tyre/road interface. (i) Direct exhaust emissions are, in major part, as fine particles ($PM_{2.5}$), and are basically a function of the vehicle and driving technologies and patterns, respectively, but not meteorological or road conditions (EMEP/CORINAIR, 2004; UBA, 2004). They are usually measured in laboratories and registered in different emission inventories and databases (e.g. NTZIACHRISTOS *et al.*, 2009; UBA, 2004; TNO, 2018;

EMEP/CORINAIR, 2004; UK-TRL, 2001). (ii) Emissions from brake wears and clutches present an amount close to fine and coarse emission fractions (PM_{10} and $PM_{2.5}$) (Garg *et al.*, 2000; EMEP/CORINAIR, 2004) and correlate well with the direct emissions and other vehicle emissions, e.g. NO_x (Wahlin *et al.*, 2006). For these emissions, there is less measurements available and they are not included in all emission databases (UBA, 2004). (iii) Emissions from road abrasion, tyre wears and road dust re-suspension are found partially in the fine fraction and mostly in the coarse fraction.

This PM source is often less correlated with the exhaust emission due to an influence from “external factors” such as tyre type, vehicle induced turbulence, road and weather condition (use of studded/friction tyres, wetness of roads, temperature, salting, sanding, road material, condition of the side-strip) (GUSTAFSSON *et al.*, 2005; KUPIAINEN *et al.*, 2005; NORMAN and JOHANSSON, 2006; JOHANSSON *et al.*, 2007; BARTONOVA *et al.*, 2002). These external factors provide a major challenge for the estimation of this type of emissions and presently much research is undertaken to elucidate this PM source.

2.2.2 Nitrogen Oxides (NO, NO_2 and NO_x)

Nitrogen oxides can be divided into two main compounds: Nitrogen monoxide (NO) and Nitrogen dioxide (NO_2). According to MMA (2006), nitrogen oxides refers to concentrations sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), being expressed as (NO_x). They form when the fuel is burned under high pressure and temperature conditions, which induces the dissociation and subsequent recombination of atmospheric N_2 and NO_2 generating NO_x. It reacts with ammonia, moisture, and other compounds to form nitric acid which can cause serious respiratory problems (DIAS, 2014).

According to Oliveira *et al.* (2011), the current norms regarding the NO_x vehicle emissions imply a reduction of up to 90% of the emissions from vehicle exhaust. Like carbon dioxide, the dissociation of nitrogen dioxide is also responsible for the formation of tropospheric ozone, as shown in Equation 1.

$$\begin{gathered} NO2_{(g)} \rightarrow NO_{(g)} + O_{(g)} \\ O2_{(g)} + O_{(g)} \rightarrow O3_{(g)} \end{gathered} \tag{1}$$

The NO_x emissions are hard to control due to energy conversion been dependant of high combustion temperatures. In addition, there is a compensatory exchange between NO_x and the gases not consumed according to the air/fuel ratio.

It also causes eutrophication (nutrient overload in water bodies), and contributes to smoke formation. The US Environmental Protection Agency (EPA) estimates that mobile sources (vehicles) on highways contribute to 34% of the total NO_x emitted in US, with 42% of this value being produced by diesel cycle vehicles. This is because diesel engines usually carry heavy loads (people and freight transportation), requiring more effort from the engine, also having to do with the combustion mode (compression). Diesel engines operate at a higher temperature and pressure than petrol engines. These conditions favor the production of NO_x gases. The quantity depends on the volume and duration of the hottest part of the flame.

The atmospheric reaction with oxidants such as ozone (O_3) during the dispersion and transport process produces NO_2 in significant concentrations. NO_2 is very important in terms of health effects, mainly respiratory tract corrosion, whereas NO has no significant effects on humans at the levels of concentration normally observed in road transport. However, NO_x emissions can result in acidification affecting buildings in cities. Combustion in vehicle engines causes the primary production of nitrogen monoxide, but also the dioxide is produced, as shown in Equation 2 (CAPPIELLO, 2002).

$$\begin{gathered} N2_{(g)} + O2_{(g)} \rightarrow 2NO_{(g)} \\ 2NO_{(g)} + O_{2(g)} \rightarrow 2NO_{2(g)} \end{gathered} \tag{2}$$

NO_x reacts with ammonia, moisture, and other compounds to form nitric acid vapor and related particles. Small particles can penetrate deeply into sensitive lung tissue and damage it, causing premature death in extreme cases. Inhalation of such particles may cause or worsen respiratory diseases, such as emphysema or bronchitis, or may also aggravate existing heart disease (GAO *et al.*, 2017).

Nitrogen oxides also can be also reduced by three-way catalytic converters, which in vehicles can reduce VOC’s, carbon monoxide and nitric oxides (KOLTSAKIS *et al.*, 1998). Nitrogen oxides react with volatile organic compounds in the presence of sunlight to form and to destroy ozone. Ozone can cause adverse effects such as damage to lung tissue and reduction in lung function mostly in susceptible populations (children, elderly, and asthmatics). Ozone can be transported by wind currents and cause health impacts far from the original sources. The American Lung Association estimates that nearly 50 percent of United

States inhabitants live in counties that are not in ozone compliance. In South East England, ground level ozone pollution tends to be highest in the countryside and in suburbs, while in central London and on major roads NO emissions are able to "mop up" ozone to form NO_2 and oxygen (LONDON AIR, 2018).

It also readily reacts with common organic chemicals, and even ozone, to form a wide variety of toxic products, which also the nitrate radical may cause DNA mutations. Recently another pathway, via NO_x, to ozone has been found that predominantly occurs in coastal areas via formation of nitryl chloride when NO_x comes into contact with salt mist (POTERA, 2008).

VOC’s escape to environment in engine combustion, in this sense, three-way catalytic converters can be used to adsorb theses air pollutants. In addition, fuel rich engines generates exhaustion gases (VOC’s), which can reduce NO_3 to NO_2, redirected to three-way catalytic converter, with generation of N_2 (KOLTSAKIS *et al.*, 1998). The reactions are showed in Equation 3:

$$\begin{gathered}
CO_{(g)} + \frac{1}{2} O2_{(g)} \rightarrow CO_{2(g)} \\
H_{2(g)} + \frac{1}{2} O_{2(g)} \rightarrow H_2O_{(v)} \\
C_xH_{y_{(g)}} + \alpha O_{2(g)} \rightarrow \beta CO_{2(g)} + \gamma H_2O_{(v)} - fastHC \\
C_xH_{y_{(g)}} + \alpha O_{2(g)} \rightarrow \beta CO_{2(g)} + \gamma H_2O_{(v)} - slowHC \\
C_xH_{y_{(g)}} + \alpha H_2O_{(v)} \rightarrow \beta CO_{(g)} + \gamma H_{2(g)} \\
2CO_{(g)} + 2NO_{(g)} \rightarrow 2CO_{2(g)} + N_{2(g)}
\end{gathered} \tag{3}$$

NO_x emissions also cause global cooling through the formation of radicals (OH) that destroy methane molecules, countering the effect of greenhouse gases. The effect can be significant. For instance, according to the OECD the large NO_x emissions from traffic lead to significant increases in hydroxyl (OH), which is the major oxidant in the lower atmosphere. Since reaction with OH is a major way of removing methane from the atmosphere, emissions decrease methane concentrations. (Reductions in methane lifetimes due to shipping-based NO_x emissions vary between 1.5% and 5% in different calculations). In summary, most studies indicate that traffic emissions actually lead to a net global cooling. However, it should be stressed that the uncertainties with this conclusion are large, in particular for indirect effects, and global temperature is only a first measure of the extent of climate change in any event (OECD, 2010). The ultimate destination of much NO_x is to end up in the soil as nitrite or nitrate, which are useful to growing plants.

2.2.3 Carbon Oxides (CO and CO_2)

Approximately 60% of carbon monoxide present in troposphere originates from human (anthropogenic) activities due to incomplete combustion of organic carbonaceous materials such as carbon, wood, paper, oil, gas, gasoline, among others (LACERDA *et al.*, 2005).

Carbon monoxide (CO) is a toxic gas that results from the incomplete combustion of engine powered vehicles. This gas is colorless, odorless, but poisonous, being derived from carbon reaction with oxygen present in the atmosphere, as presented in Equation 3. It reacts with the hemoglobin present in the blood to form carboxyhemoglobin, causing an oxygen reduction carried from lungs to body cells. High concentrations of CO can increase the risk of cardiovascular disease and prevent psychomotor functions. Children, the elderly and people who already present clinical signs of cardiovascular diseases and respiratory problems suffer from presence of these pollutants. In addition, CO indirectly contributes to ozone and methane formation, as observed in the Equation 4, which presents the CO formation cycle and its contribution to formation of indirect compounds, with the possible dissociation of CO carbon monoxide and oxygen.

$$\begin{gathered} CO2_{(g)} \rightarrow CO_{(g)} + O_{(g)} \\ O2_{(g)} + O_{(g)} \rightarrow O3_{(g)} \end{gathered} \tag{4}$$

Carbon dioxide (CO_2) is the main product of fossil fuel engines complete combustion, as observed in Equation 5. Colorless, odorless, noncombustible greenhouse gas that contributes to global warming. Although it is naturally present in the atmosphere and is not considered a pollutant, CO_2 is a greenhouse gas, which contributes to global warming potential, hence the concern with controlling the increase of such emissions (CAPPIELLO, 2002).

$$\begin{gathered} 2C_{(g)} + O_{2(g)} \rightarrow 2CO_{(g)} \\ 2CO_{(g)} + O_{2(g)} \rightarrow 2CO_{2(g)} \end{gathered} \tag{5}$$

2.3 Concentration Limits of Atmospheric Pollutants in Brazilian and European Territory

Considering the compatibility between the country economic growth and the preservation of environmental quality, the creation of a national policy focused on normative actions and institutional strengthening aimed at the prevention and control of air quality in the country was perceived as hugely important.

In this context, CONAMA created the National Air Quality Control Program (Programa Nacional de Controle de Qualidade do Ar - PRONAR), Resolution No. 05, June 15, 1989 (still used today), which establishes limits for atmospheric pollutant concentrations, in addition to having as one of its objectives the implementation of the National Air Quality Monitoring Network, aiming to improve population life quality, through the reduction of respiratory diseases.

The limits established in PRONAR, in its first legal provision (CONAMA Resolution No. 03, dated June 28, 1990) are presented in Table 3:

Table 3 - Brazilian Air Quality Concentration Limits

Pollutant	**Sampling Period**	**Primary Standard (μg/m^3)**	**Secondary Standard (μg/m^3)**	**Sampling Method**
Total Suspended Particles – TSP (< 100μm)	24 horas*	240	150	High Volume Sampler
	AGA	80	60	
Smoke	24 hours*	150	100	Reflectance
	AAA	60	40	
Inhalable Particles (< 10 μm) – PM_{10}	24 hours*	150	150	Inertial Separation/Filtration
	AAA	50	50	
Sulfur Dioxide (SO_2)	24 hours*	365	100	Pararosanilin
	AAA	80	40	
Carbon Monoxide (CO)	1 hour*	40000 (35 ppm)	40000 (35 rpm)	Non Dispersive Infrared
	8 hours*	10000 (9 ppm)	10000 (9 ppm)	
Ozone (O_3)	1 hour*	160	160	Chemiluminescence
Nitrogen Dioxide (NO_2)	1 hora	320	190	Chemiluminescence
	AAA	100	100	

Source: PRONAR (1989)
* Should not be exceeded more than one time a year.
AGA – anual geometric average
AAA – anual aritmetic average

Primary air quality standards are the concentrations of pollutants that, out of date, could affect population health. They can be understood as maximum tolerable concentration levels of atmospheric pollutants, constituting in short and medium term goals. Secondary air quality standards are the air pollutants concentrations below the minimum adverse effect on population which well-being is expected, as well as the minimum damage to fauna and flora, materials and the environment in general. They can be understood as desired concentration pollutant levels, constituting a long-term goal (MMA, 1989).

However, it is observed that the limits imposed by Brazilian legislation are far too much delayed (almost 30 years without updating the legislation, regarding technology), when compared to the European concentration limits, which receive constant updates, considering new technologies and improving the life quality of the population. Pollutants such as Total Suspended Particles - TSP are still regulated by Brazilian legislation, in part due to the lack of updating of established limits. For comparison with the European and USA reality, the limits established for the main pollutants are presented in Table 4, especially those most affected by the implementation of Low Emission Zones:

Table 4 - European and USA Air Quality Concentration Limits

Pollutant	**Europe**			**USA**		
	Sampling Period	Concentration ($\mu g/m^3$)*	Exceptions Allowed/year	Sampling Period	Concentration ($\mu g/m^3$)*	Exceptions Allowed/year
Particulate Matter (< 2.5 µm)	1 year	25	0	1 year	15.0	annual mean, averaged over 3 years
Particulate Matter (< 10 µm)	24 hours	50	35	24 hours	150	1
	Year	40	0	-	-	-
Sulfur Dioxide (SO_2)	1 hour	350	24	1 hour	196.5	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	24 hours	125	3	3 hours	1.31 mg/m^3	1
Carbon Monoxide (CO)	Max 8 hours	10 mg/ m^3	0	Max 8 hours	10.31 mg/m^3	1
Ozone (O_3)	Max 8 hours	120	Max 25 days each 3 years	8 hours	0.14 mg/m^3	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years
Nitrogen Dioxide (NO_2)	1 hour	200	18	1 hour	188	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years
	1 year	40	0	1 year	99.64	Annual Mean

Source: European Comission (2018) and EPA (2017)

The limits imposed on European territory shows the pollution reduction evolution in its territory, presenting limits that accompany the new industrial and vehicular technologies. For the pollutants concentrations monitoring, European researchers use modelling tools to improve the air pollution efficiency of Low Emission Zones (among other pollution sources). Modelling tools can also be used in Brazilian territory, more specifically in Fortaleza, provided that they are properly calibrated and adjusted for the local road characteristics. A discussion of air quality modelling is presented in Chapter 3.

3 VEHICLE ATMOSPHERIC POLLUTANT EMISSIONS AND AIR QUALITY MODELLING

A major challenge for scientific health impacts investigations of traffic-related air pollutants is the lack of information on pollutant exposure. Data provided by networks monitoring ambient air quality, including the new near-road monitoring network (WEINSTOCK *et al.*, 2013), are helpful for understanding pollutant exposure; however, these networks are not designed to provide the spatial coverage and often the temporal resolution needed to evaluate population exposures to traffic-related air pollutants.

In addition to this, a Low Emission Zone project requires detailed emissions monitoring and reliable concentration behavior data collection of each pollutant to observe the efficiency and effectiveness of the measure, however, the effort to collect emissions data from vehicles and the concentration of air pollutants can be impaired by several factors, such as: (i) the absence of on-site monitoring equipment; (ii) the size of the selected area in the project makes it impossible to data collect that represent the analyzed reality; (iii) high maintenance and monitoring costs; (iv) data collection time; among others.

However, pollutant emission and dispersion modelling tools can be used to estimate atmospheric pollutants concentrations in Low Emission Zone projects, reducing field data collection efforts, making it possible to follow the restrictive measure implementation. Before addressing the questions about modeling and simulation, it is important to understand the definition of models. Owen *et al.* (1996) believes that a model is the same as an approximation, representation or idealization of certain attributes of structure, behavior, or other aspects of a real process, concept or system. The author addresses that a model may have other model (s) as part of it.

However, in traffic analysis, experience proves that computer modelling and simulations is not always the best tool to be used. According to McLean (1989), there is always the possibility that the model obtained does not adequately represent the real system chosen to be modeled. Therefore, careful calibration and validation efforts are needed, which may not be feasible.

Calibration can be defined as the process of input parameter estimation of a model, within a determined interval, until that difference between observed and estimated values are checked by predetermined convergence criteria (OLIVA, 2003). The validation process can be defined as the comparison of model results with numerical results obtained from laboratory tests or observations of reality (DONIGIAN and RAO, 2004) or given the structure of the model and estimation of the parameters, validation is the process of determining the behavior of the model, for different input data conditions, by comparing the model with different observed situations (BECK, 1987).

Considering the calibration and validation definitions, it is important to build reliable modelling process, accordingly to real observed data, in order to assess modelling outputs close to data collected in the field. Nonetheless, in order to modelling data estimation process close to reality scenario, real emission and concentration pollutant data must be collected in order to calibrate and validate the models, allowing the pollutant concentration estimation data close to observed reality, considering that the models applied in the estimation may not have been constructed using data that represent the scenario in analysis.

3.1 Air Quality Modelling focusing Vehicle Emissions

The atmospheric pollutants dispersion models (also known as air quality models, depending on the analysis) from mobile sources began to be developed in the 1970s, especially in the United States. The first models developed were CALINE (BEATON *et al.*, 1972), GM (CHOCK, 1978) and HIWAY (ZIMMERMAN and THOMPSON, 1975). However, the first models presented several restrictions in situations of dispersion with winds not perpendicular to the road. Such fragility was corrected in the next models (RAO and KEENAN, 1980), modifying the original dispersion curves and adding an aerodynamic drag factor. Each model has specificity in its modelling or in the way it requires input data.

When conducting an atmospheric pollutant dispersion assessment, especially from mobile sources, it should be noted that the process depends, among other issues, the land use of the chosen area, the topographic conditions and the emitted sources (TAVARES, 2009). In addition, meteorological conditions are important factors in pollutant behavior suspended in the air. According to Eagleman (1991), the main meteorological conditions affecting the dispersion process are: cloudiness, atmospheric mixing height, temperature, atmospheric pressure, atmospheric stability, direction and prevailing wind speed.

The configuration of land use comprising the study area also directly affects gases and particulates dispersion, so the models must consider the terrain roughness (buildings heights and road width, for example) and the type of land use is taken into account in most dispersion models (BENSON, 1989; TASEIKO *et al.*, 2009). In Brazil, the air quality models used were developed in other countries and calibrated to Brazilian reality.

Several dispersion models have been developed in latest years, some of them are presented in Table 5, ISC/AERMOD (US-EPA, 2013), HIWAY-2, 3 and 4 (RAO and KEENAN, 1980; HOLMES and MORAWSKA, 2006), GM MODEL (SHARMA and KHARE, 2001), CALINE3 (BENSON, 1979), CAL3QHC-R (ECKHOFF, 1995; TAVARES, 2009), CALINE4 (BENSON, 1989), OCD (HANNA *et al.*, 1985), CAR-FMI (HÄRKÖNEN *et al.*, 1995; HÄRKÖNEN, 2002; LEVITIN *et al.*, 2005), OSPM (BERKOWICZ *et al.*, 1997; BERKOWICZ *et al.*, 2003), USM (TASEIKO *et al.*, 2009), CFD-VIT-RIT (WANG *et al.*, 2011):

Table 5 - State-of-art vehicular pollutants dispersion models and their main characteristics

(to be continued)

Model	**Pollutants Modelled**	**Characteristics**
ISC/AERMOD	CO, NO_x, SO_2, TSP and PM_{10}	Considers the topographic complexity, details of data collection points and meteorological data on analyzed region.
HIWAY-2, 3 and 4	CO, HC, NO_x and PM	Each lane is considered as a finite source of constant emission within one hour. The model does not obtain good answers for roads with complex topographic morphology.
GM MODEL	CO	Developed model with terrain conditions prepared. Considers the turbulence created by vehicle traffic. Requires known and stable meteorological data.
CALINE3	CO, PM and inert gases	Considers the road region as a uniform emission zone and turbulence (mechanical and thermic). The topography must be not too complex and atmospheric conditions must be stable.
CAL3QHC-R	CO and PM	Considers different ways to evaluate compound emissions in pathways with semaphorization and queue formation. Process data in hours/year.
CALINE4	CO, PM, SF_6, NO, NO_2, NO_x and O_3	Contains an extension that simulates conditions in urban canyons. The topography must be not too complex and the atmospheric conditions neutral, stable and known.
OCD	CO, inert gases, SO_2, NO, NO_2, NO_x	Assumes that all NO_x emission is converted to NO_2. Differentiate water transportation from terrestrial transportation.

Table 5 - State-of-art vehicular pollutants dispersion models and their main characteristics

(conclusion)

Model	Pollutants Modelled	Characteristics
ADMS-Roads	NO, NO_2, NO_x, SO_2, PM	Model capable of integrating fixed and vehicular sources in diverse forms, including treatment of meteorological variables, for a period of 1 year.
CAR-FMI	CO, NO, NO_2, NO_x, O_3, $PM_{2.5}$, PM_{10}	Considers dry deposition of $PM_{2.5}$ and evaluates concentrations of $PM_{2.5}$ emissions from brake wear, tires and resuspension of deposited PM in roads.
OSPM	CO, NO, NO_2, PM_{10}, $PM_{2.5}$, NO_x, COV, HC, percursores fotoquímicos, O_3	Presents a more detailed mechanism for physical behavior in roads with the presence of tunnels and urban canyons.
USM	PM_{10}, NO_x/NO_2	Considers the distribution and morphology of urban buildings by combining density, height and permeability of buildings in relation to wind flow.
CFD-VIT-RIT	NO, NO_2, NO_x, O_3 and photochemical oxidants	Considers photochemical oxidants for ozone formation.

Source: Martins *et al.* (2015)

3.1.1 Air Quality Modelling System THOR – AirPAS

In addition to the classic modelling tools presented, new models are being developed, offering integration to more modern land use databases, such as the THOR - AirPAS air quality modelling system, based on the Integrated Management and Forecasting System Air Quality - THOR, developed at Aarhus University, Roskilde - Denmark. The modelling system includes three air quality models: one to predict air quality on a regional scale (DEHM - Danske Eulerske Hemisfæriske Model, but other regional models could be used as input data), one to predict urban air quality (UBM – Urban Background Model) and one to predict air quality on a more disaggregated scale (previously presented) in OSPM® (Operational Street Pollution Model). Air quality models require meteorological input data, as well as other geometric parameters, land and vehicular use. The spatial emissions distribution modeled by UBM in individual urban areas was constructed using the SPREAD (Spatial Distribution of Emissions to Air) emission model (DCE, 2014).

In Low Emission Zone analysis, urban scale (streets or zones) and in traffic routes are appropriate. Concentrations on an urban scale include the regional contribution and emission contribution from observed city. In the urban environment, concentrations exhibit spatial variations depending on land use, traffic, topographical conditions, among other factors (JENSEN *et al.*, 2011).

Concentrations in traffic routes are concentrations in roads at heights of 2-4 meters. The concentrations in streets include the pollution observed in urban scale and the contribution of vehicle emissions in the analyzed roads.

Figure 5 presents a conceptual flowchart in air pollution assessment system for estimating the variability in urban environment air quality, representing all stages in the THOR-AirPAS air quality modelling system.

The diagram shows the total integration between the models in the three aggregation levels, however, the computational package allows pollutant dispersion analysis at any level of aggregation in isolation, considering the study request.

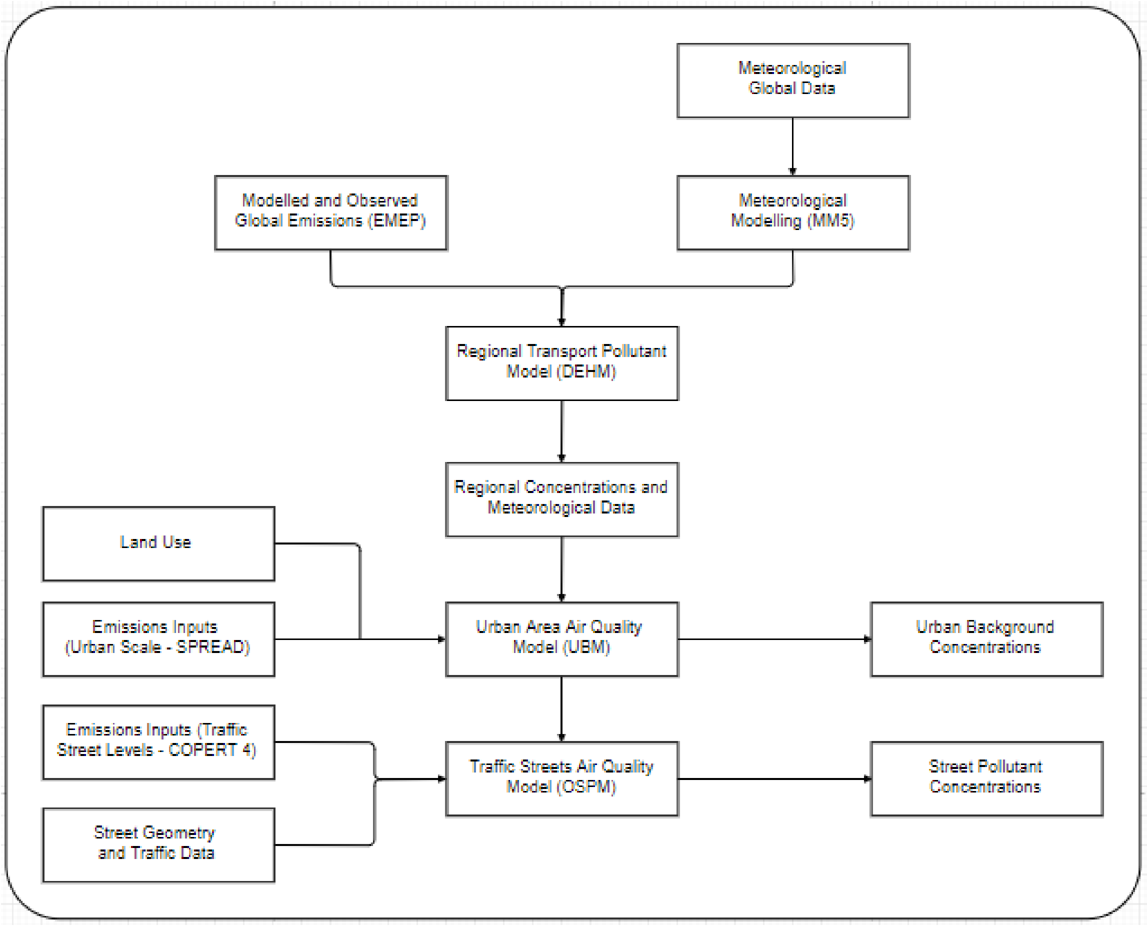
The spatial resolution of both regional emission distribution and the urban model UBM is currently set at 1 km x 1 km, however, with changes in the input data and parameters of the model, in addition to the use of the Traffic Quality Air Quality Model (OSPM), which estimates concentration data at a more detailed level of aggregation.

The regional model (DEHM) requires emission and meteorological inputs and provides regional background concentrations to the urban background model (UBM) and also outputs of meteorological data for UBM, but the regional concentrations could be estimated using different regional model, such as IFS (Integrated Forecasting System).

Apart from meteorological data UBM also requires emission data that is provided by the SPREAD emission model. This model makes a geographical distribution of national emissions based on different geographic variables for the different emission sources, or it uses a locally generated emission inventory.

Street concentrations are modelled with the OSPM. UBM provides urban background concentrations and also meteorological data as input for the OSPM. The COPERT IV emission model is integrated into OSPM. OSPM also requires input about the street geometry and traffic data at the location where calculations are carried out.

Figure 5 - Diagram of data integration between the air quality models present in the THOR - AirPAS system



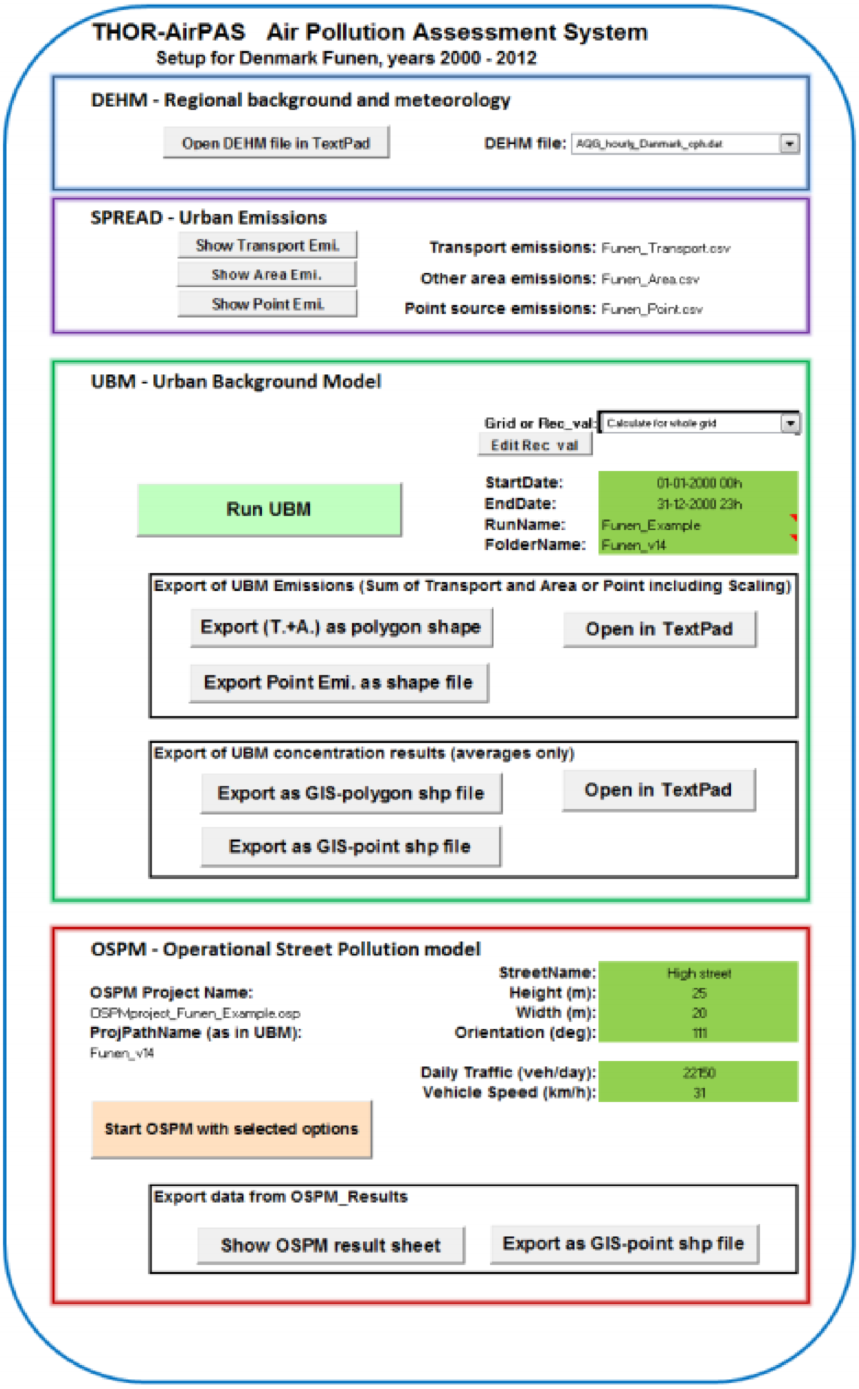
Source: Adapted from DCE (2014)

The historical meteorological model data used in the current version of the system comprises the years 2000 to 2012. The urban model UBM is configured to calculate the following pollutants: NO_x (nitrogen oxides), NO_2 (nitrogen dioxide), O_3 (ozone), SO_2 (sulfur dioxide), CO (carbon monoxide), TSP (total suspended particles), PM_{10} (particles up to 10 micrometers in diameter) and $PM_{2.5}$ (particles up to 2.5 micrometers in diameter). The most detailed model, capable of estimating data at the level of the OSPM traffic streets, allows calculating the results for NO_x, NO_2, O_3, CO, PM_{10} and $PM_{2.5}$. The data can be disaggregated by time scale, in hours or days, and be treated in classic statistical tools such as Microsoft Excel, another option is to use the internal statistical tool present in the WinOSPM modelling system, which enables the statistical analysis in zones or urban scale area, as much as in vehicular traffic street scale (DCE, 2014).

The modelling system considers the effects of buildings and other structures caused to the pollution plume, incorporating the formation of swirls formed from the wind colliding with the buildings, caused by the fluid viscous effects and the detachment of the boundary layer. These swirls cause the pollution plume to be forced down to the ground faster than if a building or structure were not present. The effect can greatly increase pollutant concentrations in surrounding streets, downstream of the building or structure.

A sample of the modelling system layout and its internal integration to the models is presented in Figure 6:

Figure 6 - Initial graphical interface of the modelling system THOR-AirPAS



DEHM file: AGG_hourly_Denmark_cph.dat

Transport emissions: Funen_Transport.csv
Other area emissions: Funen_Area.csv
Point source emissions: Funen_Point.csv

Grid or Rec_val: Calculate for whole grid

StartDate: 01-01-2000 00h
EndDate: 31-12-2000 23h
RunName: Funen_Example
FolderName: Funen_v14

OSPM Project Name:
OSPMproject_Funen_Example.osp
ProjPathName (as in UBM):
Funen_v14

StreetName: High street
Height (m): 25
Width (m): 20
Orientation (deg): 111

Daily Traffic (veh/day): 22150
Vehicle Speed (km/h): 31

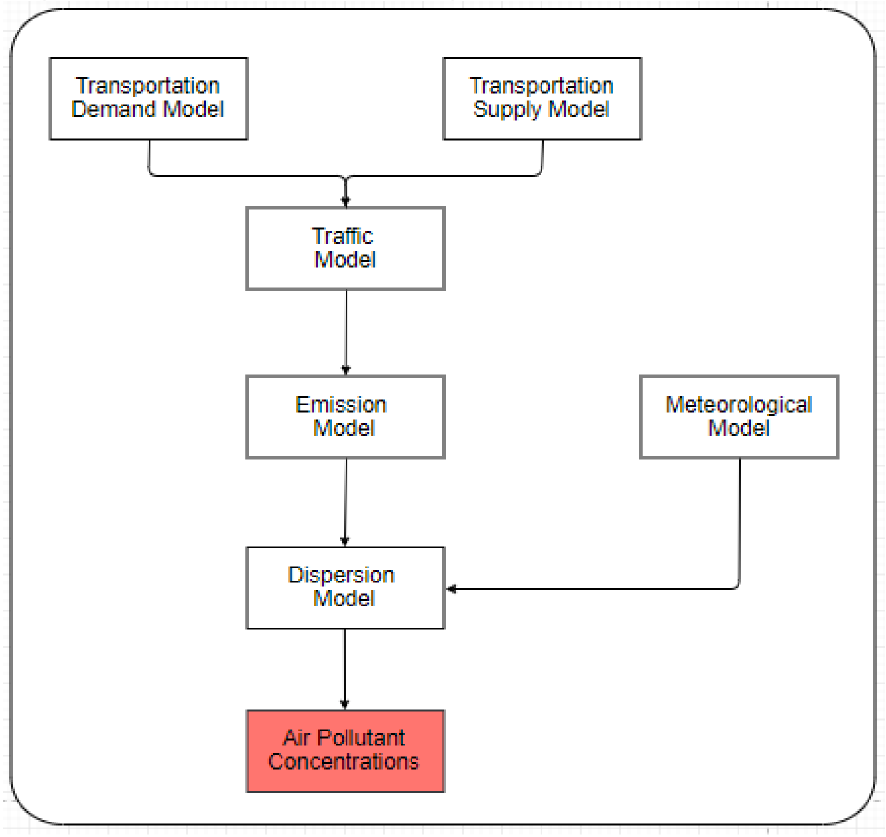
Source: DCE (2014)

The air quality modelling will be carried out using a system capable of include all contributions in air pollution: regional, urban and street concentrations, therefore by state-of-art literature in Low Emission Zone analysis shows that THOR – AirPAS system is capable of satisfactory include the three levels of air pollution contribution. In addition, the particularities of Brazilian fleet can be edited to make consistent estimations with the different conditions.

3.2 Atmospheric Pollutant Emission and Air Quality Modelling Methodologies

In order to understand the pollutant dispersion modelling, it is necessary to systematize the methodology stages, from the analysis of travel desires to the impact study that these can cause, with land use analysis and construction of emission factors from all technologies in that reality. According to Cappiello (2002), the atmospheric pollutants dispersion can be modelled after the study of the iteration between transportation demand and supply, focusing on the impacts that this iteration can have on the vehicle pollutant emissions, also considering the meteorological parameters in the analyzed area, as can be seen in the flowchart shown in Figure 7:

Figure 7 - Flowchart for estimating traffic impacts on air quality



Source: Adapted from Cappielo (2002)

- *Transportation Demand Models:* A transportation demand model can be defined as the mathematical relation between the travel demand flows and their characteristics and the activities related to transportation supply system and its characteristics (CASCETTA, 2009).

Still according to Cascetta (2009), a demand flow is the set of individual trips, and each trip is the result of multiple choices made by the users within the transportation system.

The classic approach to transportation demand modelling consists of a four-step modeling process: (i) trip generation in the network under study; (ii) how these trips are distributed within the transportation network; (iii) mode choice of transportation by users in conjunction with the (iv) travel distribution of traffic network.

Commonly in travel demand modelling, the trip distribution is observed through origin-destination (O/D) matrices by transportation mode, being this modelling to be dynamic or static, with the first being able to vary with time and the second being constant.

- *Transportation Supply Models*: According to Cascetta (2009), a transportation supply model seeks to simulate resulting behavior from user's demand, as well as the technical and organizational provision aspects of physical infrastructure for transportation distribution.

The supply models combine the traffic flow models with the network flow models, the first one used to analyze and simulate performances of traffic-related supply main elements, for example, the interactions between the vehicles using the same route, the second represents the topographical conditions and the system functional transportation structure.

The system considered in supply modelling includes network configuration, network loading or flow propagation model (model that defines the relation between routes and flows in network links), the link performance model (which defines the relationship between link performance, such as travel time or cost, and vehicle flow), and the route performance model (which defines the relationships between single-link performance and that of an entire path between any source origin-destination pairs) (CAPPIELLO, 2002).

- *Traffic Models*: Models that seek to represent the interaction between transportation supply-demand. The traffic models can be classified by characteristics related to traffic flexibility, such as uninterrupted and interrupted flow models (ARAÚJO, 2003):
  i) Uninterrupted flow models assume that there are no fixed causes of external delays or interruptions in traffic flow. Such models are suitable for representing freeways and rural highways;

ii) Interrupted flow models consider the existence of fixed obstacles that cause temporary and periodic blockages in the traffic flow. Intersection models, traffic optimization models and other models of urban networks are an example.

According to Hourdakis *et al.* (2003) and Jayakrishnan *et al.* (2003), traffic models are also divided by representation levels (parameter detail aggregation, such as driver behavior, vehicle acceleration, among others), and can be defined as: macroscopic, mesoscopic and microscopic.

The macroscopic models address traffic interactions with low detail levels, the traffic description of the system is based on the relation between speed, flow and density, being used more precisely when the analyzed network scale can provide a more aggregated traffic representation when compared to mesoscopic and microscopic models (ARAÚJO, 2003).

The mesoscopic models represents aspects common to macro and microscopic models, their aggregation level is defined as intermediate. They retain a certain level of system disaggregation in the representation when compared to microscopic models. For example, to represent lane changing movements, they can be simulated for each vehicle, but the decision is based, in aggregate, on lane densities, and not on the individual relation between vehicles (LIEBERMAN and RATHI, 1997).

Microscopic Models describe the vehicles and their interactions in an individualized way and their output results are as detailed as possible in comparison to the meso and macroscopic models. This type of model offers a higher detail level, considering this, requires a greater number of input data than other models, a larger computational effort and more time to perform the simulation (MAIA, 2007).

In Low Emission Zone analysis, usually is more appropriate to use aggregated models (macroscopic) due to area dimensions and lower traffic output details, but mesoscopic models could also be applied, depending on study aggregation e detailing levels.

- *Pollutant Emission Modelling*: Pollutant emission models aims to estimate the vehicle emissions produced in function of their characteristics and the operation conditions in which they are submitted.

Due to different specifications and emission particularities of each vehicle type, emission models represents information and parameters that best apply to each type and technology. As a result, models are usually calibrated for similar groups of vehicles, for example, passenger vehicles, buses and freight transportation, and their respective fuel technologies (CAPPIELLO, 2002).

Emission model analysis leads to conclusion that two basic methods are used. Those methods differ in relation between emission and parameters describing vehicle operation (JOUMARD *et al.*, 2000; PRONELLO and ANDRÉ, 2000):

- Instantaneous emission method applied in modal models (most appropriate to microscopic analysis);
- Average emission factor method applied in other models (most appropriate to macroscopic analysis, such as Low Emission Zone studies).

Among existing emission models, those based on the average emission factor method are often used in many studies which concern modelling of exhaust emission for real traffic. The main reason of that is the database of emission factor which is available for many different vehicle categories. Therefore, also in air quality studies, models applied the average emission factor method are commonly using for predicting air quality (BRZOZOWSKI AND GRINKE, 2005).

Emission models are usually calibrated using dynamometers, equipment that simulates vehicle conditions similar to real traffic, and filters attached to exhaust to capture pollutants emitted during use. The emission capture is usually done in two ways, during a certain interval of time, where an average will be calculated for vehicle speed and emissions also corresponds to the average, or continuously, where the observation of emitted pollutants is made in real time, usually executed second-by-second. The model based on the average emissions and speed is called the static emission model, and the model based on the continuous emission observations is called dynamic emission model (CAPPIELLO, 2002). The most important objective of emission models is to estimate the emission factors of each vehicle class, aiming to street analysis of all emissions in studied transportation network.

Beyond the emission factor database for all vehicle classes, the volume of emissions can be spatially aggregated using GIS tools, in order to evaluate the impacts of all vehicles present in traffic network. The spatial aggregation is an important step to assess the air pollution impacts in a given area, due to emission impacts in air pollution concentrations, especially in vehicle dense urban areas.

- *Meteorological Modelling*: Meteorological models are designed to calculate instantaneous atmospheric conditions (such as wind speed and temperature) in order to consider climatological factors that may interfere with the dilution of pollutants in the atmosphere (NIWAR, 2004).

For air quality modelling purposes, such as Low Emission Zone analysis, meteorological grid models are used in conjunction with chemical interaction models to provide gridded output of chemical species or pollutant data. Meteorological grid models use mathematical formulations that simulate atmospheric processes such as the change of winds and temperature in time. These meteorological parameters are calculated at distinct spatially equidistant points over an area of interest which is called a grid. When these models are applied in a retrospective mode (i.e. modeling a past event) they are able to blend ambient data with model predictions via four-dimensional data assimilation, thereby yielding temporal and spatially complete data sets that are grounded by actual observations (EPA, 2017).

There are several commonly-used meteorological grid models that can develop inputs for air quality models. These grid models differ in their simulation of atmospheric processes but each produce gridded meteorological parameters. There are also several post-processors which are needed to convert the raw meteorological modelling output to suitable air quality model input (EPA, 2017)

- *Air Quality Modelling*: Pollutant dispersion models (also called air quality models) seek to estimate how pollutants emitted react with other airborne compounds, how they disperse, and how they impact air quality in terms concentration (CAPPIELLO, 2002).

Air quality models use mathematical and numerical techniques to simulate the physical and chemical processes that affect air pollutants as they disperse and react in the atmosphere. Based on inputs of meteorological data and source information like emission rates and stack height, these models are designed to characterize primary pollutants that are emitted directly into the atmosphere and, in some cases, secondary pollutants that are formed as a result of complex chemical reactions within the atmosphere.

These models are important to air quality management system because they are widely used by agencies tasked with controlling air pollution to both identify source contributions to air quality problems and assist in the design of effective strategies to reduce harmful air pollutants. For example, air quality models can be used during restriction measure process (such as LEZ’s) to verify that a new source will not exceed ambient air quality standards or, if necessary, determine appropriate additional control requirements. In addition, air quality models can also be used to predict future pollutant concentrations from multiple sources after the implementation of a new regulatory program, in order to estimate the effectiveness of the program in reducing harmful exposures to humans and the environment (EPA, 2017).

According to the NIWAR (2004), dispersion models can also be defined as physical and chemical phenomena mathematical simulators responsible for transporting, dispersing and transforming pollutants present in the atmosphere.

The most modern dispersion models are available in computational softwares that calculate pollutant concentrations from observed sources using the following information:

a) Emission contaminant flow;
b) Emission source characteristics;
c) Local topography;
d) Meteorological conditions in analyzed area;
e) Pollutant concentrations of observed environment.

According to Scire *et al.* (1999), the characteristics that a dispersion model needs to present are: (i) ability to consider the variation of points or areas as emission sources; (ii) ability to model altitude meters to kilometers from the emission source; (iii) to provide time lapse in the range of hours to years; (iv) consider inert pollutants and applicability to adverse or complex topography conditions.

In case of air quality models for air pollutants from mobile sources, particularly for areas bounded by restrictive measures aimed at improving air quality, such as Low Emission Zones, vehicle entry data such as speed, flow, density, among others, can be obtained by traffic data collection, but usually data of all transportation network is not available, especially in developing countries, in this matter, macroscopic travel modelling tools could assist to estimate traffic flows with appropriate aggregated flow details, presented in topic 3.3.

3.3 Travel Demand Modelling for LEZ Analysis

In order to design and evaluate Low Emission Zones, the quantification of interactions among the elements of existing and potential future transportation systems are required. Values of some existing elements of transportation systems may be obtained from direct measurements, however, it is usually very costly to extend such measurements to all the elements involved (CASCETTA, 2009). Considering these problems, in the experiment carried out in this research it was decided to use modeled travel data, due to lack of reliable traffic measurements.

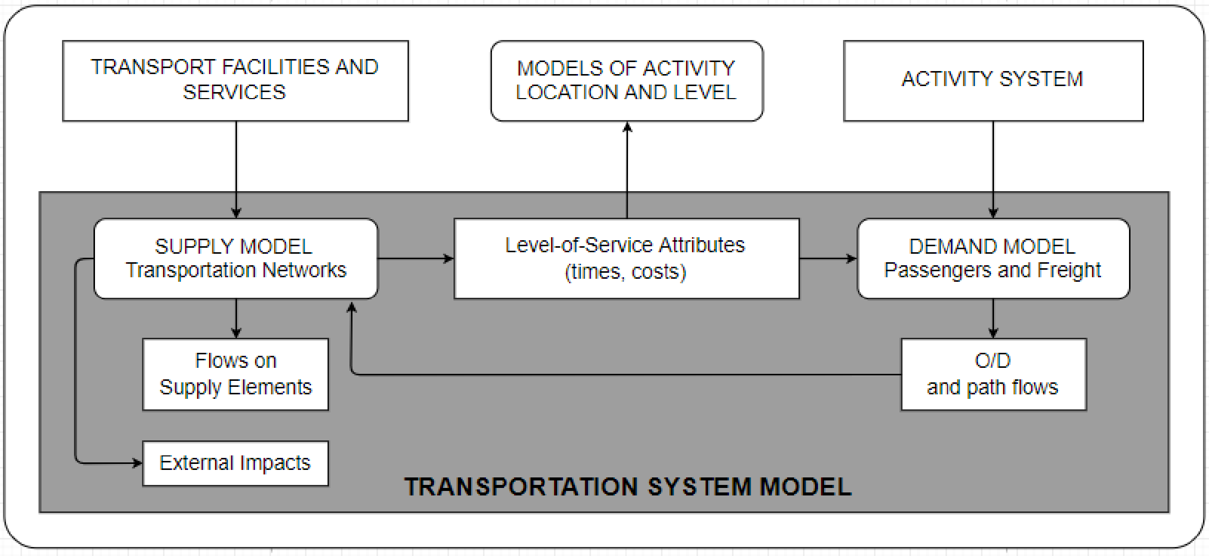
In the transportation planning process it is common to adopt modelling tools to estimate destination origin matrices, modal travel division, travel amount, among other classic indicators. The 4-step model is the traditional demand modelling process that has been applied and discussed in the national and international literature for decades, which includes demand and supply modelling However, the recognition that travel and location decisions are mutually related (HANSEN, 1959) has meant that in the last 60 years state-of-art and practice professionals have focused on understanding, integrating and predicting residential and employment locational choices, the association of this decision with the daily travel pattern, as well as the mode and route choices (ACHEAMPONG and SILVA, 2015).

To Low Emission Zone assessment, supply models represent the transportation service provided to travel between the different established zones; network flow models are frequently used for this purpose. More specifically, supply models represent the performance of transportation facilities and services for the users, and also determine the external impacts (air pollution, energy consumption, accidents) of this use (CASCETTA, 2009).

Demand models predict the relevant aspects of travel demand as a function of the activity system and the level of service provided by the supply system. Demand characteristics typically predicted include the number of trips in the reference period (demand level) and their distribution between different time intervals within the reference period, among different points, different transportation modes, and possible paths. Demand models, can be applied to passenger as well as to freight demand (ORTÚZAR and WILLUMSEN, 2011).

In addition to supply and demand modelling, activity modelling uses the technical coefficients of the Leontief Input-Output Matrix. The result is a view of how the economy works, how each sector is more or less dependent on others, however, due to the nature of this dependence, it can be shown that all sectors are directly or indirectly interconnected (GUILHOTO, 2011). Locational decisions are modeled on the theory of spatial microeconomics, where two attributes are essential to this decision: the price of land use and accessibility (VON THÜNEN, 1826, *apud* BARRA, 1989). And transport models are based on discrete choice theory, which simulates the decision of an individual among a set of options, in order to understand the decision making process that generates this decision, assuming that there are factors that determine this decision, being some observable and others not (TRAIN, 2009). The structure of transportation system models, also applied to LEZ assessment, is presented in Figure 8.

Figure 8 – Structure of Transportation System Models



Source: Cascetta (2009)

The network modelling is multimodal, where all modes can simultaneously use the same path segments, so each segment is composed of two group characteristics: (i) physical, related to the physical structure of the network, such as capacity, specific type to each segment, direction and name; and (ii) mode, those related to each mode that uses it, such as speed (DIAS *et al.*, 2016).

With the network the demand for travel originated from the land use models, the model iteratively verifies if there is capacity to supply it and recalculates two variables whenever the relation between demand and capacity changes: the waiting time for modes with routes and the speed for each segment. At the end of this interactive process, when the travel times and speeds in each link are similar from one interaction to the other, the travel routes of each destination pair can be obtained, therefore the mileage traveled by vehicle (KV_i) and the number of vehicles (PV_i) used in these displacements, which are the two remaining variables for the proper application of the emission estimation method (SOUSA, 2016).

Two caveats need to be discussed regarding the use of integrated models for this purpose. The first is that the result of this amount of emissions will be for the transport modelling time period, usually the peak period of the morning, while the usual emission indicator is emissions/day, or emissions/year. The second is that, although accessibility planning indicates the use of integrated models, the 4-step modelling itself is also capable of providing the necessary indicators for the application of the emission models, which in turn can be used to estimate the concentrations by model in urban street level, ideal for analysis of Low Emission Zones, presented below.

3.4 Atmospheric Pollutant Emission Modelling using GIS tools

In order to ensure that the emissions are estimated reliably, every effort should aim to enhance data accuracy. Also, the model calibration and specification should be precise. Still, another requirement is to view results effectively, so as to enhance the decision-making process. The geographic information systems (GIS) play an important role in emission modelling. These are interconnected systems of hardware, software, data, people, organizations, and institutional arrangements for collecting, storing, analyzing, and disseminating information (FLETCHER, 2000).

Since mobile emission estimations are the product of travel demand and emission factors, existing studies primarily focuses on two sides: either forecasting (through modelling) travel activities or providing more accurate emission factors (what demand a high amount of emission data collection and reliable traffic emission models). Although, making the linkage between emission factors and travel activities closer is equally critical for accurate emission estimations. Geographic Information System (GIS) is a natural platform to connect them based in the core of the systems, based on the capabilities: (i) both travel activities and mobile emission factors are intrinsically spatially dependent, and GIS is powerful to perform spatial analysis. (ii) GIS is vastly applied in transportation and air quality models (WU, 2006).

As shown in Figure 5, an intermediate step between transportation and air quality modelling, emission estimations should also be GIS based in order to streamline an integrated transportation and air quality analysis, specially observing Low Emission Zones, due to area dimensions. Land use patterns and clean vehicle technology dissemination are being included for a more comprehensive transportation and air quality analysis, among other factors. These studies require a platform which different types of models can be integrated and numerous sources of data can be managed, where GIS is one of the best options so far. In recognition of the strength of GIS, the National Cooperative Highway Research Program (NCHRP) has strongly suggested the new generation of transportation and air quality models to apply GIS into emission modelling (CAMBRIDGE SYSTEMATICS, INC., 2001).

Existing efforts at using GIS for transportation related emissions are still not primary used. Most previous attempts are preliminary studies focusing on incomplete sets of pollutants (e.g., CO or NO_x only) and sources of mobile emissions (e.g., running emissions only). None of the existing methods is qualified to provide inputs to both transportation emission related analysis and air quality modelling, which require more wide pollutant types. Including this, current studies in the related fields are mostly limited to using GIS techniques not updated, such as data manipulation and visualization. Modern techniques of GIS technology, such as geostatistics, spatial analysis and object oriented programming are still not widely used, although they could provide new solutions for performance improve of mobile source emission estimations. Therefore, there is still several advantages to move transportation related emissions modelling towards to be a GIS based system (WU, 2006).

As a short review of GIS application of transportation-related emission analysis, Hallmark and O'Neill (1996) integrated transportation tools and air quality models for analyze mobile pollutant emissions (e.g., CO) applying GIS based travel demand modeling software TRANSCAD. The transportation tool has been integrated to two different air quality models, CALINE3 and CAL3QHC, were used to estimate pollutant concentrations levels in road and intersection source emissions, respectively. Pollutant concentrations were ported to TRANSCAD, to generate pollutant concentration profiles, since TRANSCAD is capable of performing different visualizations and spatial analysis on GIS tools. Combining pollutant concentration profiles and land use in TRANSCAD, been able to analyze air quality impacts on some sensitive areas, such as schools and hospitals.

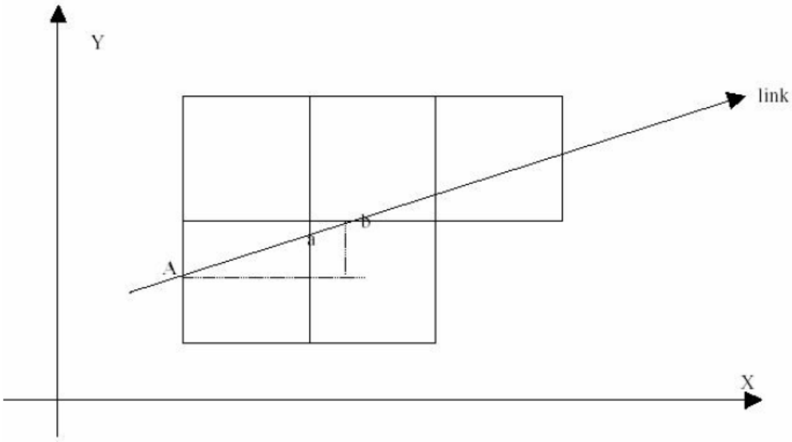
Transportation and traffic researchers can also use this integrated method to develop planning countermeasures and traffic control strategies, such as restrictive impositions (e.g. Low Emission Zones). Still according to Hallmark and O'Neill's method, they demonstrated that GIS is effective to integrated analysis involving land use, transportation and air quality models. Although, air quality models in the method are accurate in small scale analysis (e.g., intersection or corridor analysis), and only one type of pollutant is included (Carbon Monoxide).

GIS was also used to integrate travel demand models and air quality analysis in other studies (JENSEN and SATHISAN, 1996; SOULEYRETTE *et al.*, 1992). In this study, the use of GIS was done to improve transportation and air quality modelling analysis, TRANPLAN was a travel demand modelling tool to provide travel demands, and the Urban Airshed Model (UAM) was used to estimate the photochemical and dispersion process and calculate air pollutant concentrations. Emission rates were calculated by emission model MOBILE 4.0. ARC/INFO was selected as the GIS tool to make the integration between TRANPLAN and UAM. Specifically, a software package developed in ARC/INFO read traffic flows and speeds from TRANPLAN and emission rates from MOBILE 4.0 outputs, and combine them to obtain gridded emissions.

3.4.1 Method of mobile emission distribution using GIS

In travel demand modelling, usually the travel data is brought is two ways – zonal based data and link based data – considering emission estimations. Zonal based data includes interzonal movements and intrazonal movements, traffic volume and speed. Link based activities consists in traffic flow and speed. Most air quality modelling require gridded emissions, both zonal and link travel data have to be disaggregated into grid cells to obtain emissions at the grid cell level. The distribution of link travel activities should be adjusted in grid cells as shown in Figure 9. For a large network and fine grids, the method needs to consume a considerable amount of computer memory and computing time, also depending on analyzed area (ZHENG *et al.*, 2001). GIS raster modeling method provides opportunities to overcome these shortcomings when modeling gridded emissions within a GIS environment.

Figure 9 - Emissions grid construction method

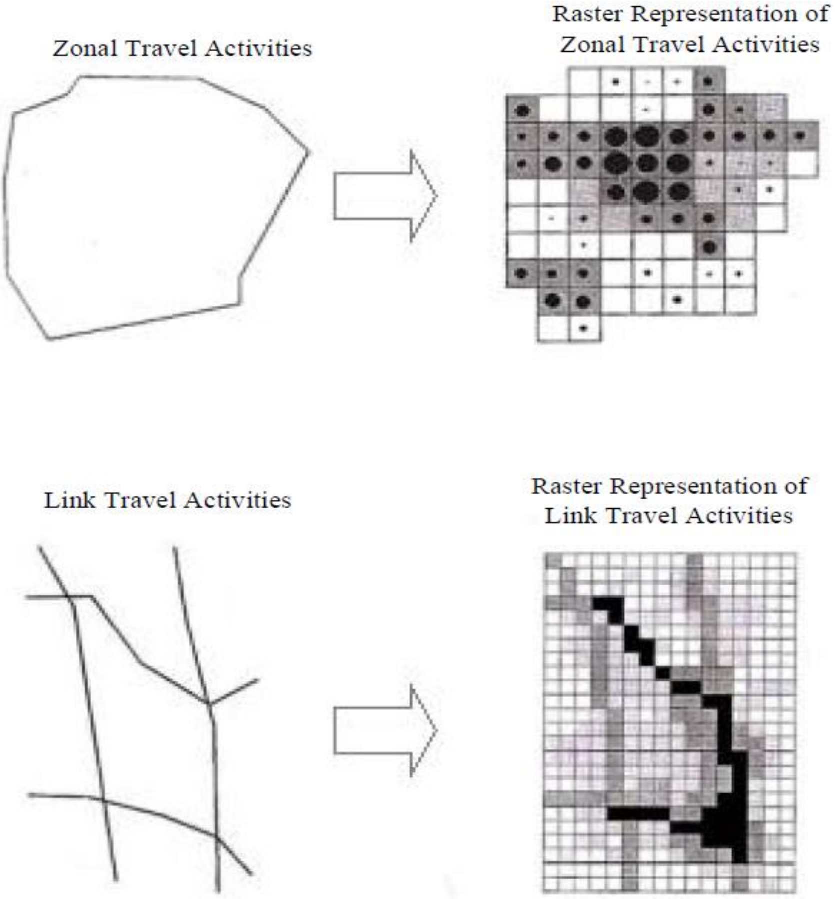


Source: Adapted from Zheng *et al.* (2001)

Zonal travel modelling can also be represented in the form of rasters. Each one represents both the geographic location and the specific characteristics of a subarea within a Traffic Analysis Zone. If there is lack of information in internal distribution of zonal travel activities, they can be uniformly allocated to each grid cell. As an example, Figure 10 shows the rasters with different dot sizes, describing the unequally distributed zonal travel activities, also the the distribution of grid cells of link travel activities (ZHENG *et al.*, 2001).

Considering that transportation network is composed of a number of links, in raster models, those links are represented by several connected cells lay over the transportation network. Each cell can be considered as a tiny portion of a link or a sum of link portions and receives traffic information associated with these links, such as traffic volume and speed. The accuracy of the representation varies with the resolution of raster dataset: the finer the cell resolution, the more accurate the representation. After transforming links into rasters, they can be used to estimate running emissions and avoid the complexity due to constructing grid meshes as a means of obtaining gridded emissions (WU, 2006).

Figure 10 - Disaggregation of zonal and link based travel data to grid cell level



Source: Adapted from Spiekermann and Wegener (2000)

With these two fundamental measures briefly presented: travel activities and emission factors. The product of them at a grid level can produce a gridded emissions inventory, it is possible to start the air quality modelling using tools as shown in Topic 3.1.

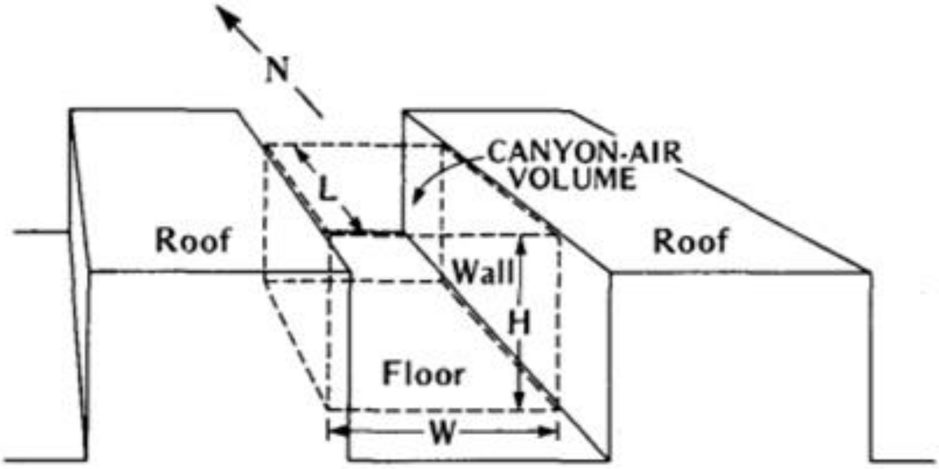
3.4.2 Urban Canyon Formation

The urban areas are characterized by different urban elements (squares, streets, avenues, among others). However, buildings are the most characteristic elements of cities and their layout can form a configuration known as "urban canyon", in which buildings are lined up along both sides of a street. Knowledge of land use has fundamental importance in Low Emission Zone projects, due to influence in absorption process of solar radiation and long wave radiation that are emitted by the soil surface and building wave reflections, in the reduction of heat losses due to the wind flows and in the anthropogenic heat production (SILVEIRA, 2007).

In order to know the thermal behavior of urban canyons, it is necessary to adopt a parameter of analysis. Among several analysis parameters, the Sky View Factor (SVF) and the ratio of buildings heights to street widths (H = height/W = width) are widely used. These indices are the two most important ones to evaluate the performance of urban space quality (SILVA, 2013).

The canyons are composed of two vertical surfaces of height (H) and a horizontal surface (W), representing the buildings facades and urban streets, respectively. In most cases, their absolute dimensions are not relevant and therefore it is common to consider this unit as dimensionless and to characterize it by the mean height and profile width, which is called the H/W ratio. The length L, for the sake of simplification, can be considered infinite. This H/W ratio is usually used to calculate airflow, thermal effects and solar access, as shown in studies by Oke (1988), Johnson and Watson (1984) and Panão *et al.* (2009). It is a suggested index for a simplified analysis of urban geometry effect (SOUZA, 2003; BARBIRATO *et al.*, 2007; KRÜGER *et al.*, 2011). Figure 11 hypothetically illustrates the geometry of the urban canyon:

Figure 11 - Hypothetical Representation of Urban Canyon Geometry

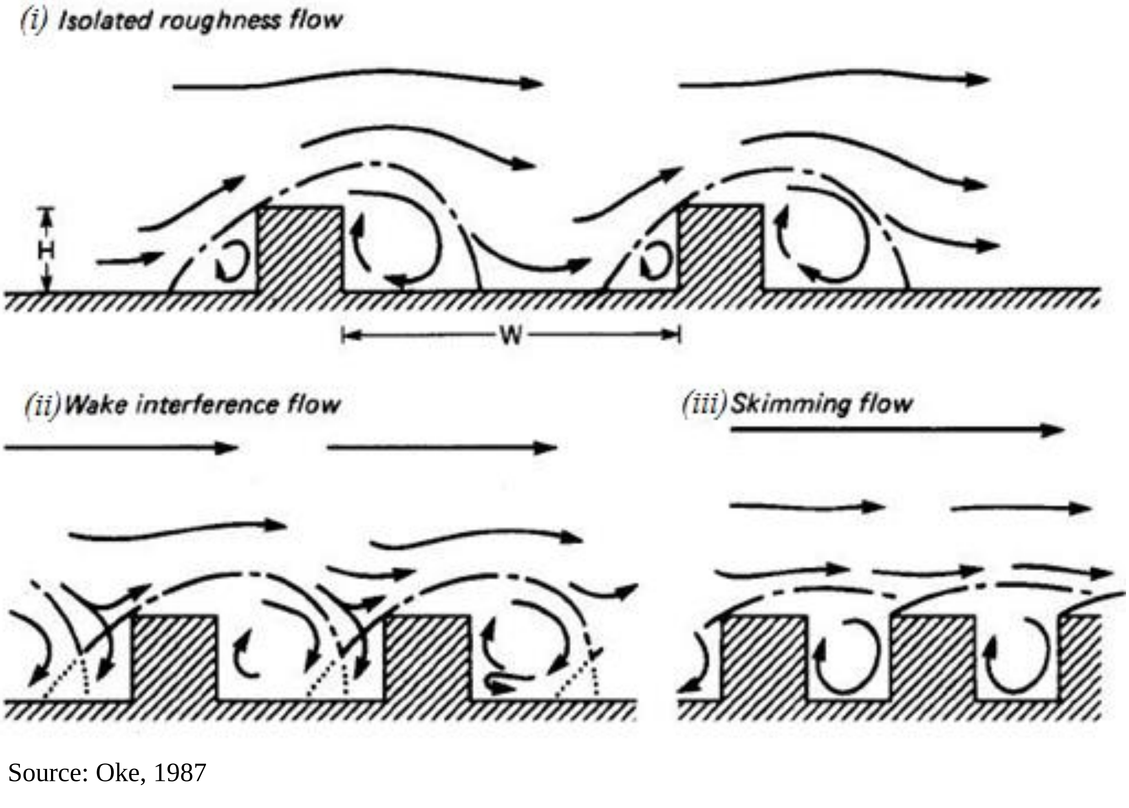


Source: Nunez and Oke (1977)

The geometry of the urban canyons can be described by three parameters: H, the mean height, W, the width and L, the length. The characteristics of air circulation within the canyons can be verified in three situations: the perpendicular air flow, parallel or inclined in relation to the axis of the canyon. Transitions between these regimes occur in critical combinations of H/W and L/W (OKE, 1988).

In order to consider the airflow perpendicular to the canyon axis (± 30 degrees), three types of flow regime can be observed according to the building geometry (L/H) and the canyon (H/W). When the buildings are distant, with H/W higher than 0.5, the airflow and buildings do not interact. As this distance decreases, the flow starts to be modified by building arrangement, and can be classified according to Oke (1987) in: (*i*) Isolated roughness flow: the building formations change the air flow; (*ii*) Wake interference flow: formation of swirling in the cavity, occurring a disturbance due to the height and the blocks of buildings; is described by the occurrence of a secondary airflow in the canyon, which is produced when the airflow in the cavity is reinforced by the flow deflection in front of the leeward building; (*iii*) Skimming flow: occurs when the H/W ratio is higher, in which a stable vortex stabilizes within the cavity and most of the airflow does not penetrate the canyon. The classifications can be observed in Figure 12:

Figure 12 - Air flow regime associated with different urban geometries



Source: Oke, 1987

The configuration of urban canyons described previously directly interferes in wind behavior, consequently in the fluid-dynamic drag of atmospheric gases, including the pollution originated from vehicle activities.

However, urban canyons can still be classified according to the work of Battista *et al.* (2015), and are divided into three types of canyons: (i) Canyon Avenues: H/W Ratio < 0.5; (ii) Regular Canon: H/W Ratio ≈ 1; (iii) Deep Canon: H/W Ratio > 2.

The particularities of each type of canyon will be observed in the definition of the study area, because the concentration of the pollutant gases will present a distinct behavior, due to the longer stay in roads with higher presence of deep canyons. In this sense, the data collection sampling will consider the formation of urban canyons, including low (canyon avenues) and high (deep canyons) ratios.

Considering state-of-art modelling mechanisms for the traffic and pollutant dispersion capable of representing pollutant behavior in urban areas, Chapter 4 presents the proposal detailing from the acquisition of traffic data, vehicular emissions, meteorological conditions and air pollutant concentrations in street levels.

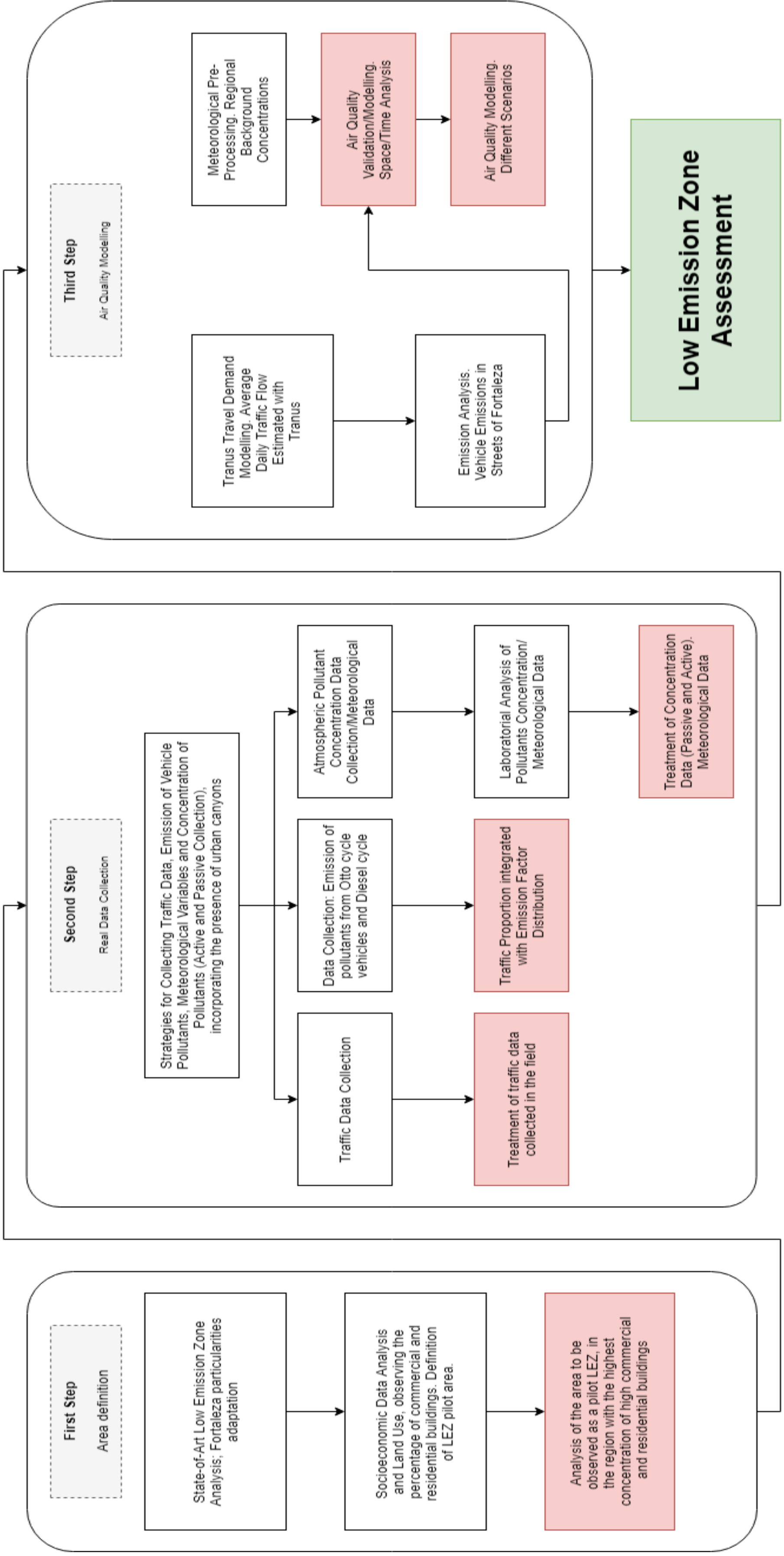
4 METHODOLOGICAL PROPOSAL FOR LEZ ASSESSMENT

In order to achieve the objectives established in this research, the proposed methodology is based on the real data collection of air pollutant concentrations, in the region established as a pilot Low Emission Zone region, and the mobile sources inventory of emission factors, considering the different technologies and their evolution, besides the different types of fuel and fleet particularities of Fortaleza and, in particular, of real traffic flow. In this case, with the objective of constructing the city travel Origin-Destination matrix, to model aggregated emissions in GIS grid cells and air pollutant concentrations data present in the analyzed area. The real data collection will seek to provide the necessary inputs for the proper travel demand modelling, pollutant emission estimation through GIS and atmospheric pollutant dispersion tools. This research will consider the whole city of Fortaleza, however, will be based on a pilot area for case study to understand the impacts of air pollution concentration reduction in function of Low Emission Zone implementation.

The choice of such region follows some criteria: (i) presents the most intense traffic flows in city of Fortaleza, and strong volume of the most pollutant vehicles, such as buses and urban freight transportation; (ii) has strong poles of attraction and travel production, together with the high population density, where the impact of air pollution is more harmful; and (iii) the presence of high-level buildings, due to the interference of gas dispersion, formation of urban canyons and heat islands.

In this area, the emissions of passenger vehicles and high-duty vehicles will be observed, concomitantly observing the vehicular flows along the main routes of the pilot network, and pollutant concentration data collection devices will be strategically positioned to observe the behavior of gases distributed along the area analyzed as possible Low Emission Zone. The study is divided into three subsequent stages: (i) determination of the area to be defined as possible Low Emission Zone, understanding the particularities of Fortaleza reality and adapting the method of area implementation: mapping the region with socioeconomic and land use data; (ii) data collection in the field: emission factors analysis considering Fortaleza fleet (vehicles and fuel technologies) and development of methodology for collecting pollutant concentration data in atmosphere, including meteorological data; and (iii) simulations: preparation of travel demand modelling, with proper calibration of vehicular parameters and vehicle behavior; emission modelling of vehicles in the network by integrating the outputs of the travel demand model to the emission factors; simulation of the space/time behavior of the pollution from vehicular activity, applying an air quality modelling system. In addition, there will be a sub-step consisting of laboratory analysis and treatment of the data collected in the field, ensuring that the data can be analyzed and used as inputs to the simulation steps. Synthesized by the flowchart shown in Figure 13, the proposed method will be implemented in a selected region of Fortaleza municipality. This city has been chosen due to dense population and traffic of people and goods. In addition, Fortaleza is the fifth biggest city in Brazil, and considered a huge urban center, in Brazilian reality.

Figure 13 - Flowchart of methodological proposal



Source: Author

4.1 First Step: Definition of the Area to be Implemented as Low Emission Zone

Before suggesting the Low Emission Zone pilot study region, it is necessary to understand the particularities of Fortaleza city, such as: (i) vehicle fleet (informations regarding engine technology, fuel consumption, production age, among others); (ii) land use (building footprints, commercial buildings, residential buildings, among others) and (iii) legislation issues (current traffic measures, municipality subsidies, public transportation policies, among others).

According to Maia (2007), two criteria must be considered during the definition of the studied area. Firstly, it is important to take into account the type of intervention that is intended to be evaluated. Considering that Low Emission Zones are strategic planning measures, the analyzes require the selection of more extensive areas in order to observe all relevant offsets, including those in and out of the traffic network, and consistently predict impacts with the implementation of the selected alternative, however, LEZ's can be implemented as smaller pilot areas, and be upgraded along the observation of pollutants concentration reduction with the adaptation of fleet technology through time. As a second characteristic of the study area, a high population density should be observed in order to verify the direct impacts on health and the use of the infrastructure area by its inhabitants, knowing that the pollutants emitted by the vehicle fleet, especially of high duty vehicles (such as buses and trucks), directly affect the health of people and negatively affect the physical infrastructure through which they circulate.

It should also be considered, how will be collected the necessary data for the accomplishment of the modelling, if the region has some mechanism of automatic data collection, or there are traffic monitoring cameras in the region, or check the feasibility of conducting research in the area selected for the study. This step of the procedure is important because based on the selected area and in the type of intervention evaluated, the necessary data are defined and how these data are will be collected, what level of simulation will be used and, consequently, how calibration and validation of the model used to represent the behavior of the vehicular flow in the studied region.

Considering the above, this methodological step will have the objective of establishing criteria for the selection of the region to be defined as Low Emission Zone. It will be analyzed as a study region with high population density and that concentrates significant amount of commercial buildings and services, which result in the higher travel amount of freight and public transportation. In addition, the area is expected to show the constant presence of traffic congestion and the movement of people who may be exposed to emissions. The idea is that, with such criteria, it is possible to evaluate a "critical" region, which causes the vehicles to be requested and the people to be exposed. The following steps define the construction strategy of the Low Emission Zone region.

4.1.1 Fortaleza Municipality

Fortaleza is a Brazilian municipality, capital of the state of Ceará, located in the northeastern region of the country. Distant 2285 km from Brasilia, federal capital, constructed by the Dutch during its second stay, between 1649 and 1654. It is located on the Atlantic coast, at an average altitude of sixteen meters, with 34 km of beaches. Fortaleza has 313140 km ² of area and 2643247 inhabitants estimated in 2018, in addition to the greater population density between the capitals of the country, with 8390.76 hab/km². It is the largest city of Ceará in population and the fifth in Brazil. The Metropolitan Region of Fortaleza is the sixth most populous in Brazil and the first in the North and Northeast, with 4 051 744 inhabitants in 2017. It is the northeastern city with the largest area of regional influence and has the third largest urban network in Brazil in population, behind only São Paulo and Rio de Janeiro.

Fortaleza has a semi-humid tropical climate, with average annual compensated temperature around 27° C. Without having exactly defined seasons, there is the rainy season, from January to June (summer and autumn), July is the transition from rainy season to drought, and the dry season, from August to December (winter and spring) . The annual rainfall index is over 1600 millimeters (mm), concentrated between February and May, and with the peak observed in March and April. Its location, between nearby mountains, causes summer rains to occur more frequently in the city and surrounding than in the rest of the state (INMET, 2018).

According to data from the National Institute of Meteorology (INMET), from 1961 to 1970, 1974 to 1985, 1990 and from 1993, the lowest recorded temperature in Fortaleza was 19.4 ° C on August 15, 1969 and July 5, 1974, while the highest reached 37 ° C on December 27, 2001. The highest accumulation of precipitation in 24 hours was 198 mm on May 1, 1974, and the highest volume in one month was recorded in April 2001, of 758.5 mm (MAGALHÃES and ZANELLA, 2011).

4.1.2 State-of-art Low Emission Zone Analysis: Fortaleza Particularities Adaptation

It is likely that LEZ will have significant impacts on environmental objectives, however, to evaluate the impacts of the restrictive measure, local particularities must be considered. The nature of the impacts will be specific and depend on the restriction location, and the LEZ impact on traffic levels by location, duration of restriction, composition of traffic and technologies involved.

The environmental impacts of the restriction will also depend on the extent to which the LEZ is combined with other measures. Table 6 describes qualitatively the potential impacts of LEZ, provided that local conditions of implementation are adequate.

Table 6 - Qualitative assessment of the potential impacts of a Low Emission Zone

(to be continued)

Inside Low Emission Zone			**Outside Low Emission Zone**	
Impact	**Qualitative Assessment**	**Assumptions**	**Qualitative Assessment**	**Assumptions**
Pollutant Emissions (NO_x, PM)	v	True for Euro-standard (or equivalente, like PROCONVE standards) based LEZ. Schemes may address NO_x and PM either individually or not.	-	Older vehicles may be sold for use in areas outside the zone but compliant vehicles that use the zone are also active outside of the zone
CO_2 Emissions	v	Assuming tax-based restriction measure (Vehicle Excise Duty (VED), for example) - based LEZ	-	
	-	Neutral or marginally negative impacts for Euro-standard (or PROCONVE) based LEZ	-	In an Euro-based standard (Proconve) LEZ

Table 6 - Qualitative assessment of the potential impacts of a Low Emission Zone
(conclusion)

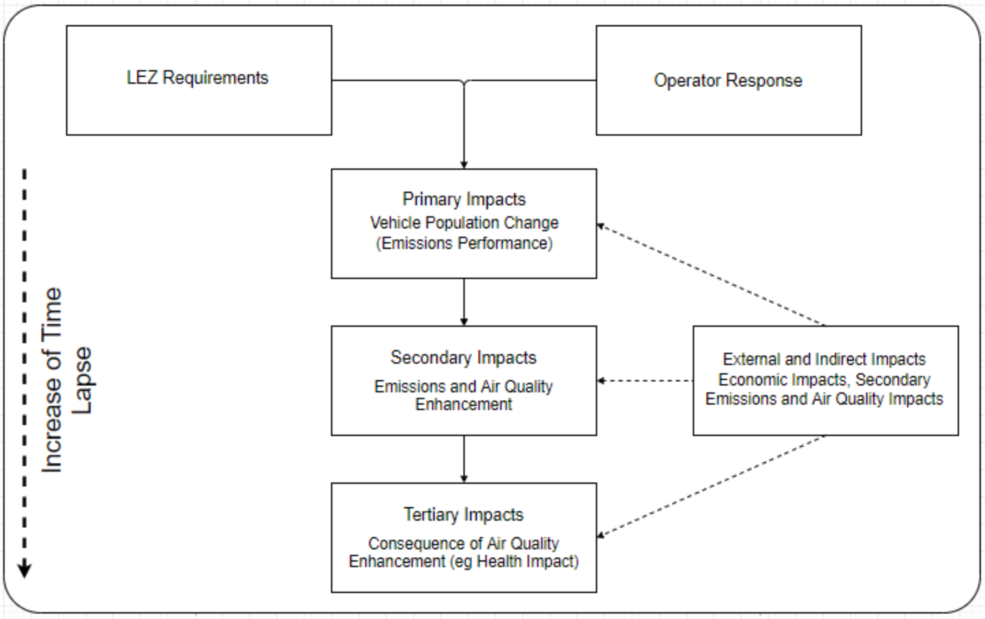
Inside Low Emission Zone			**Outside Low Emission Zone**	
Impact	**Qualitative Assessment**	**Assumptions**	**Qualitative Assessment**	**Assumptions**
Noise	v	New vehicle technologies are usually quieter	-	Older vehicles could be used outside LEZ, usually less quiet
Travel Time	-	Assuming the same number of vehicles circulate within the LEZ or no measure	-	Assuming the same number of vehicles circulate within the LEZ or no measure
Regulatory Costs	X	Wide range of potential costs. Could be partly offset by revenue raised by LEZ, like reduction in health costs	-	Potentially no regulatory costs outside of LEZ
Operator Costs	X	Additional operating costs or vehicle replacements, before end of commercially useful life.	-	Potentially neutral operator costs if travel time impacts are neutral

Source: Adapted from DEFRA (2009)
Notes:
1. Qualitative assessment: v symbolizes a beneficial impact; x symbolizes a negative impact; - symbolizes a neutral impact.
2. Low Emission Zone may have potentially significant non-air quality impacts. Therefore local authorities are advised to have regard to the generic guidance on the economic principles that apply when assessing LEZ's.

As mentioned in Table 6, the benefits and negative impacts of LEZ's are directly related to vehicle fleet technology, and are usually observing Euro standards, however, Brazilian vehicles are regulated by PROCONVE standards, with the legislation similar to Euro standards, but vehicle technology evolution in Brazilian fleet are slower than European evolution. Therefore, the objective of this sub step is to adjust to Brazilian reality the rules presented in state-of-art literature the impositions made in the implementation of LEZ's. Considering this, PROCONVE standards must be adapted to LEZ's scheme to fit in implementation stages, as mentioned in topic 2.1.3.

In addition to the adaptation of vehicular technology to the restrictive measure, land use will be observed concerning building distribution, as regards building heights and width of streets, which Brazilian big cities differs significantly when comparing to European cities (e.g. tall building constructions), as the distribution of buildings directly impacts the dispersion of pollutants along Low Emission Zone. These adaptations will seek to achieve the impacts described in the most modern LEZs, presented in Figure 14.

Figure 14 - Impacts as a consequence of LEZ introduction



Source: Adapted from Transport for London (2008)

4.1.3 Socioeconomic and Land Use Data Analysis, LEZ Pilot Area Definition

The objective of this methodological step is to collect socioeconomic and land use data from the city of Fortaleza, seeking to observe the distribution of trade in all neighborhoods of the city. To do so, the percentages of residences will be calculated in relation to the percentages of commercial establishments present in each neighborhood of the municipality. In addition, the population density of the region to be defined as the Low Emission Zone will be considered, depending on the expected reduction in the concentration of atmospheric pollutants reached by the implementation of the restrictive measure. There will be done a characterization of Fortaleza districts based on the number of residential and commercial lots. Using Fortaleza land use data (year 2015), it was possible to know how many commercial and residential lots exist in each district of the city and to make a statistical manipulation in order to group these districts, according to the standard number of lots of each one. It is noteworthy that the analysis was made separating the residential and commercial districts.

The district observation strategy will consider three possible excerpts from districts in the municipality: (i) District considered proportionally as residential: district that the percentage of residences is higher than the percentage of commercial buildings; (ii) District considered proportionally as commercial: district that the percentage of commercial is higher than the percentage of residences; (iii) District considered mixed: district that the percentages of residences and businesses were approximately equal. The importance of such analysis consists in pendular movements, which will carry higher travel flows in the pilot area.

After the observation of districts with higher proportional presence of commercial establishments, the area that will be implemented as pilot Low Emission Zone will be defined. It will be sought to delimit study area from the geographic region with higher extension of commercial districts, higher concentration of districts with borderer districts titled as commercial and with high population density, for Fortaleza population standards.

In addition to the land use criteria used, the area defined as a pilot in the study will present, in most of its extension, have vehicle traffic data collection tools, such as sensor loops and monitoring cameras, with a view to feasibility of vehicular flow analysis and observation of the historical flow series over the last years and months, aiming to correlate traffic flows with mobile emissions and air quality impacts. The expansion of traffic data observed with municipality tools will be fundamental as inputs in step 3, average annual travel modelling.

The inconsistences of database will be adjusted considering the contemporary reality of Fortaleza, such as districts which changed names, have been divided or even presents two different names in official database. Therefore, the database will be adapted to make consistent comparisons.

With the area defined as a pilot Low Emission Zone, incorporating the criteria mentioned in the previous sub-steps, some characteristics must be observed within the analyzed region, one of the most important in terms of microclimate and streets air pollution interference in the region, and especially (and consequently), the dispersion of air pollutant gases are the urban canyons. In addition to socioeconomic land use data analysis, the concepts related to urban canyon formations will be considered to air pollutant data collection, observing H/W relation to assess different points in suggested pilot Low Emission Zone.

The data collection points will be chosen with low H/W (canyon avenues), medium H/W (regular canyons), and high H/W (deep canyons). The choice of different depths of urban canyons will seek to observe different behaviors in air pollution concentrations within the area and the accuracy of estimations using the air quality modelling tools in different situations, commonly observed in Brazilian urban areas.

4.2 Second Step: Real Data Collection in Field

With the area defined as Low Emission Zone delimited following the sub steps described above, it is necessary to study the variables capable of directly impact emissions and concentration of atmospheric pollutants from mobile sources, namely: (i) vehicular flows; (ii) vehicle flow pollutant emissions; (iii) meteorological parameters and; (iv) concentration of atmospheric pollutants.

The acquisition of data of each of the variables is essential for the modelling step (third and last step), since they will provide the necessary inputs for the application of the modelling tools, besides the calibration and validation of the models.

The data collection strategies will be presented in the following sub topics, describing the particularities of each type of methodology. The samplings will occur simultaneously.

4.2.1 Traffic Data Collection and Processing

The traffic data will be collected through the SCOOT system, provided by CTAFOR (Controle de Tráfego em Área de Fortaleza), in all streets that enable such data acquisition. The objective of automated data collection is to expand the traffic data through the filming and to perform the generation of the Origin/Destination Matrix within the city of Fortaleza, which will be necessary for travel demand modelling tool output analysis.

The Split Cycle Time and Offset Optimization Technique (SCOOT) system was developed to perform traffic control in real time, requiring constant data between field controllers and a central computer over private telephone lines. This system allows monitoring the operation of all traffic lights: controllers, detectors, focus groups and lamps (LOUREIRO *et al.*, 2002). This system works in real time with traffic signal programming determined dynamically by dedicated systems, based on traffic data collected by field inductive loop-type sensors in the streets (OLIVEIRA, 1997).

The SCOOT system provides data on traffic demand and time delay for technicians in the control center, via computers terminals. The model estimates various traffic performance measures based on its detection system. These measures are stored in a database called Automatic SCOOT Traffic Information Database (ASTRID). This database is designed to compile all traffic data from periodic messages generated by SCOOT system. ASTRID stores traffic data compiled in aggregate periods of 15 minutes in a specific database in the SCOOT system (MENESES, 2003). The basic and derived variables that make up the database modeled by SCOOT are described by Peek (2001), presented as follows:

a) Vehicular flow (vehicles/h): Represents the vehicle flow modeled by SCOOT. This flow is measured in link profile unit (lpu), with standard equivalence of 17 lpu per standard vehicle. If the flow exceeds a user-defined maximum queue value, the model is not computed in the SCOOT system database;
b) Vehicular stops (vehicles/h): represents the number of stops modelled by SCOOT. This is also measured in lpu/h, ASTRID converts it into vehicles/h, using a standard factor of 17 lpu per vehicle;
c) Delay ((Vehicle*h)/h): Represents the delay modeled by SCOOT. The variable delay is measured in lpu*h/h, and converted to (Vehicle*h)/h. The numerator corresponds to a kind of delay, that is, the product between the number of vehicles was delayed and the time lost by these vehicles, during the period of an hour. This variable can be understood as the average queue in a given period;
d) Congestion (%): Represents a percentage of occupation of a detector loop, being calculated by the ratio between the number of 4s that the detector was occupied and the total number of periods observed, within a certain time interval;
e) Saturation (%): Represents the saturation of a link when modelled by SCOOT;
f) Vehicle flow in the detector (vehicles/h): Represents a value for calculated flow on basis of detector switch number from idle to busy. This parameter is not suitable for SCOOT optimization models, but can be used by the SCOOT Incident Detection Sub-System INGRID;
g) Vehicle occupancy in the detector (%): Represents the percentage value of occupancy of a detector, by a standard vehicle. This variable is determined by the division between the number of periods (0,25s) which the detector was busy and the total number of observed periods (0,25s) within a certain range;
h) Vehicle Delay (s): Represents the delay of a standard vehicle. This variable is determined by the division between the basic delay and vehicular flow, corresponding to a value in seconds;

i) Time of journey (s): Consists in estimated vehicle travel time in a specific link, as modelled by SCOOT. This parameter is obtained by adding the basic variable vehicular delay and the cruise time parameter, on a given link;
j) Speed (km/h): Represents the estimated vehicle speed in a specific link, as modelled by SCOOT;
k) Vehicle occupancy (ms/vehicle): Represents an average occupancy of a detector by a vehicle. This variable consists of division between vehicular occupation in the detector and vehicular flow in the detector;
l) LPU factor (lpu/vehicle): Represents an estimation of relative equivalence between a standard vehicle and the link profile unit parameter. This variable is derived from the vehicular occupancy variable in the detector.

While the vehicle flows will be data collected using SCOOT (briefly described above), the traffic classification will be manually collected in specific links to observe the traffic proportions in Fortaleza. These proportions will be applied to vehicle fleet and be considered in the study.

4.2.2 Vehicle Emissions Data Collection and Processing

The vehicle emissions in this study will use Brazilian inventory emission factors, calculate by CETESB (Companhia Ambiental do Estado de São Paulo) methodology, which is the most robust mobile emissions Brazilian database. To calculate the emissions of most pollutants, the bottom-up approach is used in this method, which the annual distance traveled for each vehicle type is considered, in addition to other factors, such as: fleet size, emission factor and fuel consumed. The choice of degree of accuracy depends on the availability and quality of the data.

Autonomy data are required (distance traveled in kilometers with one liter of fuel) and intensity of use or average annual mileage travelled, per year and category of vehicles, for example.

The emission factors for each pollutant are determined in advance by information from PROCONVE for new vehicles that are corrected by deterioration curves that increase the emission factors as the age of the vehicle increases.

For the calculation of emissions of carbon dioxide (CO_2), sulfur dioxide (SO_2), methane (CH_4) in the case of diesel vehicles and nitrous oxide (N_2O) was adopted the top-down method, due to the unavailability of emission factors appropriate to Brazilian scenario.

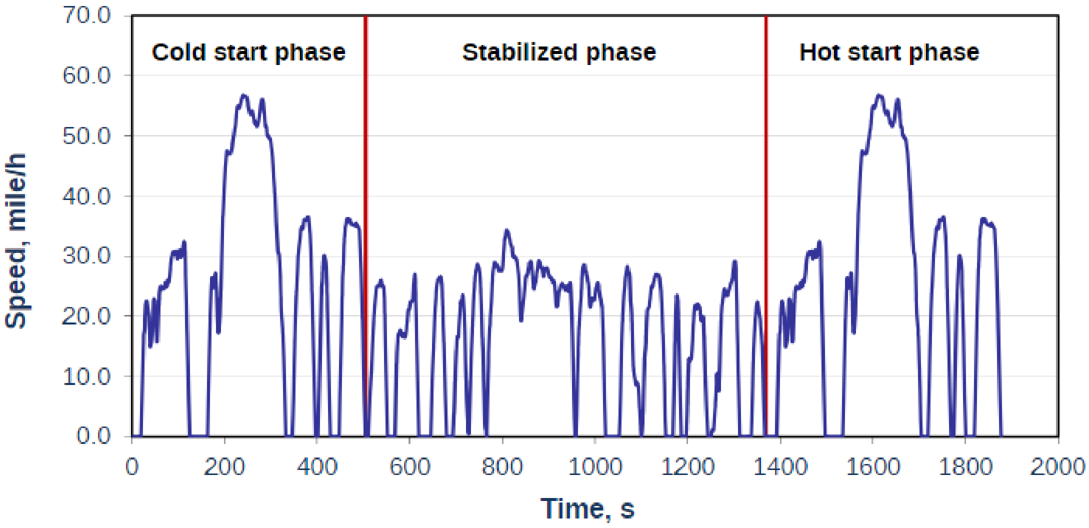
In the top-down method only the fuel consumption observed in the regions of interest or in the State of São Paulo and the characteristic emission factor of the fuel are used.

The Resolution of the National Environmental Council (CONAMA) No. 299 of 10/25/20014, considering the provisions of CONAMA Resolution 18/865, which established PROCONVE, created the Production Emission Values Report (RVEP). In those reports manufacturers or importers shall report the emission values of the tests carried out on samples of vehicles in production. Sampling rates range from 0.1% to 0.4%, implying approximately 10,000 tests annually. CETESB receives reports every six months.

For calculation of emission factors and the autonomy of light vehicles, the results of the (RVEP) emissions weighted by the respective sales expressed in g/km have been used since 2008. In the case of light commercial vehicles, the emission factors are calculated since 1996 using the same methodology as for light vehicles. In models that use Diesel cycle engines, until 2011 there was the possibility of carrying out emission tests such as heavy vehicles. Since 2012, all models have been rehearsed as lightweights (CETESB, 2017a).

The emission cycle used for emission factor and fuel consumption calculation of Otto cycle light and light commercial vehicles is divided into three phases: (i) cold or cold start; (ii) transient and (iii) warm or hot start, as shown in Figure 15. The cycle runs 18 kilometers and has a total duration of about 40 minutes, including the 10 minute interval between the second and third phases when it remains off. The tests are executed in laboratories using chassis dynamometers.

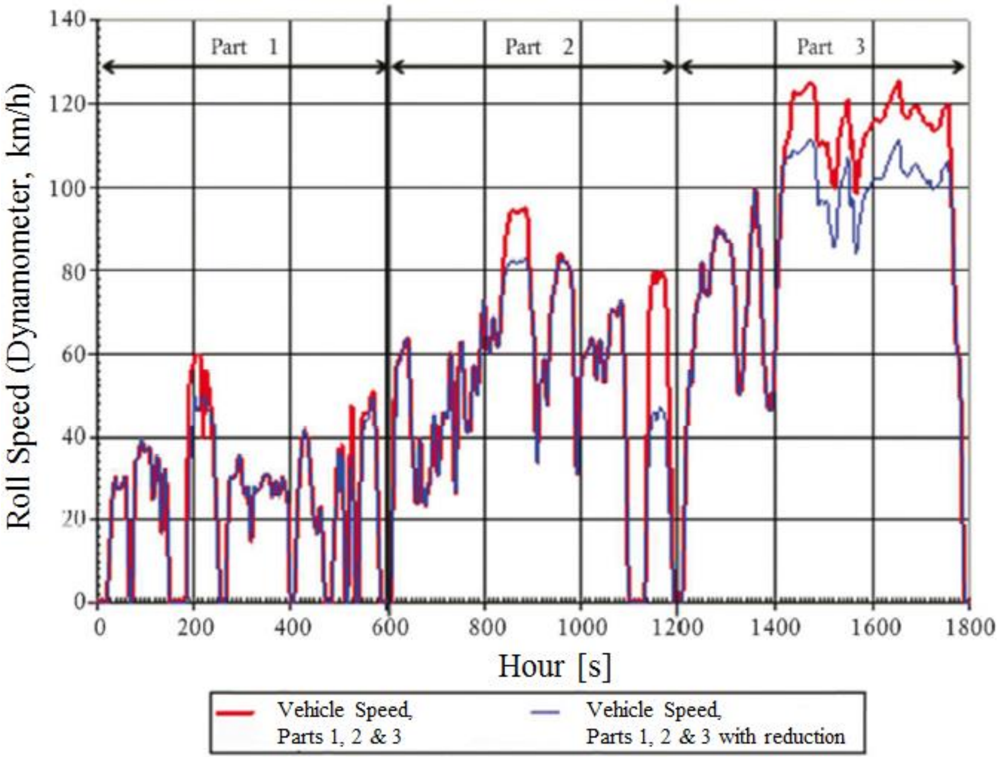
Figure 15 - Emission driving cycle for light and light commercial vehicles (FTP-75, based on US EPA Urban Dynamometer Driving Schedule)



Source: Dieselnet (2018)

In order to calculate motorcycle emission factors, RVEP was used since 2013. In previous years, they were calculated from homologation data obtained from PROMOT and weighted by sales. This category was divided into: less than or equal to 150 cc and higher than 150 cc, separated by gasoline, flex-fuel and flex-ethanol. Figure 16 presents the new cycle for motorcycles, adopted from 2014, the World Motorcycle Test Cycle (WMTC), replacing the European standard cycle used until then. Most motorcycles of Fortaleza fleet are included in this modern motorcycle types (such as flex-fuel motorcycles).

Figure 16 - WMTC cycle for motorcycles emission tests (dynamometer)



Source: European Union (2014)

In the case of heavy-duty vehicles (e.g. buses and trucks), the emission factors are obtained from engine tests reported in RVEP, weighted by vehicles sales, where proportional vehicle engine technologies were applied. The emission factor values, originally in g/kWh, are converted to g/km. For this conversion, Equations 5 and 6 are used, depending on the specific fuel consumption and the vehicle autonomy values (MMA, 2011).

$$\frac{g_{pollutant}}{km} = \frac{g_{pollutant}}{g_{diesel}} * \frac{g_{diesel}}{L_{diesel}} \div \frac{km}{L_{diesel}} \tag{5}$$

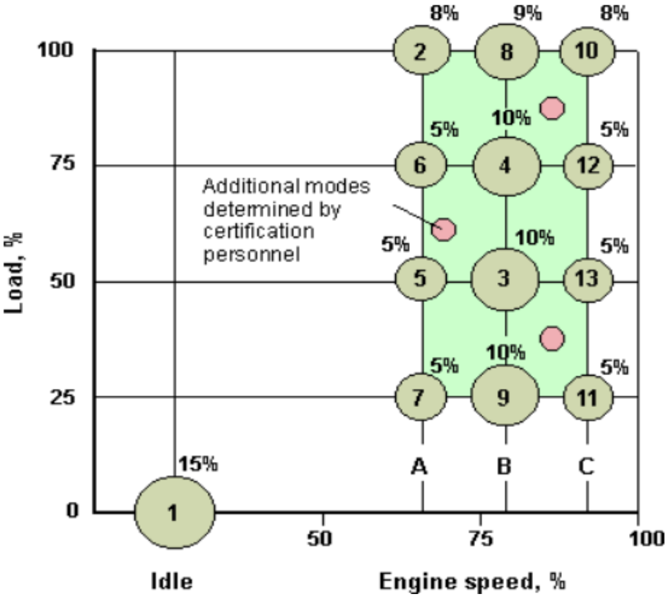
Where:

$$\frac{g_{pollutant}}{g_{diesel}} = \frac{g_{pollutant}}{kWh} \div \frac{g_{diesel}}{kWh} \tag{6}$$

To calculate heavy-duty emission factors, the European Stationary Cycle (ESC) engine test cycle used in the emission test. In the cycle, the engine is driven to 13 different load and rotation conditions. Emissions are obtained from each condition and weighted by percentages, shown in Figure 17. The emission factors are calculated using the presented methodologies and an annual database is created for all types of vehicle technologies and fuel consumption.

The only exception for emission factors used in this research is non-exhaust PM_{10} emission factors, which are not calculated in Brazilian database, because of this, European emission factors will be applied to estimate the total non-exhaust PM_{10} emissions. These emission factors will be collected using COPERT 4 database, it includes non – exhaust EFs (in g/km) of various vehicle categories and technologies for several pollutants. COPERT 4 approach is based on the methodology on the calculation of emissions for tyre, break and asphalt wear that has been included as the relevant chapter in the EMEP/EEA air pollutant emission inventory guidebook.

Figure 17 - Emission cycle test of Diesel engines for obtaining emission factors (based on European Stationary Cycle, ESC)



Source: Dieselnet (2018)

4.2.3 *Meteorological Data Collection*

To achieve the objectives of the research meteorological variable are used as inputs in the final modelling, at least basic parameters are necessary to start the study, such as: temperature, wind speed, pressure, precipitation, wind direction, among others. The monitoring of meteorological variables in the State of Ceará (including Fortaleza municipality) has been carried out by FUNCEME (Fundação Cearense de Meteorologia e Recursos Hídricos) since its inception in 1972. The monitoring activities are developed following three lines of action: (i) Gross Data Collection; (ii) Data Analysis and Consistency and (iii) System Development and Integration.

Currently the data collection network operated by the institution includes Conventional Pluviometers, Automatic Data Collection Platforms, Meteorological Radar and Meteorological Satellites and its operation and control is performed in the Hydro meteorological and Environmental Monitoring Room continuously and in real time. From the raw data collected, analysis and consistency are performed through the application of specialized techniques, detecting inconsistent data, thus improving the quality of information so that it can be made available to society to technical and academic issues. The current methodologies of data collection used by FUNCEME are (FUNCEME, 2018):

a) Conventional pluviometers: To monitor precipitation, FUNCEME has a conventional pluviometer network composed of 550 pluviometers, distributed in the state of Ceará according to a spatial density of 280km^2/pluviometer. This configuration allows all municipalities and their main districts to be monitored;

b) Data Collection Platform (PCD): PCDs are electronic devices that allow the automatic collection and transmission of hydro meteorological and environmental data. The network of PCD's operated by FUNCEME is made up of 76 stations, distributed in four types: meteorological, agro meteorological, hydro meteorological and agro-hydro meteorological, depending on the set of sensors used. This network performs the automatic data collection on air temperature, relative air humidity, atmospheric pressure, wind speed and direction, precipitation, solar radiation, soil temperature, soil moisture and soil heat flux, among others. These data are transmitted through the Brazilian satellites integrated with the French satellites, as well as telephone modems;

c) Meteorological Radar: Meteorological radars are remote sensors used primarily to map the spatial distribution of precipitation, to describe the nature of cloud particles, and to determine the movement of precipitating systems. The use of meteorological radar as a tool to support meteorology and hydrology has been increasing, especially in regions where the spatial-temporal variability of precipitation distribution is high, as observed in the state of Ceará. With a coverage area that reaches the maximum radius of 120 kilometers, this radar allows the monitoring of precipitation over the entire capital metropolitan region of Ceará (Fortaleza city and surrounding municipalities) and several municipalities in the coastal region, as well as part of the Atlantic Ocean. In its present technical configuration, the equipment allows a continuous monitoring within its area of coverage, allowing the visualization of the meteorological phenomena that is used for the visual monitoring of precipitating systems;

d) Meteorological satellites: Monitoring by meteorological satellites has been carried out by FUNCEME since the end of the 1980s and uses two types of satellites: the NOAA series polar orbiting satellites and the METEOSAT series geostationary orbit satellites. A satellite of geostationary or geosynchronous orbit is one that orbits in the equatorial plane on Earth at an altitude of approximately 36,000 km with equal angular speed of the planet, which allows the almost continuous monitoring of the planetary disc facing the satellite. For its location, at 0° longitude, the images of the METEOSAT satellite allow visualizing the Northeast of Brazil and the adjacent Atlantic Ocean, which allows the monitoring of the systems operating in the region, such as the Vortex Vortexes of the Upper Air (VCAS) High Volcanic Cyclonic (VCAN), which cause precipitation during the pre-rainy season (November to January), the influence of cold fronts, undulating disturbances from the east, Mesoscale Convective Complexes (CCM), Instability Lines and Convergence Intertropical Zone.

The elementary data collected by FUNCEME with the described methodologies will be used as inputs in meteorological pre-processor in LEZ modelling step to calculate complex meteorological inputs to air quality model, such as: boundary mixing height, friction velocity, among others.

4.2.4 Air Pollutant Concentration Data Collection within the LEZ

Two strategies of data collection of atmospheric pollutants concentration will be used in the method, classic methodologies will be applied, active and passive samplers. For active sampling, pumps and airflow controllers will be used, requiring batteries or electricity for continuous operation, through a structure that holds pollutants (CETESB, 2017c).

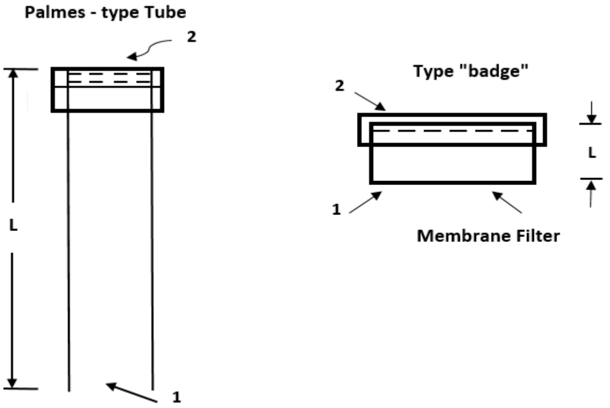
The active sampling can be performed as continuous sampling, discontinuous and without pre-concentration. Continuous sampling is based on the appropriate and automated combination of sampling and analysis systems via analyzers or monitors, with the advantage of results in a short time. Discontinuous samplings are performed by non-automated sampling methods, with established time and analysis of the material collected in the laboratory. In case of non-pre-concentration, plastic bags, canisters, have limitations in relation to the volume of the sample collected and may be insufficient in case of low concentrations (CRUZ, 2008).

According to Cruz (2002), the application of such techniques is often ineffective both by the continuous need for energy and by the need for trained personnel to operate the equipment. These factors make it impossible to collect samples in regions where such requirements are not available. The sampler, monitor or passive dosimeter is defined as one that does not use electric energy or batteries, and there is no active movement of air through the sampler, consequently there is no need to calibrate air flows (measure volume), nor are small and easy to transport, built in the form of a tube or emblem, with the ability to fix gaseous compounds or atmospheric vapors through chemical substrate, in open or closed environments, and can be left in the field for long periods, from hours to months.

Ease of handling favors the use of these devices, also in the monitoring of personal exposure in work environments. The fixation rate is controlled by physical processes, such as permeation and diffusion (CRUZ, 2002). The exposure time varies depending on the pollutant concentration in atmosphere and the absorption capacity of the device.

Due to the low cost, a significant number of samplers can be installed, including in several places simultaneously and, consequently, important information about the geographic and spatial distribution of the pollutants under study (PORFÍRIO, 2008). One of the disadvantages of passive samplers is that they do not distinguish transient episodes of high and low concentrations in a given period and are not indicated as a reference method for air monitoring in international and national standards, and the accuracy of calculated concentrations are lower when compared do active samplers (CRUZ, 2007). Figure 18 shows the passive collection scheme developed by Palmes and Lindeboom (1979):

Figure 18 - Palme-Type tube for gas data collection based on the 1st Fick Law of Mass Transfer



Source: CETESB (1998)
Notes: L = Tube Length
1. Sampler Air Input
2. Absorbent Filter

The strategy for data collecting active and passive pollutant concentration data will include the data previously observed in the definition stage of the area, especially links with the formation of urban canyons. The collectors will be distributed along the observed area, covering all the geographic distribution of pilot Low Emission Zone defined area, being collected sections with the lowest H/W ratios up to the highest ratio streets, and the green areas present in the region, with the objective to include the differences of traffic flow related to lowest and highest buildings and the capacity/accuracy of the applied air quality modelling tool.

The passive data collectors will make sampling of fourteen days in a roll, all with the same time of absorption of the pollutants observed, which will be one of the most important pollutants reduced in Low Emission Zones, NO_2. The active collectors will perform collections of 24 hs running, being able to collect data, Particulate Matter with up to 10 micrometers.

4.2.5 Laboratory Analysis of Air Pollutant Concentrations

Prior to the passive and active data collection, the reagents and filters for the data collection will be prepared in a chemical laboratory. Subsequent to the collection of concentration with the active and passive devices, the equipment will be analyzed in the laboratory, allowing the observation of the concentrations of each pollutant and its collection mechanism.

The data processing of collected air pollutant concentrations will be performed through the construction of the regression function, for the calculations of the pollutants collected by the passive samplers. The values will be obtained by means of spectrophotometry and chromatography techniques, and the Particulate Matter will be based in gravimetric analysis to calculate the concentrations. The PM mass is accumulated in the filtering membrane, by gravimetry, and the filters are weighted before and after the data collection, through 24 hours, and divided by the total sampled volume, reaching the PM concentrations.

This procedure finishes the real data acquisition step, the next topic presents the description of Low Emission Zone Assessment modelling step.

4.3 Third Step: LEZ Modelling

The final objective of the methodological proposal is to observe the behavior of atmospheric pollution within the region selected as pilot Low Emission Zone. For this purpose, travel demand, emissions and air quality modelling tools will be used to analyze the impacts of LEZ in air pollutant concentration reductions.

As inputs to the air quality model, vehicular flows, vehicle classification, vehicle pollutant emission data and meteorological parameters are requirements for the application of the tool. As a result, traffic models, emission models of vehicles and meteorological models will be used to enable the final modeling of the Low Emission Zone.

4.3.1 Travel Demand Modelling in Urban Area

In order to acquire travel demand output data, TRANUS modelling platform will be used because it is capable of providing aggregated data of traffic volumes as a function of the Low Emission Areas being characterized as restrictive measures at a strategic level, being necessary data of traffic volumes with lower detail levels. In addition, TRANUS modelling tools is capable of export travel output data as GIS shapefiles, necessary to integration with emission modelling methodology. The modelling tool must be calibrated to Fortaleza reality, in order to estimate reliable travel demand data, considering the particularities of this Brazilian region. The volumes estimated using TRANUS modelling platform will be compared to traffic data previously extracted from SCOOT (described in section 4.1.1) and adjusted (calibrated), when necessary.

One of the first decisions to be made in the calibration process concerns the zoning, in other words, the delimitation of the analyzed region and how it will be subdivided.

One of the TRANUS manuals (BARRA *et al.*, 2012) describes how to define the areas. Recognizing that the number of zones has an effect on the whole modelling process, the manual goes against common sense that the larger amount of zones, the model better. Still according to him, the results also depend on the quality of information available. As an example, the demographic information is usually found in units of small areas, since they usually see census data; however, the jobs and travel numbers between zones generate less precise information. In the manual description is not defined a rule for the number of zones, since this detail depends directly on the purpose of the study, but points out that an urban model has about 100 zones per million of population. In urban applications, these zones are smaller in the denser regions. In TRANUS, there is no need for homogeneity of sectors between zones, including a zone may have only one type of them. However, homogeneity must be internally verified in each zone, relative to transportation supply.

In TRANUS, subdivisions also occur in terms of activities, what means that how many and which sectors will be used. These sectors are defined according to the the desired application, as well as the most convenient units to represent them. This make possible to make an adaptation of the model for urban and regional applications, as well as to allow incorporating peculiarities of the local culture. Most applications share the population in at least three socioeconomic groups and the sectors of productive activities are subdivided into three or four types (BARRA *et al.*, 2012). As an example, the application of Belo Horizonte divided the population into three sectors according to household income; and the activities sectors in five types of activities: educational, governmental, industrial, health and services (WERNECK, 2015).

A third decision in this case concerns the temporal representation of each subsystem. Some input data depends directly on the simulation period considered, for example: the average frequency of public transportation routes, the total roads and land rental prices, for example. This makes all results in the same time unit of this input data. It is common for models of land use (and activities) are represented on a different time scale of the transportation model. In an urban application, such as the implementation of Low Emission Zones, monthly units are probably the most convenient way of representing wages and expenses, while a simulation may be sufficient to represent the transportation subsystem, and this representation can be generated as GIS shapefiles to further analysis (TRANSPORTATION DEVELOPMENT BRANCH, 1999).

The transportation network can be exported to TRANUS from a GIS database, through 4 network files: (i) Nodes: the file must specify zone centroids (where the trips generated by the zones enter the transport network); (ii) Links: physical ways (streets, train ways, highways, and if needed cycleways and pedestrian ways), shared by different operators or exclusive; (iii) Opers: list of transit routes and their characteristics (for e.g. buses, trains, planes); (iv) Routes: geographical description of the routes, specifying the links they pass by and whether they stop at a link (making transfers possible) (PUPIER, 2013). The GIS shapefiles generated in TRANUS will bring information of traffic volumes and average speed, in order to be used as input to emission modelling, described in next section.

4.3.2 Travel Demand Modelling Integrated to Emission Modelling

To estimate emissions in Fortaleza city road network, the outputs of travel demand modelling step will be used to generate the aggregated emission maps. The volume flows will be disaggregated to all vehicle type proportions, considering: (i) vehicle technologies (PROCONVE standards); (ii) fuel type consumption (such as alcohol, gasoline, diesel, LPG and Flex vehicles); (iii) vehicle types (buses, trucks, passenger cars, vans and motorcycles).

The emission modelling will be applied as input in air quality modelling step, therefore, it is important that the emission estimation is performed as precisely as possible. In the model, it is possible to provide activity data at different levels (level 1-4).

To move up in levels means that more detailed information is needed. However, to get a reliable emission estimate it is necessary to have detailed data on vehicle fleet and mileage data. Level 1 only requires the number of vehicles and total mileage per vehicle category. Level 2 requires split per vehicle sub category (and fuel type). Level 3 requires a further split into engine size (passenger cars), and gross vehicle weight (trucks and buses). Finally, level 4 requires a further split into the emission details. In addition, information is needed regarding the sulphur content of the fuel and the ambient temperature (DCE, 2014). This study will apply detail level 4, seeking for higher precision in emission estimates for the air quality analysis.

The methodology will use emission factors from the CETESB for NO_x, CO and Exhaust PM_{10}, and COPERT IV model (Version 10) for Non-Exhaus PM_{10}, together with assumptions for specific vehicle type/emission information, which will ve used for Fortaleza.

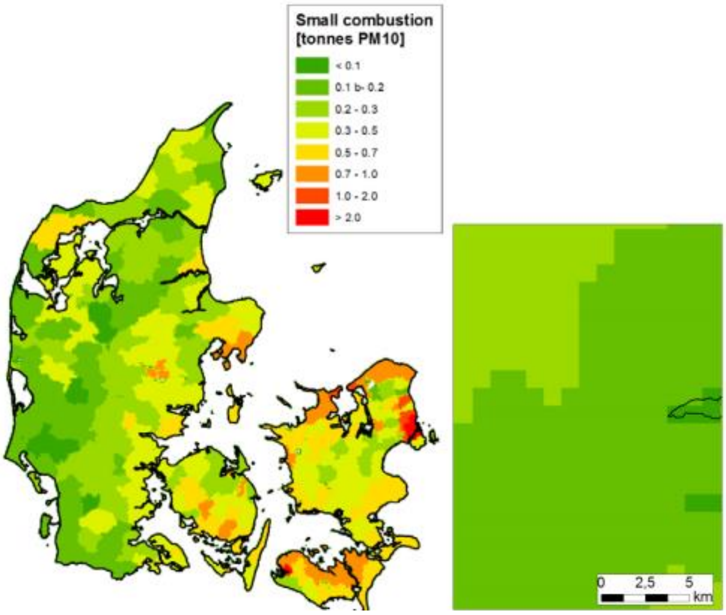
The database contains the emission factors and the queries calculating the emissions. From the database the results can be exported to MS Excel, where they serve as input to the spatial emission distribution. In addition, the emission factors will include default values (summarized in Brazilian inventory) and also the revised emission factors will be included in the modelling.

The revised emission factors for Brazilian fleet have been studied by Krecl *et al.* (2018), and suggest increments to national emission factors due to underestimations in the methodology.

The revised emission factors will be included in emission modelling step and also in street level air pollution modelling step. This approach will seek to analyze the differences between the modelling with default and revised values to Fortaleza city reality, considering that the emission factors have been revised in Londrina-PR reality (UBM calibration differences).

The output from the emission models must represent the geographical distribution of the emission at the exact location (X,Y) is needed (for air quality modelling step), the resolution for this output will 1 x 1 km grid cells and these grid cells will present emission information in tons/year (BRANDT *et al.*, 2013). Figure 19 presents an example of emission estimation and the needed resolution for the air quality modelling step.

Figure 19 - Representation of emission estimations in Denmark



Source: DCE (2014)

The vehicle distribution will be presented AADT (Annual Average Daily Traffic) of roads in urban areas is determined for each grid cell based on the assumption that roadwork is distributed in the same proportion as the area of urban and rural areas within each grid cell. This approach is chosen over an analysis of the entire road network since it is far less labor intensive and since it is assumed that the benefit to the total uncertainty will be insignificant, the purpose (modelling of air quality) taken into account (BRANDT *et al.*, 2013).

The emissions estimated in grid cells will be applied in THOR-AirPAS system as inputs to Urban Background Model, seeking to estimate urban background pollutant concentrations, presented in section 4.3.4.

4.3.3 Meteorological Parameters Pre-Processor Modelling

For the beginning of air quality modelling with the dispersion model, the modelling of the meteorological parameters will be prepared previously, with a pre-processing of meteorological parameters within the pilot Low Emission Zone analyzed area.

The meteorological pre-processor works as an interface between the data of the meteorological variables and the air quality models. To this end, the meteorological pre-processor is used to calculate complex parameters with the available data from a meteorological station (real data collected previously). These data may include wind speed and direction, air temperature, humidity, pressure, precipitation intensity, net radiation balance, surface heat flux, cloud cover, building model, urban canyon and heat island formation, mixing layer and atmospheric stability. These are then processed to provide more complete and systematic information about a three-dimensional computational grid. (ANDRONOPOULOS and BARTZIS, 2009)

Considering the pre-processor present in the THOR-AirPAS air quality modeling system, the OSPM model requires wind speed, wind direction, temperature and global radiation and pollution data in urban area as input. Other meteorological data should be obtained by station in urban area (Top of buildings) or near surface station. Atmospheric chemical data and transport models can also be used optionally in case of data acquisition. (DCE, 2014)

The meteorological pre-processor that will be used to calculate the complex variables is embedded in OML-Highway model, described by Olesen and Brown (1988). Each hour, the module computes a mechanical and, during daytime, a convective mixing height (MH) and selects the larger one as the actual value. A minimum of 150 m and a maximum of 3500 m are enforced, however. The mechanical mixing height is calculated from Equation 7 (ZILITINKEVICH, 1972):

$$MH = c_1 * \frac{u_*}{|f|} \tag{7}$$

Where:

c_1 = 0.25;

u_* = friction velocity;

$|f|$ = coriolis parameter = $2 * \omega * \sin\ (Latitude)$.: (ω = 7.292 * 10^{-5}).

The pre-processor is also capable of calculating friction velocity (u_*) and convective velocity (u), both necessary as inputs in air quality modelling.

It starts with the observed temperature profile and uses observed or parameterized values of the friction velocity u* and the surface heat flux H_o. If a so-called convective lid is found in the noon sounding, the calculated MHs before noon are multiplied by the ratio of the base height of this lid to the calculated MH at the time of the radiosonde ascent. The integration in the afternoon is continued with the profile from the noon sounding. If a so-called sustained lid is found also in the following midnight sounding, the interpolated lid height is used as an upper bound for the MH (BERKOWICZ and PRAHM, 1982).

The pre-processor is also capable of estimation of aerodynamic resistances, expressed in terms of flux-profile relationships, based on Monin-Obukhov theory, represented by Monin-Obukhov Length (L), presented in Equation 8 (MONIN and OBUKHOV, 1954):

$$L = -\frac{{u_*}^3 * \theta_v}{kg(w'\theta_v{}')_s} \tag{8}$$

Where:

u_* = friction velocity;

θ_v = mean virtual potential temperature;

k = Von Kármán constant (≈ 0.40);

g = gravitational acceleration;

$(w'\theta_v{}')_s$ = surface virtual potential temperature flux.

The meteorological (basic and advanced) parameter will be used in the final modelling steps, as inputs to air quality modelling and Low Emission Zone Assessment.

4.3.4 Air Quality Modelling – Real Traffic Analysis

The final substep in this research consists in estimate air pollutant concentrations in street levels within the pilot area analyzed as Low Emission Zone. For this, the air quality assessment carried out in this research will be based in the concepts presented in THOR – AirPAS system (DCE, 2014), which includes three levels of air pollution contribution:

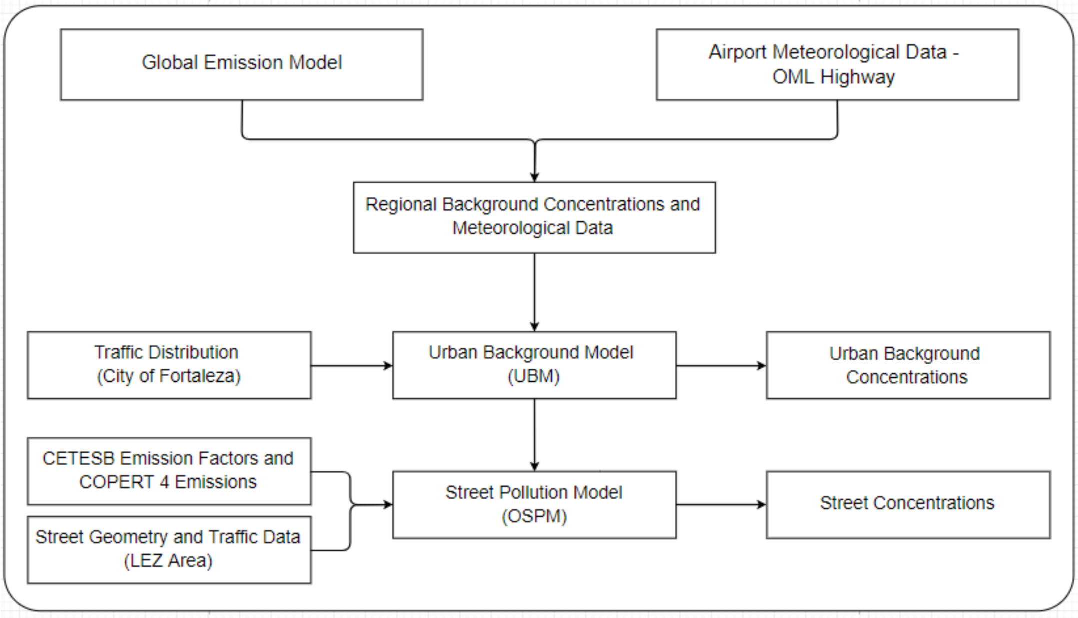
a) Regional background concentrations: influenced by emissions on the Southern hemisphere, including national emissions and represent the whole South America (long range) transported air pollution. Regional concentration levels represent the air quality of a larger area and air quality monitor stations measuring regional can be classified as regional, rural, or background stations. The regional concentrations provide contributions to the background concentrations to a city like Fortaleza, for example;

b) Urban background concentrations: include the regional contribution and the contribution from emissions of the city, in this case, Fortaleza. Urban background concentrations exhibit geographical variation over a city depending of the geographical variation of emissions and represent the air quality at roof top level or in a park and are not directly influenced by a single nearby local emissions. Air quality monitor stations that measure urban background concentrations are usually located in a park or on top of a building and are referred to as urban background stations. The increment from regional to urban background concentrations is named the urban increment;

c) Street concentrations: concentrations in the street at a receptor height of 2-3 m. Street concentrations include the urban and regional background concentrations, and the contribution from vehicle emissions in the specific street. The difference between the street and urban background concentrations is called the street increment. Air quality monitor stations that measure street concentrations are usually placed at sidewalks or kerbs and are named kerb, street or traffic stations.

The air pollution assessment in this research will make an adaptation to original Danish methodology, due to impossibility of applying DEHM model to Brazilian global position, the IFS (Integrated Forecast System) will be used to estimate regional background concentrations, the meteorological data will be based in FUNCEME measurements and OML-Highway pre-processor and emission factors will based in CETESB inventory (for NO_x and Exhaust PM_{10}) and COPERT IV (for Non-Exhaust PM_{10}). The conceptual outline adjusted methodology for Fortaleza air quality assessment is given in Figure 20.

Figure 20 - Adjusted methodology for air quality assessment in Fortaleza



Source: Author

The modelling method starts with IFS global model to estimate the regional background concentrations including Fortaleza. The IFS is a global numerical weather prediction system, an extension of previous NWP (Numerical Weather Prediction) for forecast and assimilation of atmospheric composition (FLEMMING *et al.*, 2015).

The transport by advection, convection and turbulent diffusion of the chemical tracers in IFS model uses the same algorithms as developed for the transport of water vapour in the NWP in its application. The advection is simulated with a three-dimensional semi-Lagrangian method, which applies an interpolation of the departure values. The semi-Lagrangian advection does not formally conserve mass, therefore a global mass fixer is applied. This effect is presented in Diamantakis and Flemming (2014) and Flemming and Huijnen (2011). The mass fixer according to McGregor (2005) is used for the runs in this model because of the overall best balance between the results and computational cost. The IFS model considers dry deposition, wet deposition, gas-phase chemistry reactions and photolysis rates.

The vertical turbulent transport in the atmospheric boundary layer is estimated by a first order K-diffusion closure. The surface emissions are injected as lower boundary flux in the diffusion procedure and the lower boundary flux condition also take into account for the dry deposition flux based on the projected surface mass mixing ratio in an implicit way. The vertical transport by convection is simulated as part of the cumulus convection. It applies a bulk mass flux method, proposed by Tiedtke (1989). The method considers deep, shallow and mid-level convection. Clouds are represented by a single pair of plumes which determine the upstream and downstream mass fluxes.

The operator splitting between the transport and the sink and source terms follows the implementation for water vapour (BELJAARS *et al.*, 2004). Advection, diffusion and convection are medelled in a step-by-step sequential process. The sink and source processes are simulated in parallel using an intermediate update of the mass mixing ratios with all transport tendencies. At the end of the time step tendencies from transport and sink and source terms are added together for the final update the concentration fields. Resulting negative mass mixing ratios are corrected at this point by setting the updated mass mixing ratio to a “chemical zero”. This model methodology is capable of estimate hemispheric Ozone (O_3), Nitrogen Monoxide (NO), Nitrogen Dioxide (NO_2), Carbon Monoxide (CO) and disaggregated particles, such as: seasalt (0.03~0.5 µm, 0.5~5 µm, 5~20 µm); dust (0.03~0.55 µm, 0.55~0.9, 0.9~2 µm), hydrophilic organic matter, hydrophobic organic matter, hydrophilic black carbon and hydrophobic black carbon. These pollutants will be used as regional background concentration inputs in THOR Air-PAS system.

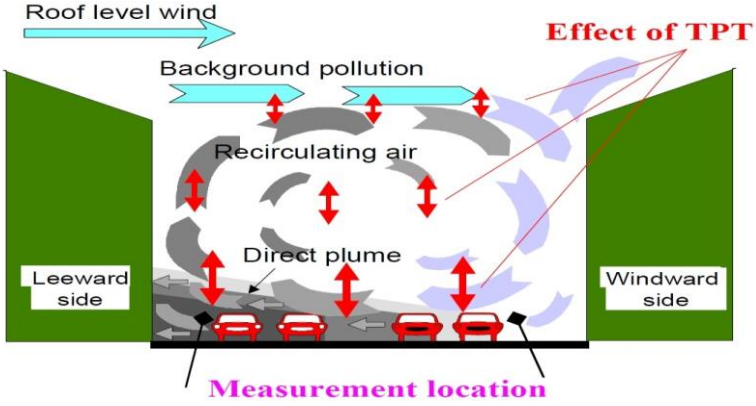
Concerning urban background concentrations, the Urban Background Model (UBM) will be used, embedded with THOR Air-PAS system. UBM is set-up to calculate the following pollutants: NO_x (nitrogen oxides), NO_2 (nitrogen dioxide), O_3 (ozone), SO_2 (sulphur dioxide), CO (carbon monoxide), TSP (total suspended particulate matter), PM_{10} (particles less than 10 µm in diameter) and $PM_{2.5}$ (particles less than 10 µm in diameter) (DCE, 2014).

The Urban Background Model estimate concentrations at a receptor by numerical integration of contribution from each of the individual area sources along each actual wind direction path upwind to 30 km from the receptor, where the rural background is used as boundary condition (in this case, results from the IFS model). The horizontal diffusion is assumed to follow a Gaussian function. The step size is 50 m in the numerical integration both along the wind direction and perpendicular to the wind direction, where horizontal diffusion is taken into account (BERKOWICZ, 2000).

Horizontal dispersion is accounted by averaging the calculated concentrations over a given wind speed, dependent wind direction sector centered on the average wind direction with the average concentration and the angle between the mean hourly wind direction and the wind speed dependent sector, where emissions are contributing to the receptor. The angle is wider for low wind speeds and narrower for higher wind speeds (KUMAR *et al.*, 2018).

With the urban background concentrations estimated using UBM, the final step described in this method is estimating street concentrations using OSPM (Operational Street Pollution Model). OSPM is an atmospheric dispersion model for simulating the dispersion of air pollutants in so-called street canyons. In OSPM concentrations of traffic-emitted pollution are calculated using a combination of a plume model for the direct contribution and a box model for the recirculating part of the pollutants in the street. The NO_2 concentrations are calculated taking into account NO-NO_2-O_3 chemistry and the residence time of pollutants in the street. The model is designed to work with input and output in the form of one-hour averages (BERKOWICZ *et al.*, 1997). Figure 21 represents how pollution flow is modelled within urban canyons in OSPM.

Figure 21 - Flow pattern inside a street canyon for near perpendicular roof level wind direction and schematic picture of the main processes assumed in OSPM



Source: DES (2018)

A receptor point in leeward position is affected by the direct plume showing considerably higher concentrations than a receptor in windward position being exposed to the less concentrated recirculating air. The turbulence produced by the moving traffic (TPT) is acting in addition to the turbulence created by the roof level wind. This leads to a faster dispersion of the direct plume but also to an improved air exchange at roof level between the street canyon and the background air (DES, 2018). The OSPM is capable of estimate the following pollutants: NO_x, NO_2, O_3, CO, PM_{10} and $PM_{2.5}$.

With the final step of the adapted methodology prepared, the modelling process will be applied to current traffic conditions, considering: vehicle technologies (current PROCONVE standards); fuel used and fleet composition. The final street pollution concentrations will be compared to real measured concentrations (Step 2 of this method) in order to validate the modelled street pollution. The proposed scenarios for Low Emission Zone Assessment will be described in the next section.

4.3.5 Air Quality Modelling – Scenario Proposal Analysis

As described in state-of-art Low Emission Zone Analysis, LEZ must be assessed considering stages and public feasibility of restrictions. The European countries are the most advanced in Low Emission Zone implementation in the world, therefore the scenario proposition in this sub step will follow the restrictions suggested in European cities, however, the Brazilian particularities will be considered due to difference in technology and public measures feasibility. In this regard, Table 7 presents the summary of European Low Emission Zones and the most important restrictions in consolidated LEZ throughout the countries. It is important to know that Brazilian fleet does not met EURO 6 equivalent standards (the upgrade is scheduled to 2023 only).

Table 7 - Summary of European Low Emission Zones

Country	**Number of LEZ**	**Applicable Vehicles**	**National Framework/Legislation**
Austria	3	High Duty Vehicles (HDV’s)	Yes
Czech Republic	1	High Duty Vehicles (HDV’s)	No
Denmark	6	High Duty Vehicles (HDV’s)	Yes
Finland	1	Buses and Refuse Trucks	No
France	1	High Duty Vehicles (HDV’s)	No
Germany	~70	All vehicles except motorcycles	Yes
Greece	1	All vehicles within LEZ; Vehicles > 2.2 tonnes outside LEZ	No
Italy	~92	Varies depending the LEZ	No
Netherlands	13	High Duty Vehicles (HDV’s)	Yes
Portugal	1	Cars and High Duty Vehicles (HDV’s)	No
Sweden	8	All vehicles > 3.5 tonnes	Yes
UK	3	HDVs and in London also large commercial cars.	No
Europe	~200	---	No

Source: Sadler Consultants (2014)

Considering all vehicles exposed in Table 7, seven scenarios will be proposed in this method, as follows: (i) Buses scenario: all buses will be restricted to PROCONVE 4 (EURO 2 equivalent) and the modelling will redistribute the buses equally; (ii) Trucks scenario: all trucks will be restricted to PROCONVE 4 (EURO 2 equivalent) and the modelling will redistribute the trucks equally; (iii) Pickups, SUV’s and Vans scenario: all pickups, suv’s and vans will be restricted to PROCONVE 4 (EURO 2 equivalent) and the modelling will redistribute them equally; (iv) Passenger Cars scenario: all passenger cars will be restricted to PROCONVE L2 and the modelling redistribute them equally; (v) Buses and Trucks scenario: all buses and trucks will be restricted to PROCONVE 4 (EURO 2 equivalent) and the modelling will redistribute them equally; (vi) Buses, Trucks and “PickupSUVVans” scenario: all buses, trucks and pickups, SUV’s and vans will be restricted to PROCONVE 4 (EURO 2 equivalent) and the modelling will redistribute them equally; and the last, most restrictive scenario (in order to analyze the potential of Ultra Low Emission Zone) (vii) ULEZ scenario: all HDV’s will be restricted to PROCONVE 7 (EURO 5 equivalent) and the passenger cars will be restricted to PROCONVE L2 (EURO 2 equivalent) and the modelling will redistribute them equally.

The experiments and results carried out in this research following the proposed method will be presented in Chapter 5 and further discussed in Chapter 6.

5 EXPERIMENT AND RESULTS DISCUSSION

In order to achieve the general objective established in Chapter 1, the experiment performed in this research contemplates the three steps described in flowchart (Figure 13) proposed in previous chapter.

To fulfillment of the three steps, data, equipments and computational tools have been acquired to execute the Low Emission Zone Assessment. First, the municipality of Fortaleza has been contacted to provide land use information (year of 2015), including lot distribution, with commercial and residential data, simultaneously with populational information in order to choose as LEZ pilot area with most commercial lots and high populational density. In addition to land use information, traffic information has been collected with Fortaleza traffic control department (CTAFOR, using SCOOT system), in streets available (through cameras and inductive loop-type sensors). Emission factors data have been acquired with Brazilian inventory (CETESB), meteorological data with FUNCEME and for real concentration data collection, an active particulate matter equipment has been used, and for NO_2, passive data collectors have been specially built to carry out the research.

In addition to modelling step of this research, GIS, geometric draw and tridimensional visualization tools have been used. The partnership with Aarhus University – Denmark made possible the modelling in the method final step, including AirGIS, IFS, UBM and OSPM, which combined constitutes THOR –AirPAS air quality system methodology from mobile sources.

5.1 Low Emission Zone Analysis: Fortaleza Particularities Adaptation

Observing the most important Low Emission Zones in the world, the European zones are shown to be the most advanced restrictive measures, and the British, Danish and German (among others) LEZ’s are considered to be references among that region, therefore, the adaptation of Fortaleza Low Emission Zone take into account the European restrictive measures, especially the reference countries previously mentioned, with Brazilian specificities. First, the focused change in Low Emission Zones is the efficiency in vehicle construction with regard of pollutant emissions. For example, German and British LEZ’s have been established in 2008, in Berlin and London, respectively, and initially aimed to reduce pre-EURO 3 high duty vehicles (OBRECHT *et al*., 2017). In January 2012, the London LEZ has been upgraded to EURO 4 high duty vehicles (TRANSPORT FOR LONDON, 2018).

Finally, the most restrictive, therefore with higher potential in air quality improvement is the Ultra Low Emission Zone, which will start in 2019 in inner London and be expanded to north and south circular region of London in 2021, the affected vehicles are (TRANSPORT FOR LONDON, 2018):

- Motorcycles that do not meet Euro 3 standards;
- Gasoline cars and vans that do not meet Euro 4 standards (roughly the equivalent to not being more than fifteen years old for cars in 2021);
- Diesel cars and vans that do not meet Euro 6 standards (roughly the equivalent to not being more than six years old for cars in 2021).

This study has taken into account the exposed European restrictions (also presented in Table 1), however, Brazilian technologies have been considered to Low Emission Zone imposition. The technology advance in most pollutant diesel vehicles and respective equivalent European standards is presented in Table 8.

Table 8 - Brazilian and European emission standards comparison for heavy duty diesel engines

PROCONVE Standard	**EURO Equivalent**	**Pollutants (g/kWh)**		
		CO	**NO_x**	**PM**
P1 (1989)	Pre - EURO	Just smoke index		
P2 (1996)	Pre - EURO	11.2	14.40	0.60
P3 (2000)	EURO I (1991)	4.9	9.0	0.40
P4 (2002)	EURO II (1996)	4.0	7.0	0.15
P5 (2006)	EURO III (2000)	2.1	5.0	0.10
P6 (skipped)	EURO IV (2006)	1.5	3.5	0.02
P7 (2012)	EURO V (2008)	1.5	2.0	0.02
P8 (2023)	EURO VI (2014)	1.5	0.4	0.01

Source : Adapted from ICCT (2016); CONAMA (2017)

In Europe, EURO 7 standard is been planned to be implemented until 2021, however, this technology evolution will focus in CO_2 reduction, while in Brazil, EURO VI equivalent (PROCONVE 8) will be imposed in 2023 only (CONAMA, 2017). Considering this, the analyzed LEZ in this study has adjusted the restrictions to EURO 2 equivalent (PROCONVE 4), and the extreme imposition, the Ultra Low Emission Zone, has restricted to updated Brazilian technology, EURO V equivalent (PROCONVE 7) for heavy duty vehicles (trucks, buses and vans), and EURO II equivalent to light duty vehicles, due to delayed Brazilian standards.

In addition to PROCONVE standards, the fuel technology used in Fortaleza has also been adapted to Low Emission Zone Assessment, therefore, vehicle fleet disaggregated by fuel has been acquired with Brazilian vehicle department (DENATRAN, 2015), presented in Table 9.

Table 9 - Fortaleza Vehicle Fleet Distribution

Type of Fuel	**Passenger Cars**	**Pickups, SUV's and Vans**	**Trucks**	**Buses**	**Motorcycles**	**Total Type**
Gasoline	231805	0	0	0	194921	426726
Alcohol	33482	0	0	0	0	33482
Diesel	0	47742	27336	10797	0	85875
Flex	358505	0	0	0	78437	436942
Flex/LPG	30211	0	0	0	0	30211
Total	654003	47742	27336	10797	273358	1013236

Source: Adapted from DENATRAN (2015)

The vehicle fleet is presented by DENATRAN in a disaggregated distribution, however, for this study, the vehicle fleet is aggregated in groups of vehicle types, in order to carry out the data adequate to modelling tools format, such as: (i) Passenger Cars: light duty vehicles, including cars and gasoline/flex compact SUV's (Brazilian legislation prohibits diesel fuelled small cars); (ii) Pickups, SUV's and Vans: all pickups, larger SUV's and Vans fuelled by diesel; (iii) Trucks: Light, Medium and Heavy Trucks, the major Brazilian truck fleet is fueled by diesel (with few minimum exceptions, disregarded in this study, for modelling purposes); (iv) Buses: Micro buses, urban buses and coaches are considered in this type, the major Brazilian bus fleet is fueled by diesel (with few minimum exceptions, disregarded in this study, for modelling purposes) and; (v) Motorcycles: all motorcycles in Fortaleza fleet, only fueled by gasoline/flex vehicles. This aggregation level has been constructed in function of the third step in suggested methodology, due to OSPM model in the last sub step on THOR – AirPAS system.

The imposition to PROCONVE 4 (for diesel vehicles) in initial scenarios has been suggested due to feasibility of the pilot Low Emission Zone. In Brazilian economic reality, start the restrictive measure with higher imposition (e.g. PROCONVE 5 standard) would be unfeasible in initial stages (e.g. the bus urban fleet in Fortaleza could have tax incentives to upgrade vehicle composition, using new vehicles or retrofitted older technologies).

In or order to make the tax incentive feasible and upgrade the technologies in LEZ, the municipality of Fortaleza should promote the policy. To the public, environment and health issues must be comprehended as more important than traffic congestion. Therefore, public support for the policy depended not only on the policy per se, but on its objectives. To gain support from society, the Low Emission zone should won acceptance as an environmental measure, the municipality has to emphasize the health benefits of reduced air pollution, making the restrictive measure more appealing to the public (WANG *et al*., 2017).

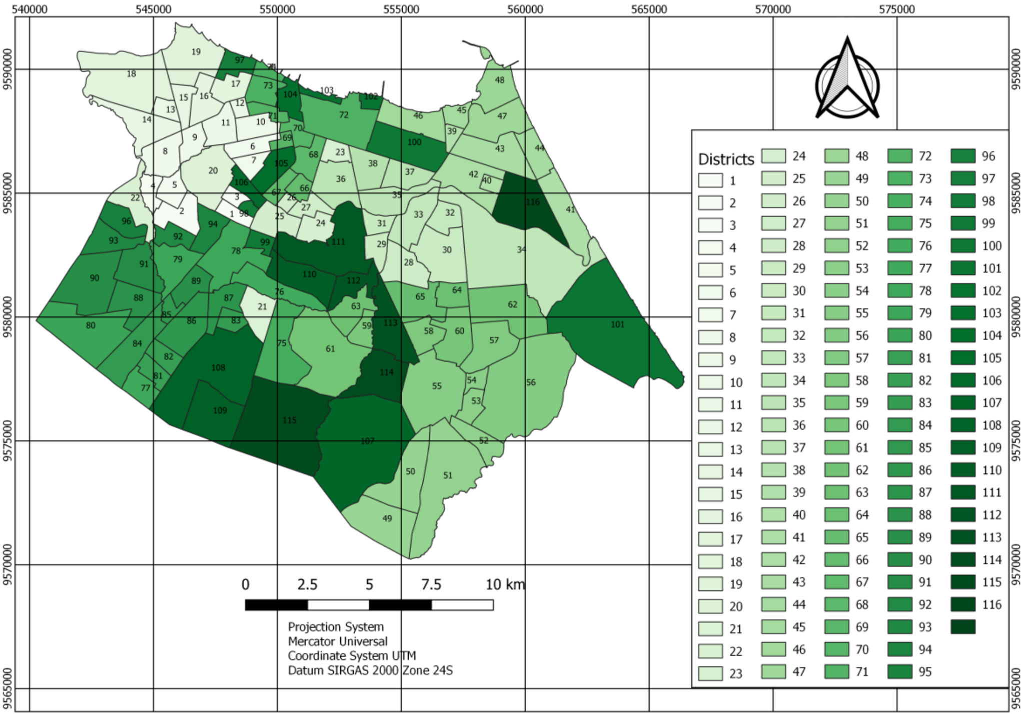
To supervise the operation of Low Emission Zone, Fortaleza municipality could implement stickers in regulated vehicles that meet the specifications. In addition, cameras could be installed in the pilot studied area to check license plates, in order to application of fines to vehicles without attending requirements (LUO, 2009).

With these adaptations to Fortaleza fleet described, the next step will present the established method to observe socioeconomic data and land use of Fortaleza municipality, in order to suggest the pilot LEZ area with significant presence of residential and commercial buildings.

5.2 Socioeconomic and Land Use Data Analysis

For this research, the first step in land use analysis was carried out with Brazilian Geographic Institute (IBGE), regarding the number of resident population and private domiciles, by disctrict, in order to analyze which districts have higher populational density, presented in Figure 22 and respective representation (number of districts) in Table 10.

Figure 22 - Representation of all Fortaleza Districts



Source: Fortaleza (2015)

Table 10 - Population and Domiciles by Districts in Fortaleza

(to be continued)

District	Resident Population	Private Domicile	District	Resident Population	Private Domicile
Aerolândia (29)	11.360	3.289	Jardim Cearense (83)	10.103	2.907
Aeroporto (Base Aérea) (111)	8.618	2.382	Jardim das Oliveiras (28)	29.571	8.286
Alagadiço (10)	14.505	4.414	Jardim Guanabara (13)	14.919	4.287
Aldeota (100)	42.361	13.723	Jardim Iracema (15)	23.184	6.570
Alto da Balança (31)	12.814	3.772	João XXIII (92)	18.398	5.231
Álvaro Weyne (17)	23.690	6.705	Joaquim Távora (38)	23.450	7.419
Amadeu Furtado (7)	11.703	3.374	Jóquei Club (São Cristóvão) (94)	19.331	5.670
Ancuri (50)	20.070	5.829	José Bonifácio (23)	8.848	2.834
Antônio Bezerra (8)	25.846	7.478			
Arraial Moura Brasil (103)	3.765	1.050	Lagoa Redonda (56)	27.949	7.948
Autran Nunes (4)	21.208	5.609	Lagoa Sapiranga (Coité) (62)	32.158	8.629
Barra do Ceará (19)	72.423	20.279	Manoel Sátiro (86)	37.952	11.124
Barroso (114)	29.847	8.321			
Bela Vista (106)	16.754	4.922	Maraponga (87)	10.155	3.064

Table 10 - Population and Domiciles by Districts in Fortaleza

(continuation)

District	Resident Population	Private Domicile	District	Resident Population	Private Domicile
Bonsucesso (79)	41.198	11.740	Mondubim (Sede) (108)	76.044	22.094
Bom Jardim (88)	37.758	10.462	Messejana (sede) (55)	41.689	12.174
Bom Futuro (26)	6.405	1.970	Meireles (46)	36.982	12.690
Benfica (68)	8.970	2.975	Mata Galinha (59)	6.273	1.907
Cais do Porto (48)	22.382	6.321	Monte Castelo (71)	13.215	3.838
Cajazeiras (113)	14.478	4.412	Montese (25)	25.970	7.946
Cambeba (60)	7.625	2.154	Mucuripe (45)	13.747	4.447
Canindezinho (84)	41.202	11.544	Padre Andrade (Cachoeirinha) (9)	12.936	3.758
Carlito Pamplona (73)	29.076	8.317	Pan-Americano (3)	8.815	2.580
Castelão (63)	5.974	1.640	Papicu (43)	18.370	5.549
Centro (72)	28.538	9.717	Parangaba (78)	30.947	9.225
Cidade 2000 (40)	8.272	2.624	Parque Araxá (69)	6.715	2.007
Cidade dos Funcionários (65)	18.256	5.338	Parque Dois Irmãos (75)	27.236	7.479
Coaçu (52)	7.188	2.038	Parque Iracema (58)	8.409	2.735
Cocó (42)	20.492	6.439	Parque Manibura (64)	7.529	2.040
Conjunto Ceará I (93)	19.221	5.473	Parque Presidente Vargas (77)	7.192	1.947
Conjunto Ceará II (96)	23.673	6.743	Parque Santa Rosa (Apolo XI) (81)	12.790	3.725
Conjunto Esperança (82)	16.405	4.753	Parque São José (85)	10.486	3.017
Conjunto Palmeiras (95)	36.599	9.113	Parquelândia (6)	14.432	4.428
Couto Fernandes (98)	5.260	1.555	Parreão (27)	11.072	3.209
Cristo Redentor (97)	26.717	7.237	Passaré (61)	50.940	14.957
Curió (54)	7.636	2.100	Paupina (51)	14.665	4.214
Damas (67)	10.719	3.513	Pedras (49)	13.420	3.700
Demócrito Rocha (1)	10.994	3.275	Pici (Parque Universitário) (20)	42.494	11.871
Dendê (21)	5.637	1.539	Pirambú (74)	17.775	4.775
Dias Macedo (112)	12.111	3.481	Planalto Ayrton Senna (109)	39.446	11.037
Dom Lustosa (5)	13.147	3.831	Praia de Iracema (102)	3.130	1.089
Edson Queiroz (34)	22.210	5.901	Praia do Futuro I (41)	6.630	1.925
Engenheiro Luciano Cavalcante (30)	15.543	4.472	Praia do Futuro II (44)	11.957	3.442

Table 10 - Population and Domiciles by Districts in Fortaleza

(conclusion)

District	Resident Population	Private Domicile	District	Resident Population	Private Domicile
Estância (Dionísio Torres) (37)	15.634	4.844	Prefeito José Walter (115)	33.427	9.593
Farias Brito (70)	12.063	3.605	Presidente Kennedy (11)	23.004	6.670
Fátima (36)	23.309	7.251	Quintino Cunha (14)	47.277	13.146
Floresta (16)	28.896	8.270	Rodolfo Teófilo (10)	19.114	5.673
Genibaú (22)	40.336	11.343	Sabiaguaba (101)	21.170	5820
Granja Lisboa (90)	52.042	14.425	Salinas (33)	4.298	1.225
Granja Portugal (91)	39.651	10.791	São João do Tauape (35)	27.598	8.301
Guajeru (53)	6.668	1.855	Serrinha (110)	28.770	8.274
Guararapes (32)	5.266	1.546	Siqueira (80)	33.628	9.253
Henrique Jorge (2)	26.994	7.816	Varjota (39)	8.421	2.792
Itaóca (99)	12.477	3.734	Vicente Pinzon (47)	45.518	12.712
Itaperi (76)	22.563	7.055	Vila Ellery (12)	7.863	2.292
Jacarecanga (104)	14.204	4.167	Vila Pery (89)	20.645	6.093
Jangurussu (107)	50.479	14.252	Vila União (24)	15.378	4.513
Jardim América (66)	12.264	3.624	Vila Velha (47)	61.617	17.326

Source: IBGE (2010)

In addition to population data by districts, a data survey was carried out together with municipality of Fortaleza, regarding the number of commercial and residential establishments, by district, and was possible to build the Table 11, which presents the percentage of discriminated types, denominated in this study as: (i) Commercial (C); (ii) Mixed (M) or; (iii) Residential (R).

Table 11 - Classification of districts by percentage of commercial and residential buildings

(to be continued)

Districts	% Commerce	Type	% Residential	Districts	% Commerce	Type	% Residential
Aerolândia	0.71%	M	0.61%	Itaóca	0.71%	M	0.61%
Aeroporto (Base Aérea)	0.13%	M	0.10%	Itaperi	0.13%	M	0.10%
Alagadiço	0.60%	M	0.43%	Jacare-canga	0.60%	C	0.43%
Aldeota	4.40%	C	1.07%	Jangurussu	4.40%	C	1.07%
Alto da Balança	0.66%	R	0.95%	Jardim América	0.66%	M	0.95%

Table 11 - Classification of districts by percentage of commercial and residential buildings
(continuation)

Districts	% Commerce	Type	% Residential	Districts	% Commerce	Type	% Residential
Álvaro Weyne	1.48%	R	1.78%	Jardim Cearense	1.48%	M	1.78%
Amadeo Furtado	0.80%	M	0.98%	Jardim das Oliveiras	0.80%	R	0.98%
Ancuri	0.31%	M	0.37%	Jardim Iracema	0.31%	R	0.37%
Antônio Bezerra	1.33%	R	1.65%	Joquei Clube (são Cristovão)	1.33%	M	1.65%
Arraial Moura Brasil	0.27%	M	0.38%	José Bonifácio	0.27%	R	0.38%
Autran Nunes	0.37%	M	0.56%	José de Alencar	0.37%	R	0.56%
Barra do Ceará	1.41%	R	2.01%	Lagoa redonda	1.41%	M	2.01%
Barroso	0.68%	M	0.71%	Lagoa da Sapiranga (Coité)	0.68%	R	0.71%
Bela Vista	0.69%	R	0.97%	Manoel Sátiro	0.69%	R	0.97%
Benfica	1.42%	C	0.66%	Manuel Dias Branco	1.42%	M	0.66%
Bom Futuro	0.94%	C	0.56%	Maraponga	0.94%	M	0.56%
Bom Jardim	1.07%	R	1.35%	Mata Galinha	1.07%	M	1.35%
Bonsucesso	1.60%	R	1.89%	Messejana (Sede)	1.60%	R	1.89%
Cais do Porto	0.49%	M	0.44%	Mondumbim (Sede)	0.49%	C	0.44%
Cajazeiras	0.38%	M	0.38%	Montese	0.38%	R	0.38%
Cambeba	0.48%	M	0.48%	Mucuripe	0.48%	M	0.48%
Canindezinho	0.43%	R	0.73%	Padre Andrade (Cachoeirinha)	0.43%	M	0.73%
Carlito Pamplona	1.15%	R	1.56%	Pan-americano	1.15%	M	1.56%
Castelão	0.22%	M	0.17%	Papicú	0.22%	M	0.17%
Centro	17.10%	C	1.96%	Parangaba	17.10%	C	1.96%
Cidade 2000	0.38%	R	0.87%	Parque Dois Irmãos	0.38%	R	0.87%
Cidade dos Funcionários	1.20%	M	1.07%	Parque Iracema	1.20%	M	1.07%
Coaçu	0.21%	M	0.13%	Parque Manibura	0.21%	M	0.13%
Cocó	0.50%	C	0.21%	Parque Presidente Vargas	0.50%	M	0.21%
Conjunto Ceará I	0.72%	R	1.74%	Parque Santa Rosa (Apolo XI)	0.72%	M	1.74%

Table 11 - Classification of districts by percentage of commercial and residential buildings *(continuation)*

Districts	% Commerce	Type	% Residential	Districts	% Commerce	Type	% Residential
Conjunto Ceará II	1.10%	R	2.16%	Parque São José	1.10%	M	2.16%
Conjunto Esperança	0.41%	M	0.61%	Parreão	0.41%	R	0.61%
Conjunto Palmeiras	0.21%	R	1.22%	Passaré	0.21%	M	1.22%
Couto Fernandes	0.23%	M	0.17%	Paupina	0.23%	M	0.17%
Cristo Redentor	0.65%	R	1.70%	Pedras	0.65%	M	1.70%
Curió	0.15%	M	0.17%	Pici (Parque Universitário)	0.15%	M	0.17%
Damas	0.88%	C	0.58%	Pirambú	0.88%	C	0.58%
De Lourdes	0.09%	M	0.07%	Planalto Ayrton Senna	0.09%	M	0.07%
Demócrito Rocha	0.77%	M	0.91%	Praia do Futuro I	0.77%	M	0.91%
Dendê	0.09%	M	0.05%	Praia do Futuro II	0.09%	M	0.05%
Dias Macedo	0.43%	R	0.80%	Prefeito José Walter	0.43%	R	0.80%
Dom Lustosa	0.60%	M	0.78%	Presidente Kennedy	0.60%	R	0.78%
Edison Queiroz	0.43%	R	0.69%	Quintinho Cunha	0.43%	R	0.69%
Engenheiro Luciano Cavalcante	0.61%	R	0.93%	Rodolfo Teófilo	0.61%	R	0.93%
Estância (Dionísio Torres)	2.01%	C	0.53%	Sabiaguaba	2.01%	M	0.53%
Farias Brito	1.20%	C	0.92%	Salinas	1.20%	M	0.92%
Fátima	1.99%	C	0.91%	São Bento	1.99%	M	0.91%
Floresta	0.50%	R	1.22%	São João do Tauapé	0.50%	R	1.22%
Genibaú	0.04%	M	0.01%	Serrinha	0.04%	M	0.01%
Gentilândia	0.41%	M	0.27%	Siqueira	0.41%	M	0.27%
Granja Lisboa	0.97%	R	1.89%	Varjota	0.97%	R	1.89%
Granja Portugal	1.03%	R	1.64%	Vincente Pinzon	1.03%	R	1.64%
Guajeru	0.18%	M	0.28%	Vila Ellery	0.18%	R	0.28%
Guarapes	0.28%	M	0.16%	Vila Pery	0.28%	C	0.16%

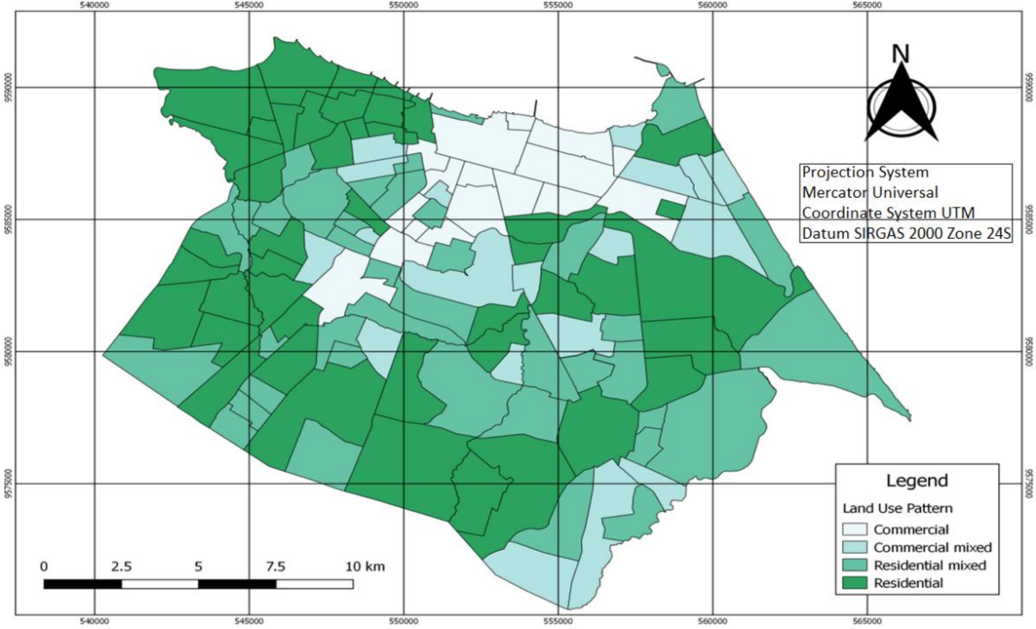
Table 11 - Classification of districts by percentage of commercial and residential buildings *(conclusion)*

Districts	% Commerce	Type	% Residential	Districts	% Commerce	Type	% Residential
Henrique Jorge	1.50%	R	1.83%	Vila Velha	1.50%	R	1.83%
				SUM	100.00%	---	100.00%

Source: Fortaleza (2015)

The data collected with IBGE and Fortaleza municipality provide information of the three defined categories, however, this data presentation does not allow the visualization throughout the municipality of higher presence of commercial districts. The Geographic Information System tool QGis (in this project, QGis 2.18 open source was applied) to build the representation, with the percentage data obtained. The generated representation using QGis is shown in Figure 23.

Figure 23 - Representation of districts characterization in Fortaleza



Source: Author

The digital representation shows that the northern region of Fortaleza municipality is predominantly commercial. In addition to the high concentration of commercial buildings, the region also has a high population density, as shown in Table 10, where a large number of people live, mainly due to increased number of high residential buildings within the area.

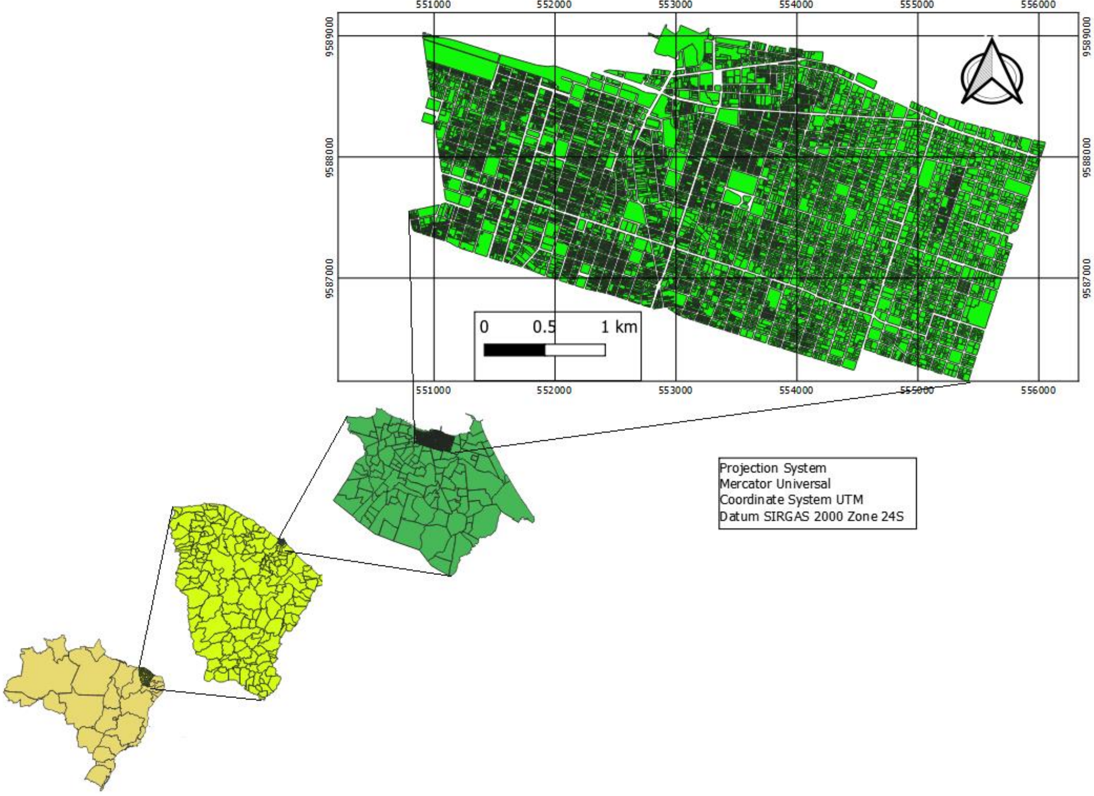
The northern region of Fortaleza also presents higher number (considering Fortaleza standards) of inductive loop-type sensors in streets and traffic data collector cameras, important to carry out traffic data collection, in order to expand the annual average daily traffic (AADT) through travel demand modelling. The estimation of AADT has been modelled and calibrated using the average daily traffic collected with the sensors and will be presented in traffic modelling section.

The next section will present the Low Emission Zone pilot area, following the pre requisites described in method section, including strategies to air pollution data collection.

5.3 Area Definition to be Observed as Pilot Low Emission Zone

The study area defined as pilot Low Emission Zone has been chosen in northern region of Fortaleza municipality, including districts: Centro, Praia de Iracema, Meireles and Aldeota, also the transition districts of Farias Brito, Benfica, José Bonifácio, Dionísio Torres and Joaquim Távora. The defined area is presented in Figure 24, with approximation of pilot LEZ highlighted in Fortaleza.

Figure 24 - Highlighted observed pilot LEZ in Fortaleza, Ceará – Brazil

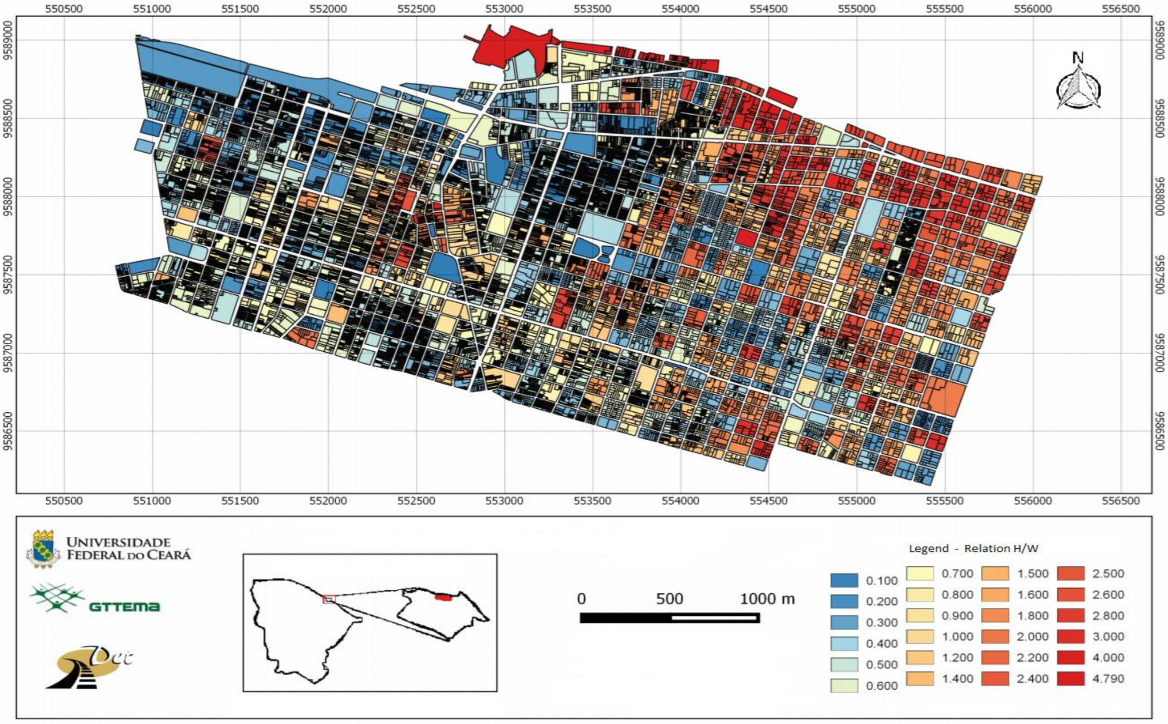


Source: Author

The choice of study area followed the criteria established in the proposed methodology (Chapter 4), where the representation presented in Figure 23 shows high density of commercial buildings, and Table 10 presented the chosen districts as highly populated. In addition, these districts have the best structure of inductive loop-type sensors and cameras to traffic data collect, and the area has been intentionally defined to future extensions, due to implementation in stages (small area, potentially extendable).

Understanding that Low Emission Zone must be implemented in steps, the suggested pilot area is intentionally smaller than the area showed in Figure 24, with potential to expand gradually with air pollution reduction and population acceptance, including the districts of Jacarecanga, Rodolfo Teófilo, Gentilândia, Fátima, Mucuripe, among other districts. The defined pilot Low Emission Zone area is represented in Figure 25.

Figure 25 - Representation of region defined as pilot Low Emission Zone



Source: Author

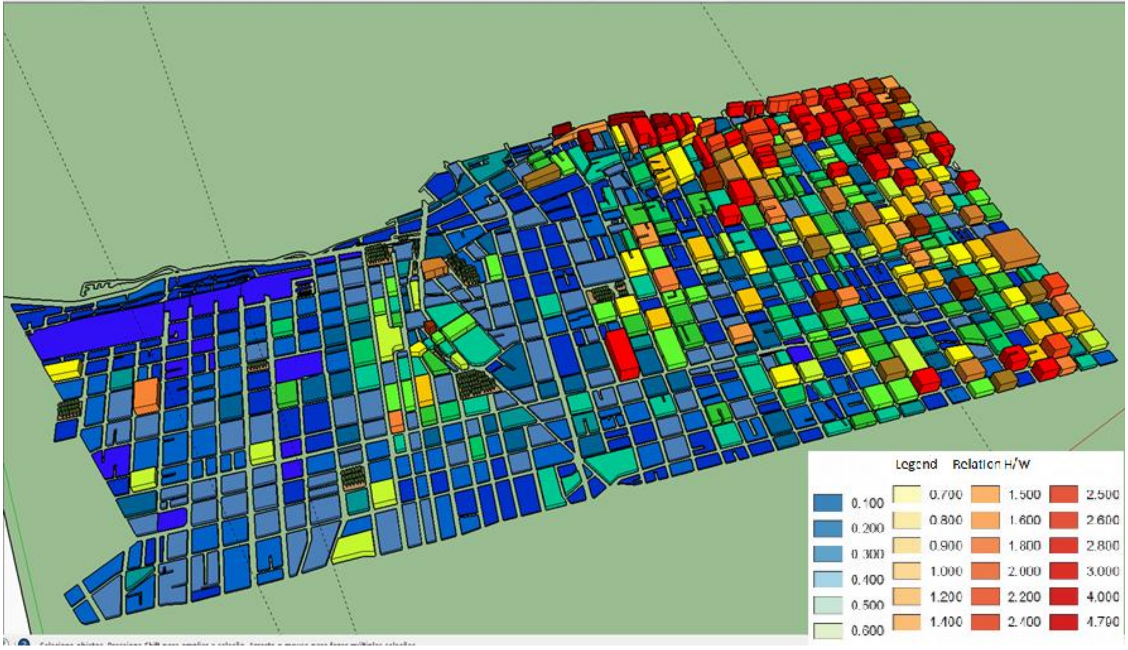
The defined area measures approximately 11 km^2 and its boundaries have been defined within the economic center of Fortaleza (northern region). Fortaleza land use database provide all heights with the building footprints shape files, which can be used to visualize using GIS tools, and be analyzed to observe the relation with road widths, important to understand air pollution concentrations, especially pollution emitted by vehicles in street levels.

5.3.1 Urban Canyon Formation Analysis within the defined LEZ pilot Area

With the previously established area, analyzes were carried out in building heights and aggregated by lot, in order to observe urban canyon formations. The data of building models were obtained with Fortaleza municipality infrastructure department, and aggregated with Microsoft Excel spreadsheets and plotted in AutoCAD to further visualization.

The geometric drawing obtained through AutoCAD (in this project, Caliper AutoCAD 2013 Professional was applied) was expanded to a second modelling tool, in three-dimensional modelling, with the help of SketchUP (in this project, Google SketchUP Pro 2015 was applied) computational package, being possible to observe, through the distinct color palette, with the blue tone for buildings of lesser height to buildings of bigger heights with red tone. The three-dimensional model of the area is shown in Figure 26.

Figure 26 - Three-dimensional model of the Low Emission Zone highlighting differences in building structures

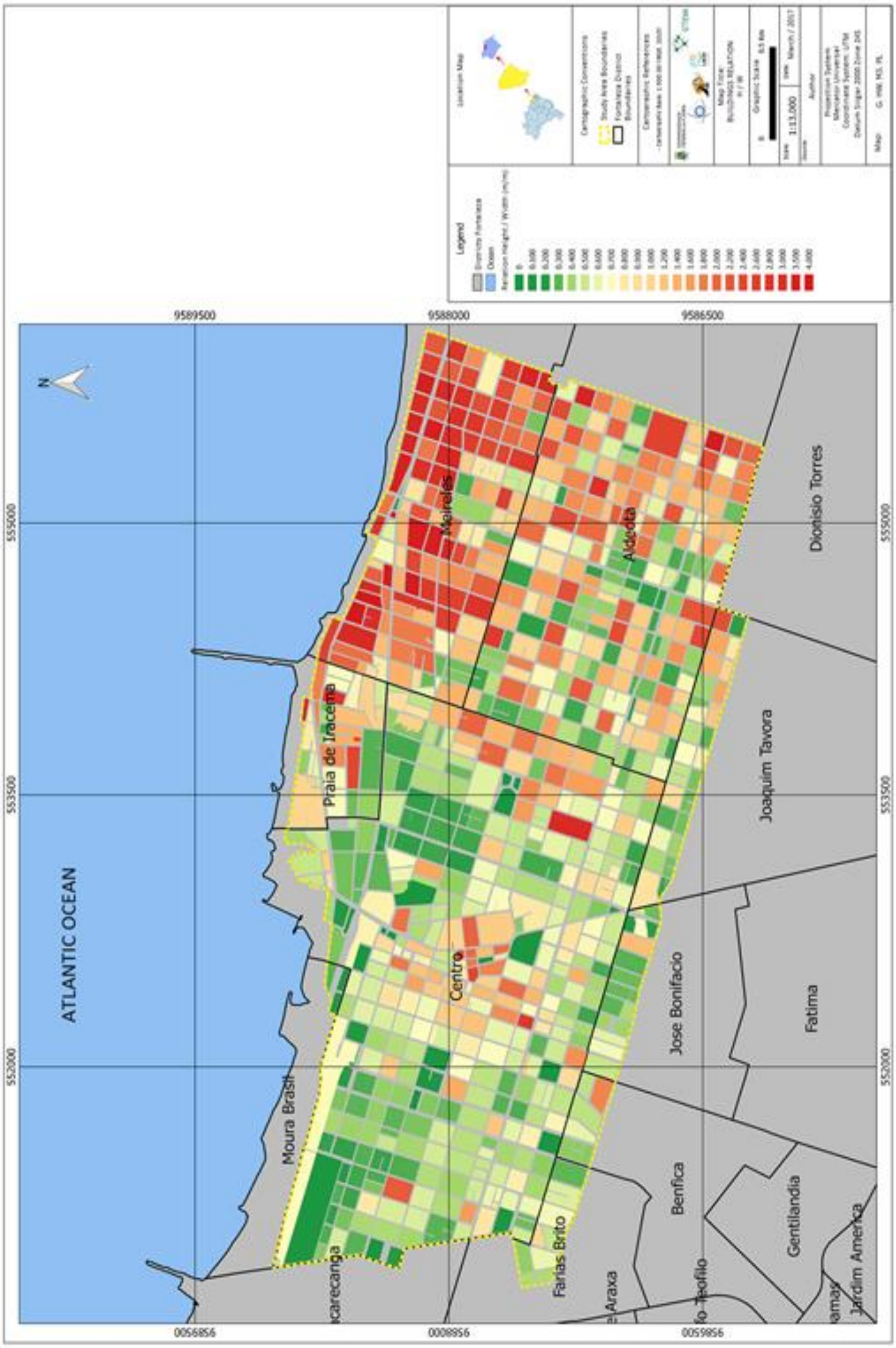


Source: Author

It can be observed that, besides the progression of building heights have been standardized in blue to red color, some micro regions were observed and defined as green areas. The areas designated as green areas were defined as a function of the high tree concentration and vegetation in the Zone, mostly due to the presence of parks and forests. The green areas have also been object of study in the air pollution data collection and air quality modelling step of this research, been considered with the building footprints in modelling codification step. Building heights and their relation with street widths are crucial do estimate air pollution.

Subsequent to building heights and widths data acquisition within the pilot Low Emission area, all urban canyons formed in the North, South, East and West directions in all lots of the region were mapped. For mapping the canyons, all H / W ratios were calculated, per lot, and the maps were constructed using the QGis tool. In order to illustrate the study carried out in this research, the east map is shown in Figure 27, identifying canyon formations.

Figure 27 - Thematic Map of urban canyon formation, East perspective



Source: Author

5.4 Traffic Data Collection Equipment, Vehicle Emissions, Meteorological Parameters and Atmospheric Air Pollutant Concentrations

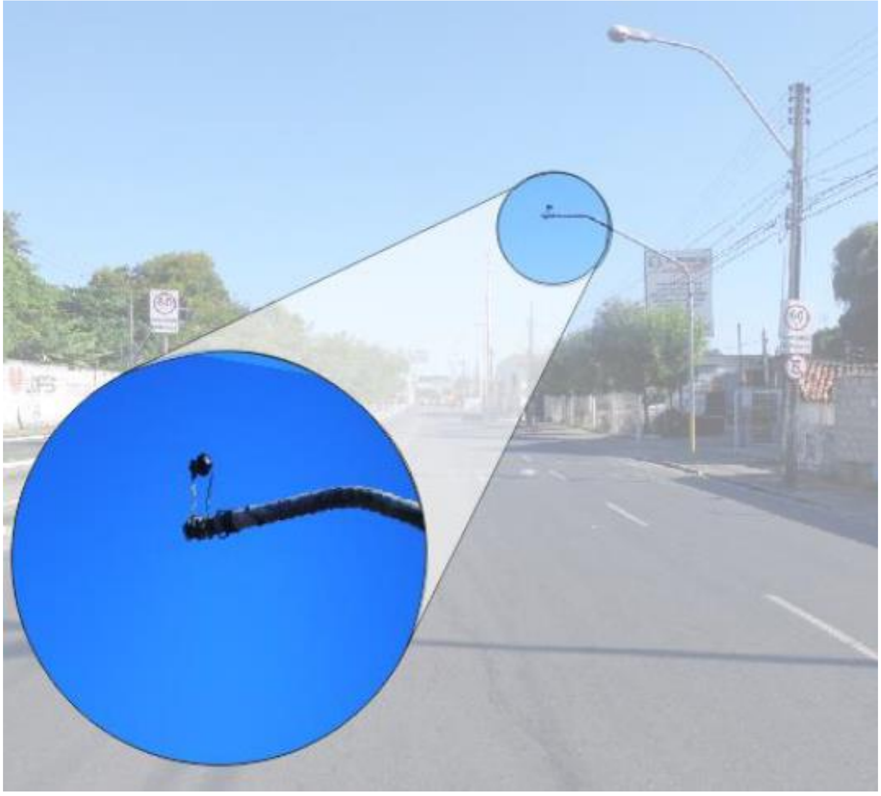
In this section is presented the real data collection of all necessary parameters for this research, including: (i) traffic data equipments; (ii) vehicle emission factors; (iii) meteorological basic data and; (iv) atmospheric air pollutant concentration equipments.

5.4.1 Traffic Data Collection Equipments and Annual Average Daily Traffic (AADT)

As mentioned in method section, the traffic data has been collected with SCOOT system, which used inductive loop-type sensors and video cameras to acquire samples on monitored streets.

The samples are monitored during intervals of 15 minutes and expanded to whole day by SCOOT system. In Fortaleza, only main traffic streets are monitored due to financial issues. The video cameras and inductive loop-type sensors are shown in Figure 28 and Figure 29, respectively.

Figure 28 - Fortaleza municipality traffic monitoring video camera



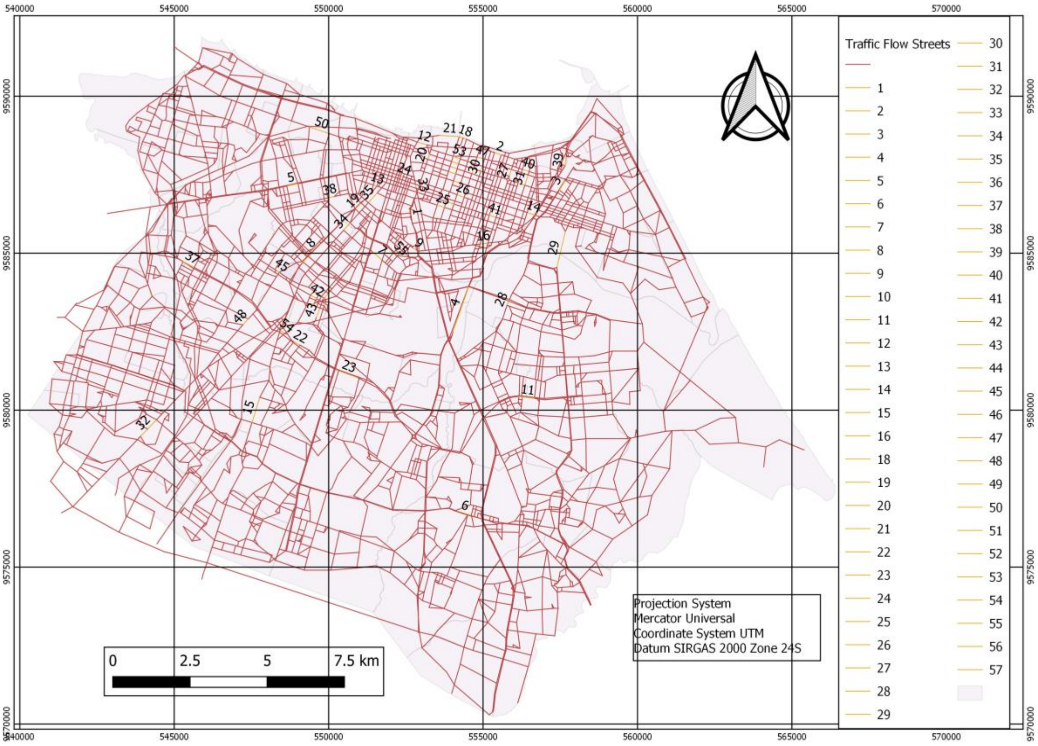
Source: Alves (2014)

Figure 29 - Typical inductive loop-type sensor in Fortaleza street

Source: Alves (2014)

The Annual Average Daily Traffic (AADT) was collected using SCOOT system for monitored streets in Fortaleza and is shown in Table 12, the respective streets are shown in Figure 30.

Figure 30 - Representation of monitored streets in Fortaleza by SCOOT



Source: Author

Table 12 - Annual Average Daily Traffic (AADT) in monitored Fortaleza Streets

Street	AADT	Street	AADT
Aguanambi (1)	53 000	Br. De Studart (30)	31 501
Abolição (2)	49 977	Sen. Virgílio Távora (31)	30 980
Eng. Santana Junior (3)	49 316	Osório De Paiva (32)	30 958
Raul Barbosa (4)	47 068	Visc. Do Rio Branco (33)	30 217
Bezerra De Menezes (5)	46 429	Joao Pessoa (34)	28 469
Pres. Costa E Silva (6)	46 027	Universidade (35)	28 266
Borges De Melo (7)	45 765	Equador (36)	28 250
José Bastos (8)	45 255	Sen. Fernandes Távora (37)	27 486
13 De Maio (9)	43 399	Jovita Feitosa (38)	25 822
Santos Dumont (10)	42 607	Via Expressa AHS (39)	23 477
Oliveira Paiva (11)	41 090	Ana Bilhar (40)	23 006
Pres. Castelo Branco (12)	40 499	Beni De Carvalho (41)	21 864
Domingos Olimpio (13)	39 669	Br. De Sobral (42)	21 817
Pe. Antônio Tomás (14)	38 745	Antônio Fiúza (43)	21 039
Godofredo Maciel (15)	38 709	Gomes De Matos (44)	20 985
Pontes Vieira (16)	38 559	Rua Ceará (45)	20 951
Dom Luís (17)	36 944	Pe. Valdevino (46)	20 936
Hist. Raimundo Girão (18)	36 894	Dep. Moreira Da Rocha (47)	20 895
Carapinima (19)	36 599	Beni De Carvalho	20 847
Dom Manuel (20)	36 497	Augusto Dos Anjos (48)	20 642
Alm. Barroso (21)	35 380	Costa Barros (49)	20 281
Dedé Brasil (22)	35 272	Francisco Sá (50)	19 650
Silas Munguba (23)	35 219	César Rossas (51)	19 070
Duque De Caxias (24)	34 386	Rui Barbosa (52)	18 484
Antônio Sales (25)	34 280	Ten. Benévolo (53)	17 887
Heráclito Graça (26)	33 367	Eduardo Perdigão (54)	17 649
Des. Moreira (27)	32 445	Eduardo Girão (55)	17 094
Rogaciano Leite (28)	32 186	Pereira Filgueiras (56)	15 415
Wahington Soares (29)	50 239	Pinto Madeira (57)	14 748

Source: CTAFOR (2015)

The shown AADT’s will be used in travel demand modelling step to observe the accuracy in calibration of estimated traffic volumes through TRANUS, however, the AADT’s only presents aggregated traffic volumes, not considering classificatory traffic data, which is hugely important to estimate air pollutant concentrations (due to different emission factors from buses, trucks, passenger cars, vans and motorcycles), therefore, classificatory traffic data collections have been carried out to estimate typical vehicle distributions in Fortaleza main traffic streets. The buses traffic flow was also carried out using official Fortaleza bus tables provided by ETUFOR (buses time table daily outputs).

In order to include the variation of Fortaleza municipality traffic type distribution, the classificatory data collection has been carried out both inside and outside the pilot Low

Emission Zone Area. The traffic data collection samples occurred between 07:00 to 10:00 and 21:00 to 24:00, in intervals of 15 minutes, and observed the movement of passenger cars, buses, trucks, vans and motorcycles. The selected streets were: Av. Osório de Paiva, Av. Presidente Castelo Branco, Av. Domingos Olímpio, Av. Imperador, Av. Coronel Matos Dourado, Av. José Bastos, St. Ceará, Av. Bernardo Manuel, Av. Presidente Costa e Silva, Av. Jornalista Tomaz Coelho and Av. Desembargador Gonzaga. The streets were selected due to Fortaleza municipality traffic dispersion (in order to consider traffic in all Fortaleza territory, this will be important to estimate urban background concentrations, which includes all Fortaleza territory and generate concentrations impacted by all vehicles in the city) and also for safety reasons. The aggregated traffic distributed by vehicle type is presented in Table 13.

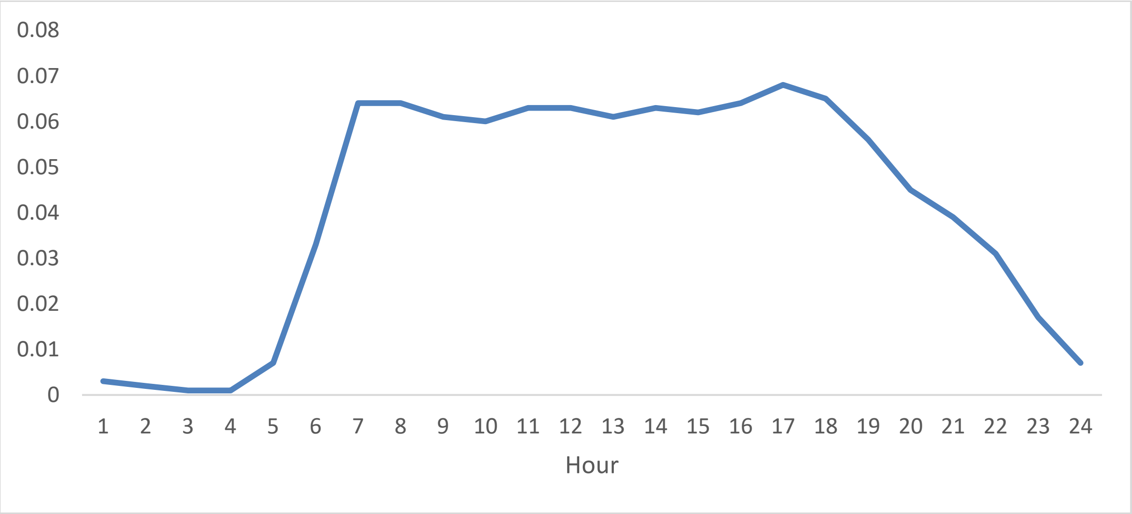
Table 13 - Average traffic proportions in Fortaleza

Average Proportion Passenger Cars	**Average Proportion PickupSUVVan**	**Average Proportion Truck**	**Average Proportion Bus**	**Average Proportion Motorcycle**
0.6268	0.0458	0.0192	0.0247	0.2836

Source: Author

And the final traffic data collected with CTAFOR (with monitoring traffic system) was the hourly traffic distribution throughout the day. For that, counts of the month of October were used, to estimate the percentage of the vehicular flow during the day. This data will be used in modelling step of street level air pollutant concentrations. The traffic distribution is presented in Figure 31.

Figure 31 - Vehicular Flow Distribution throughout the day - Traffic Proportion (Percentage) – Fortaleza



Source: CTAFOR (2015)

With traffic data collected with Fortaleza municipality equipments, the next sub-step of this research consisted of carrying out the survey of the emission factors aggregated by vehicle types used in the modelling stage, presented in the next sub-section.

5.4.2 Vehicle Emission Factors Aggregated by Vehicle Types

In order to adapt Fortaleza fleet to Brazilian official emission factors and vehicle type distribution necessary to carry out the final modelling step (street level air pollutant concentrations), the vehicles have been aggregated in 5 classes: (i) passenger cars; (ii) pickups, SUV's and vans, aggregated in one class designated PickupSUVVan; (iii) trucks; (iv) buses and; (v) motorcycles.

In addition to vehicle classes, the vehicles have been classified by engine sizes/weight, fuel technology distribution within vehicle fleet and emission classes with Brazilian emission factors disaggregation, presented in Table 14.

Table 14 - Fortaleza Vehicle Fleet Aggregated by Engine Sizes and Weight, Fuel Technology Distribution and Emission Classes.

(to be continued)

Vehicle Classes	**Engine Sizes/Weight**	**Fuel Type Distribution**	**Emission Classes**
Passenger Cars	No distinction of engine sizes/weight (just one aggregated type)	Gasoline Ethanol Flex (Gasoline + Ethanol, any proportion) Flex + LPG	Pre L1 L1 L2 L3 L4 L5
Pickups, SUV's and Vans	No distinction of engine sizes/weight (just one aggregated type)	Only Diesel Engines	Brazilian Emission Standard Stages - Comparison with Euro Emission Standard Stages (HDV) Br Standard Year EURO Standard Year Proconve 1 1989 X X Proconve 2 1996 X X Proconve 3 2000 EURO 1 1991 Proconve 4 2002 EURO 2 1996 Proconve 5 2006 EURO 3 2000 Proconve 6 X(Skip) X X Proconve 7 2012 EURO 5 2008
Trucks (No distinction in engines sizes, only in weights)	Light Weight Trucks: (TGW < 10 t) Medium Weight Trucks(10 t <= TGW < 15 t) Heavy Weight Trucks(TGW > 15 t)	Only Diesel Engines	
Buses	Urban Buses Micro Buses Coaches	Only Diesel Engines	

Table 14 - Fortaleza Vehicle Fleet Aggregated by Engine Sizes and Weight, Fuel Technology Distribution and Emission Classes.

(conclusion)

Vehicle Classes	**Engine Sizes/Weight**	**Fuel Type Distribution**	**Emission Classes**
Motorcycles	No distinction of engine sizes/weight (just one aggregated type)	Gasoline	M1 M2 M3
		Flex	

Source: Adapted from CETESB (2017a); DENATRAN (2015)

Considering Fortaleza vehicle fleet, fuel types and emission factor classes, the aggregation of CETESB (Companhia Ambiental do Estado de São Paulo) emission factors have been carried out in order to emission and air quality assessment in modelling final step of the proposed method. The emission factors are shown in Table 15 for pollutants CO, NO_x and PM_{10}.The Brazilian motorcycle emission factor inventory present only three technology categories, due to emission legislation delayed in relation to 4 wheel vehicles.

All light gasoline vehicles have been considered passenger cars, medium sized diesel vehicles have been aggregated as PickupSUVVans. All trucks with TGW > 3.5 tons have been aggregated as light (3.5 tons < Trucks < 10 tons), medium (10 tons < Trucks < 15 tons) and heavy (Trucks > 15 tons). All buses have been disaggregated in urban buses, micro buses and coaches (diesel). Motorcycles have been aggregated in one vehicle type.

Table 15 - Emission Factors by vehicle classes, fuel technology and engine size/weights

(to be continued)

Vehicle Classes	**Emission Factors (g/km)**						
Passenger Cars		PRE	L1	L2	L3	L4	L5
	Gasoline (NO_x)	1.633	1.525	0.64	0.18	0.067	0.022
	Gasoline (CO)	27.667	14.625	5.4	0.64	0.328	0.234
	Gasoline (PM_{10} - Exhaust)	0.002	0.002	0.002	0.001	0.001	0.001
		PRE	L1	L2	L3	L4	L5
	Alco**h**ol (NO_x)	1.333	1.175	0.640	0.163	0.065	0.028
	Alco**h**ol (CO)	16.967	11.325	4.18	0.72375	0.483	0.47
	Alcohol (PM_{10} - Exhaust)	0.002	0.002	0.002	0.001	0.001	0.001

Table 15 - Emission Factors by vehicle classes, fuel technology and engine size/weights *(continuation)*

Vehicle Classes	Emission Factors (g/km)						
Passenger Cars		PRE	L1	L2	L3	L4	L5
	Flex (NO_x)	-	-	-	0.045	0.044	0.027
	Flex (CO)	-	-	-	0.445	0.497	0.267
	Flex (PM_{10} - Exhaust)	-	-	-	0.001	0.001	0.001
		PRE	L1	L2	L3	L4	L5
	FlexLPG (NO_x)	-	-	-	0.17	0.13	0.13
	FlexLPG (CO)	-	-	-	0.38	0.37	0.37
	FlexLPG (PM_{10} - Exhaust)	-	-	-	0.001	0.001	0.001
Pickup SUV Van		P1	P2	P3	P4/P5	P5	P7
	Diesel (NO_x)	2.459	2.490	2.479	2.138	1.697	1.468
	Diesel (CO)	0.274	0.315	0.279	0.488	0.576	0.477
	Diesel (PM_{10} - Exhaust)	0.076	0.082	0.075	0.064	0.039	0.032
Trucks	Light Truck (W < 10 t)	P1	P2	P3	P4	P5	P7
	Diesel (NO_x)	5.790	3.658	3.572	2.774	2.371	0.748
	Diesel (CO)	1.007	0.905	0.493	0.624	0.487	0.063
	Diesel (PM_{10} - Exhaust)	0.357	0.178	0.070	0.057	0.044	0.006
	Medium Truck (10 t < W < 15 t)	P1	P2	P3	P4	P5	P7
	Diesel (NO_x)	7.190	4.543	4.435	3.299	3.002	1.051
	Diesel (CO)	1.250	1.124	0.612	0.637	0.493	0.095
	Diesel (PM_{10} - Exhaust)	0.444	0.221	0.086	0.064	0.055	0.008
	Heavy Truck (15 t < W < 40 t)	P1	P2	P3	P4	P5	P7
	Diesel (NO_x)	11.585	7.319	7.146	5.550	5.117	1.593
	Diesel (CO)	2.014	1.810	0.986	0.958	0.875	0.198
	Diesel (PM_{10} - Exhaust)	0.715	0.355	0.139	0.123	0.082	0.016
Buses	Urban Bus	P1	P2	P3	P4	P5	P7
	Diesel (NO_x)	17.368	10.973	10.713	8.475	8.434	2.665
	Diesel (CO)	3.019	2.714	1.478	1.677	1.925	0.538
	Diesel (PM_{10} - Exhaust)	1.071	0.533	0.209	0.164	0.153	0.021
	Micro Bus	P1	P2	P3	P4	P5	P7
	Diesel (NO_x)	7.185	4.539	4.432	4.769	4.712	1.284
	Diesel (CO)	1.249	1.123	0.612	1.561	0.996	0.159
	Diesel (PM_{10} - Exhaust)	0.443	0.22	0.086	0.11	0.086	0.013
	Coach	P1	P2	P3	P4	P5	P7
	Diesel (NO_x)	13.182	8.329	8.131	6.009	5.581	1.617
	Diesel (CO)	2.292	2.060	1.122	0.999	0.658	0.284
	Diesel (PM_{10} - Exhaust)	0.813	0.404	0.158	0.110	0.085	0.016

Table 15 - Emission Factors by vehicle classes, fuel technology and engine size/weights
(conclusion)

Vehicle Classes	Emission Factors (g/km)			
Motorcycle		M1	M2	M3
	Gasoline (NO_x)	0.163	0.157	0.073
	Gasoline (CO)	4.490	1.800	0.643
	Gasoline (PM_{10} - Exhaust)	0.011	0.004	0.004
		M1	M2	M3
	Flex (NO_x)	-	-	0.050
	Flex (CO)	-	-	0.718
	Flex (PM_{10} - Exhaust)	-	-	0.004

Source: Adapted from CETESB (2017a)

Brazilian emission factor inventory presents exhaust mobile emissions, however, non-exhaust particle emissions are not inventoried by CETESB, therefore, COPERT IV emission factors have been included in this research, in order to carry out an accurate estimation in emission and air pollutant concentrations in modelling step (including all PM_{10} sources). The non-exhaust PM_{10} emission factors from COPERT IV are shown in Table 16.

Table 16 - COPERT IV non-exhaust PM_{10} emission factors (g/km)

Passenger Cars	Pickup SUV Van	Truck	Bus	Motorcycle
0.048	0.07	0.229	0.229	0.018

Source: EEA (2016)

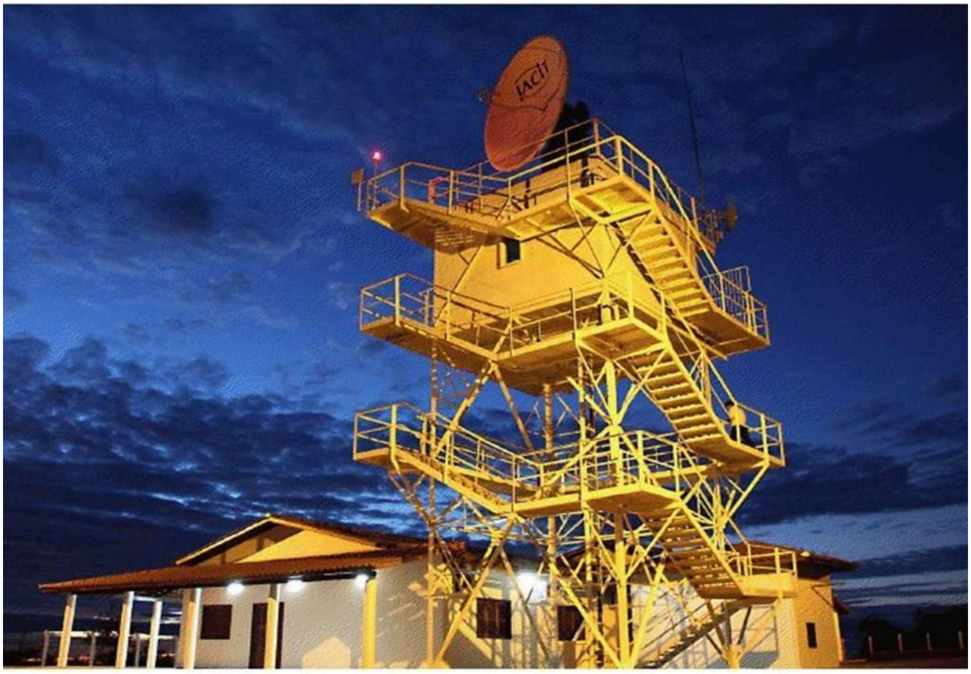
The emission factors presented in COPERT IV inventory for non-exhaust PM_{10} are calculated for any vehicle or fuel type, due to source of these emissions, such as brake, tyre, clutch and road surface wear or already exist in the environment as deposited material and become re-suspended due to traffic induced turbulence (EEA, 2016).

The next sub section will present the meteorology data collection carried out in this research.

5.4.3 Meteorology Data Collection to Low Emission Zone Assessment

The meteorology data collection carried out in this study was attained with Ceará meteorology state company FUNCEME (Fundação Cearense de Meteorologia e Recursos Hídricos). The meteorology data necessary for final modelling step has been acquired with non-urban station. The stationary station used to data collect in year 2017 is shown in Figure 32.

Figure 32 - Stationary Meteorology Monitoring Station (Fortaleza – Passaré)



Source: FUNCEME (2018)

The real meteorology data collected have been disaggregated hourly for all year of 2017, and includes the parameters: (i) temperature (C); (ii) pressure (hPa); (iii) wind speed (m/s); (iv) wind direction (degrees); (v) humidity (%); (vi) precipitation (mm) and; (vii) global radiation (KJ/m^2, which can be converted to W/m^2). These parameters have been chosen due to inputs necessary to run THOR –AirPAS air quality model. The real data acquired with Ceará meteorology station have been used to calculate the more complex parameters necessary to modelling step. To illustrate the weather conditions in Fortaleza, the meteorology collected data is presented in Table 17 for 24 hours in one day of 2017. In addition, the predominant wind directions and wind speed is presented in Figure 33.

Table 17 - Meteorological Data Disaggregated Hourly

(to be continued)

Year	**Day-Month**	**Hour (UTC)**	**Pres. (hPa)**	**Temp. Ar(°C)**	**Humi. Ar(%)**	**Spe (m/s)**	**Dir (Graus)**	**Precip (mm)**	**Rad (KJ/m^2)**	**Rad (W/m^2)**
2017	01-01	1:00	1006.4	28.12	80.6	4.284	125.8	0	0	0
2017	01-01	2:00	1006.2	28.11	78.4	3.977	121	0	0	0
2017	01-01	3:00	1005.8	27.97	79.9	3.663	125.2	0	0	0
2017	01-01	4:00	1005.7	27.76	80.7	2.507	128.2	0	0	0
2017	01-01	5:00	1006.3	27.69	82.3	2.13	143.5	0	0	0
2017	01-01	6:00	1006.9	27.83	82.4	1.915	151.4	0	56.3	15.6

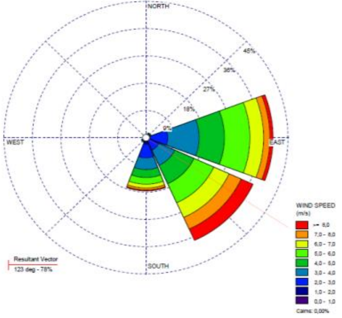
Table 17 - Meteorological Data Disaggregated Hourly

(conclusion)

Year	Day-Month	Hour (UTC)	Pres. (hPa)	Temp. Ar(°C)	Humi. Ar(%)	Spe (m/s)	Dir (Graus)	Precip (mm)	Rad (KJ/m²)	Rad (W/m²)
2017	01-01	7:00	1007.4	28.49	78.6	2.826	145.5	0	548.4	152.3
2017	01-01	8:00	1007.8	29.66	74.2	4.722	141	0	1404.1	390.0
2017	01-01	9:00	1007.9	30.49	68.77	3.67	158.4	0	1780.3	494.5
2017	01-01	10:00	1008.1	31.41	62.4	5.243	135.1	0	2397.1	665.8
2017	01-01	11:00	1007.7	32.18	57.38	5.992	127.8	0	3294.8	915.2
2017	01-01	12:00	1007.2	32.26	55.4	6.74	124.7	0	2864.4	795.6
2017	01-01	13:00	1006.1	32.61	56.38	6.898	123.2	0	3457.8	960.5
2017	01-01	14:00	1005.2	32.64	54.75	7.04	119.7	0	3052.5	847.9
2017	01-01	15:00	1004.6	32.14	58.85	6.676	112.8	0	2452.5	681.2
2017	01-01	16:00	1004.1	31.61	61.25	6.575	111.5	0	1633.8	453.8
2017	01-01	17:00	1004.6	30.26	68.41	5.766	102.8	0	847.9	235.5
2017	01-01	18:00	1005.1	29.02	74.2	4.764	95.9	0	127.6	35.4
2017	01-01	19:00	1006.1	28.71	79.1	4.228	102.9	0	0	0
2017	01-01	20:00	1006.9	28.56	81.3	3.344	104	0	0	0
2017	01-01	21:00	1007.7	28.38	82.6	3.089	106.4	0	0	0
2017	01-01	22:00	1008.1	28.46	82	2.845	108.7	0	0	0
2017	01-01	23:00	1008.2	28.42	80.8	3.516	102.6	0	0	0
2017	01-01	24:00	1007.9	28.33	82.3	3.559	108	0	0	0

Source: FUNCEME (2018)

Figure 33 - Fortaleza Wind Rose between 2002 and 2016 (Average Data)



Source: FUNCEME (2018)

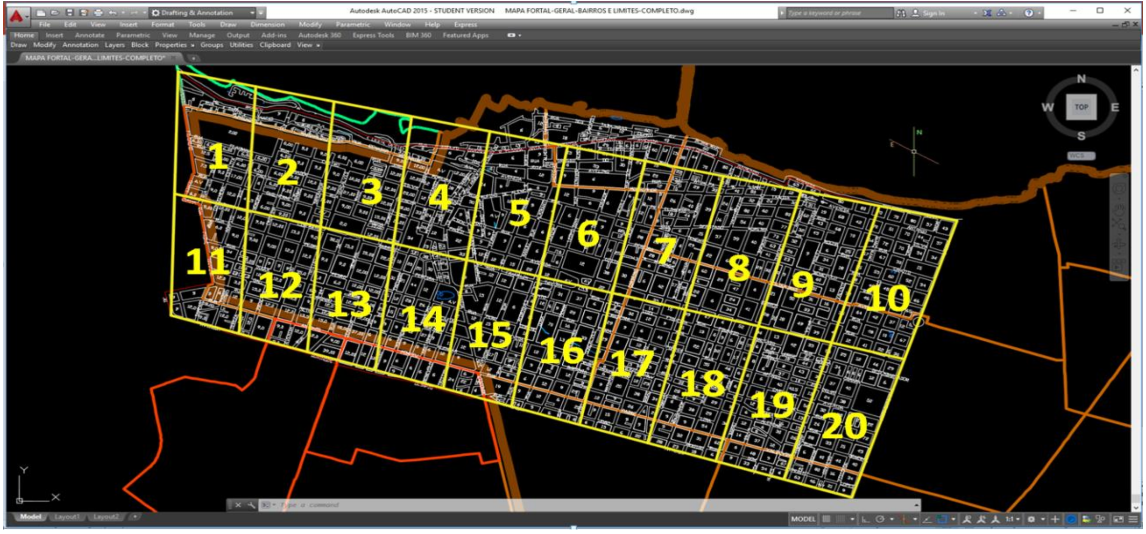
Next section will present air pollutant concentration strategy and data collection adopted in this research.

5.4.4 Atmospheric Air Pollution Concentrations Data Collection Strategy

The chosen pilot area used as Low Emission Zone has been divided in 20 subareas of approximately 500 m^2, in order to distribute the data collection points as homogeneous as possible throughout the study area. The reason to define 11 km^2 of LEZ area is related to commercial area (Figure 5.1) definition, with the possibility of enhancement within the defined commercial area. The 20 subareas in 500 m^2 were defined aiming to improve the passive data collection points, within a limit to cover the whole LEZ region.

The data collection points have been distributed taking into account the formation of different urban canyon levels, starting with canyon avenues, which are most present in west direction of studied area, regular canyons, mostly observed in the central region, and deep canyons, which can be observed in northeast region (Figure 25). Figure 34 shows the subdivision made in the pilot area used as pilot Low Emission Zone.

Figure 34 - Pilot Area Subdivided for Air Pollutant Concentrations Data Collection



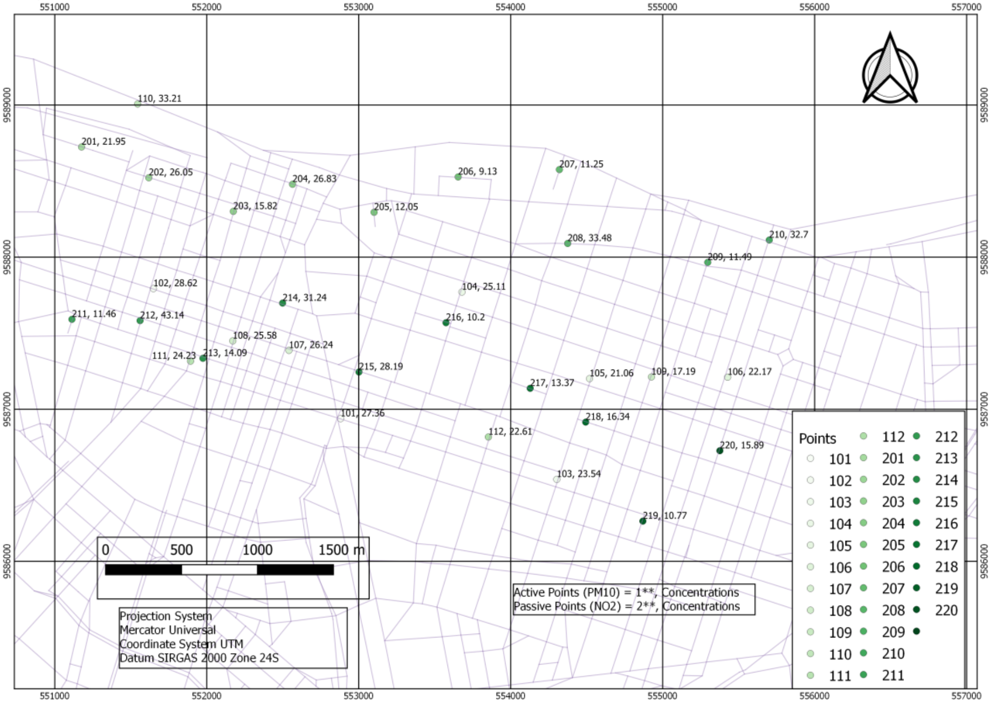
Source: Author

The passive data collection occurred in 20 points for nitrogen dioxide (NO_2), throughout the study area, one in each subregion defined in Figure 34. The selected point in each subregion had the selection criteria of the lots H / W ratios, with (0.1 to 2) in the western area of the zone, the highest H/W (> 2) in the eastern area of the zone, and the inclusion of three green areas within the 20 points, in order to assess the influence of areas with vegetation to air pollution (Subareas 6, 13 and 15).

Passive data collection samplers were adapted on public light posts in central sections of the observed streets, seeking, whenever possible, the geometric center of zone subregions. The passive NO_2 data collection has been carried out for fourteen consecutive days and same period. Figure 35 illustrates the distribution of the active and passive samplers along the area in this research.

The average height of passive data collection samplers were installed at 2.5 meters from the ground within the Low Emission Zone studied area, in order to be consistent with the established methodology (the recommendation heights are between 2 ~ 3 meters from the ground). The samplings have been conducted in July 2017 (first campaign) and November 2017 (second campaign). The observed climate conditions were similar, due to Fortaleza not varying climate conditions throughout the year (except raining season during March to May, which was conducted the first campaign for active PM sampling).

Figure 35 - Active and Passive Sampler Distribution within Pilot LEZ



Source: Author

The passive NO_2 samplers have been created especially for this research, celluloses filters with absorbent of NO_2 solution. The absorbent solution was made with KI 0.5 mol/L + KOH 0.2 mol/L in methanol, using the following quantities of reagents presented in Equation 9.

$$M = \frac{m}{MM*v} \tag{9}$$

$0.5 = \frac{\mathrm{mKI}}{166*1}$ mass of KI = 83 g .: $0.2 = \frac{\mathrm{mKOH}}{56{,}1.1}$ mass of KOH = 11.22 g

Where:

M = Molar concentration (mol/L);

m = mass (g);

MM = Molar mass;

V = Volume (L).

The calculated quantities of KI and KOH were diluted in 1 L of methanol (totally soluble). The filters with absorbent solution were inserted in supports to data collect NO_2. The supports with passive samplers are illustrated in Figure 36.

Figure 36 - Installed NO_2 passive sampler in public light post

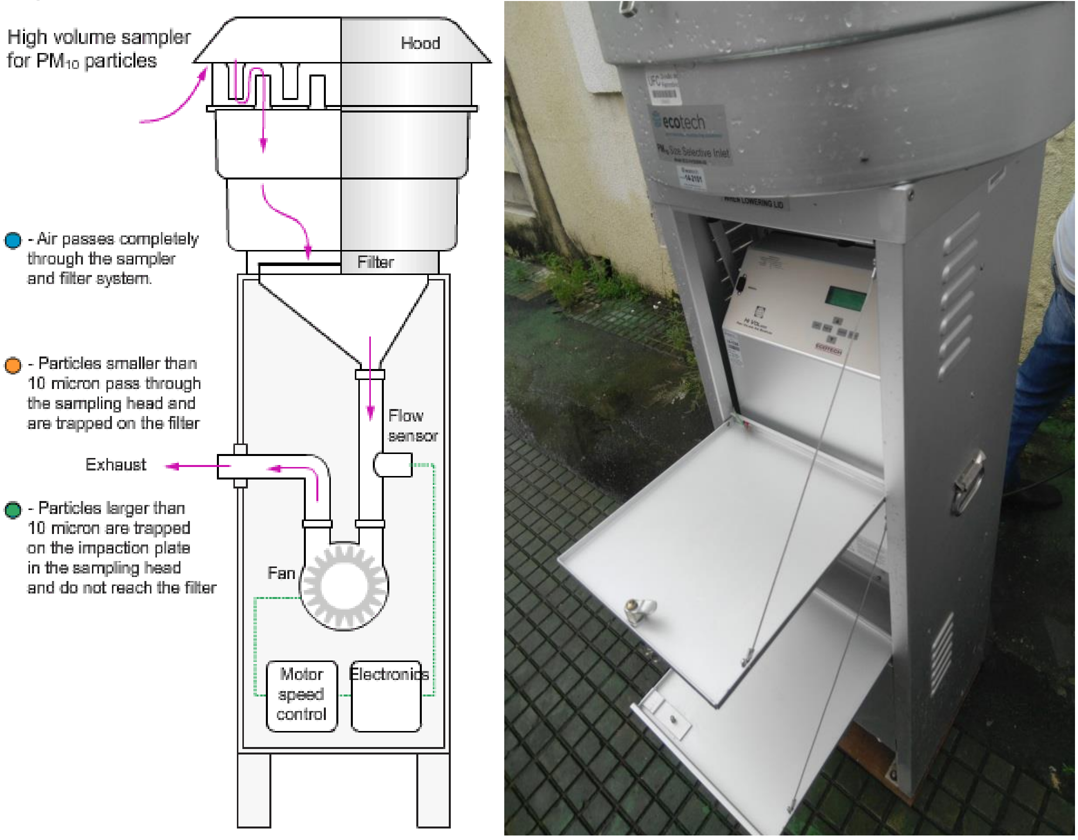
Source: Author

The active data collection was carried out in public buildings along the pilot area defined as Low Emission Zone, with grid iron gates that minimized the impediment of the wind action and equipment sampling. The data collection sampling occurred in a period of 24 hours and was performed at 12 points of the study area, starting between 08:00 and 11:00 and finishing at same time in the next day, due to equipment limitations and safety reasons.

All meteorological conditions and parameters related to experiments were summarized in Table 17. The data collections have been carried out during 24 hours due to equipment limitations and simulations inputs and outputs.

The equipment used in active PM_{10} data collection was an Ecotech HiVol 3000 (High Volume Particulate Sampler), also used in Brazilian reality. The HiVol 3000 Particulate Sampler provides a flexible platform for sampling of PM_{10}, $PM_{2.5}$ or TSP particulate and for monitoring basic meteorological parameters. The sampler is microprocessor based and features internal data logging of flow and meteorological parameters (Ecotech, 2013). In function of having one equipment available, only PM_{10} has been data collected, and also due to this particulate aggregation been the only registered in Brazilian emission factor inventories (shown in CETESB, 2017c). The principle involved in PM_{10} data collection and HiVol 3000 used in data collection are shown in Figures 37 and 38, respectively.

Figures 37 and 38 - HiVol 3000 Ecotech. Principle and equipment in field



Source: Queensland Government (2018) Source: Author

The filters were weighted before and after data collection. The airflow used in data collection was the equipment default airflow, 67.8 m^3/h. A sample of a filter before and after data collection is shown in Figure 39.

Figure 39 - Filter before data collection (left) and filter after data collection (right)

Source: Author

The PM_{10} concentration was calculate through the density difference of the filters, as shown in Equation 10.

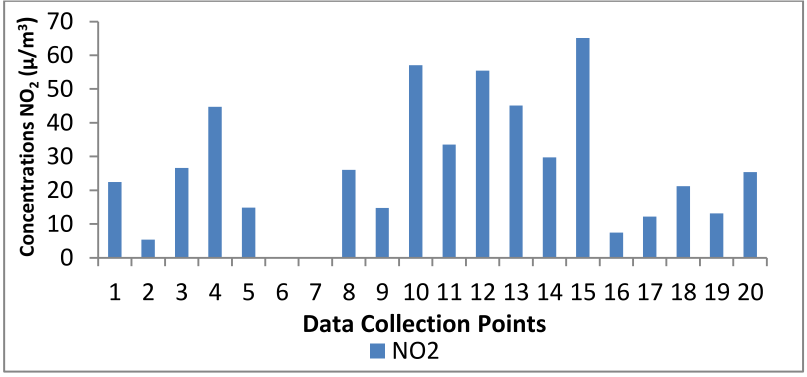
$$C_{PM10} = \frac{(W_{DF} - W_{CF})}{Q_{air}} \tag{10}$$

Where:

C_{PM10} = Concentration of PM_{10} ($\mu m/m^3$);
W_{DF} = Mass of dirty filter (µg);
W_{CF} = Mass of clean filter (µg);
Qair = Air flow passed through filter during data collection (m^3/h).

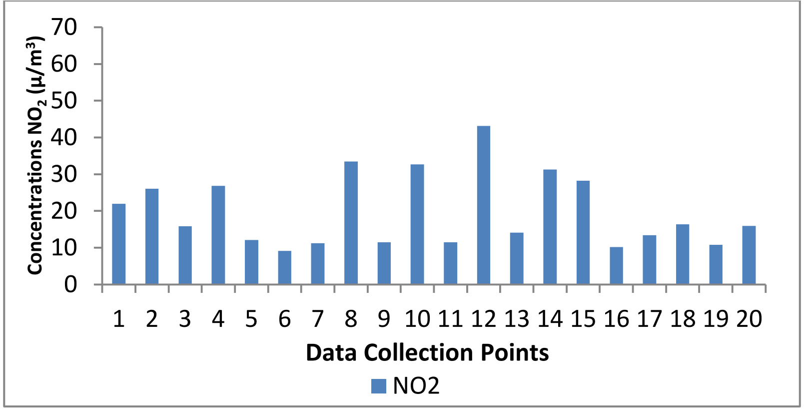
Two data collection campaigns have been carried out, one in the first semester and the last in second semester of 2017, due to laboratory and equipment limitations, and to increase the number of samplings, in order to analyze the Low Emission Zone modelling throughout all year of 2017. The concentrations of NO_2 and PM_{10} collected in the two campaigns are shown in Figures 40 and 41.

Figure 40 - Real NO_2 Concentrations ($\mu g/m^3$) Collected in First Campaign



Source: Author

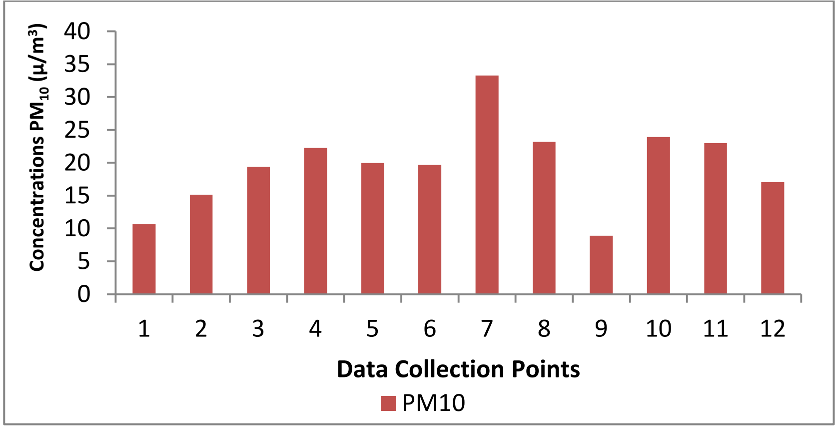
Figure 41 - Real NO_2 Concentrations ($\mu g/m^3$) collected in Second Campaign



Source: Author

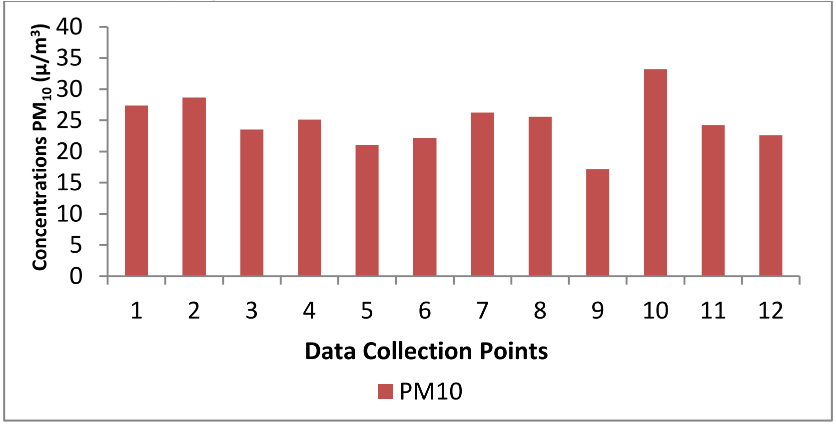
Figure 40 shows that data collection point 6 and 7 are missing, due to these two samplers have been destroyed by unknown reasons (this problem has not occurred in second campaign). In addition, the concentrations in data collection points 10 to 15 in first campaign were observed with higher values due to traffic during the observed time, and higher wind speeds and precipitation during that time. Data collection points 1 to 9 and 16 to 20 follows the same tendencies in both campaigns. Figures 42 and 43 presents the concentrations of PM_{10} in the two campaigns.

Figure 42 - Real PM_{10} Concentrations ($\mu g/m^3$) Collected in Second Campaign



Source: Author

Figure 43 - Real PM_{10} Concentrations ($\mu g/m^3$) collected in Second Campaign



Source: Author

The concentrations of PM_{10} are strongly affected by precipitation levels, which can be observed in data collection point 1 and 9 in first campaign (high precipitation levels during all day of data collection). The observed results can be compared to other experiments with consistency in order of magnitude. The precipitation has not repeated during second campaign, reflecting what can be observed in Figures 42 and 43 concentration levels.

Next section will present the final step of this research, all the modelling steps used to carry out the Low Emission Zone Assessment, using the real data collection to validate and compare to modelled values.

5.5 Annual Average Daily Traffic Estimated by Travel Demand Modelling

In order to code and calibrate the travel demand model, data have been collected with Fortaleza municipality (public and private sector), Ceará Research Department and Brazilian transit and geography departments. The data have been used as input to activity, land use and transportation models, aiming to estimate the travel demand with TRANUS model within the municipality of Fortaleza during 2015. The base data used to calibrate the travel demand modelling is presented in Table 18.

Table 18 - Data used to calibrate the Travel Demand Model

Data	Source	Year
Labour Annual Informations	Ministério do Trabalho e Emprego	2014
Elementary School Census	Instituto Nacional de Estudos e Pesquisas Educacionais Anísio Teixeira	2015
Universitary Degree Census	Instituto Nacional de Estudos e Pesquisas Educacionais Anísio Teixeira	2015
PostGraduate Programs Register	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior	2015
2010 Census	Instituto Brasileiro de Geografia e Estatística	2010
Projections of Brazilian Population and States	Instituto Brasileiro de Geografia e Estatística	2010
Family Budget Research	Instituto Brasileiro de Geografia e Estatística	2009
Tax Registration of the Property and Property Urban Territorial	Secretaria de Finanças de Fortaleza	2015
Fortaleza Public Road Transportation Eletronic Ticket System	Empresa de Transporte Urbano de Fortaleza	2014
SCOOT	Autarquia Municipal de Trânsito e Cidadania de Fortaleza	2014
Traffic Flow Countings	Atlanta	2014
Traffic Flow Countings	Trana	2014
Traffic Flow Countings	Inductive Loop-Type Sensors	2014
Screen Line Research	Fundação Cearense de Pesquisa e Cultura	2015

Source: Adapted from Sousa (2016)

In order to model the average traffic, were defined as decision phenomena the location of households and jobs for the the year of 2015. Households were subdivided by income class and types of economic activities (e.g. commerce and service provision), assuming so each type has peculiarities when making locational and interaction decisions of activities, which are the transportable sectors of activity models and land use.

Regarding the transportation models, the interest is to understand the pattern of population displacement, focusing on those that occur for work or education reasons and that occur by motorized modes. These travels have been analyzed for a typical peak hour of the year, and expanded to whole day using the traffic distribution throughout the day, considering that the accessibility estimated in this period is what influences the locational decisions throughout the year.

The modelling was based in zoning the city's 119 districts, the zoning was suggested in order to build the transportation planning to Fortaleza municipality, assuming that there are a small number of interest trips with origin and destination in the same district and that the transportation (road network and public transportation network) within each district is homogeneous.

As for land use, it is assumed that the spatial occupation pattern of each district occurs homogeneously without the sectors having interests in certain parts of these districts. Another factor that contributed to the selection of districts as zoning units was the data that are available at this level of spatial aggregation for the most part.

The travel demand modelling carried out in this research aimed to estimate the travels only in Fortaleza municipality, being disregarded the travels in metropolitan region, however, it is important to take into account the metropolitan region of Fortaleza in a more robust study, since the metropolitan municipalities have important relations with Fortaleza.

This was considered due to emission estimation and urban background concentrations been analyzed only in city area, which presents the higher contribution of air pollution to pilot Low Emission Zone Area. The road network with the modelled average daily traffic speeds of Fortaleza main streets is shown in Figure 44.

Figure 44 - Modelled Road Network with Average Daily Traffic Speeds – Fortaleza

Source: Author

The calibration of average daily traffic flows has been carried out with the inductive loop-type sensor traffic data collection with aid of SCOOT system. The modelled travel demand and measured traffic flow of huge traffic streets inside and outside the pilot analyzed LEZ area are shown in Table 19.

Table 19 - Measured and Modelled Average Daily Traffic in Fortaleza Streets

Street/Avenue	Simulated	Measured	Difference	Relative Error (%)
Washington Soares	52625	50239	2386	+4.75
Santos Dumont	44671	42607	2064	+4.85
Antônio Sales	26934	34280	-7346	-21.43
Presidente Castelo Branco	46736	40439	6297	+15.57
Padre Antônio Tomás	39909	38745	1164	+3.00
Padre Valdevino	27967	20936	7031	+33.58
Sen. Virgílio Távora	31637	30980	657	+2.12
Br. De Studart	25292	31501	-6209	-19.71
Rui Barbosa	15626	18484	-2858	-15.46
Ana Bilhar	22828	23006	-178	-0.77

Source: Author

With annual average daily traffic modelled in Fortaleza municipality carried out, the next step of this research aimed to estimate vehicle emissions in all city area, and aggregate the emissions in grid cells of 1 km x 1 km, in order to estimate urban background concentrations in the further step.

5.6 Vehicle Emissions in Streets of Fortaleza: Grid Creation

The vehicle emissions have been estimated using traffic vehicle type and technology proportions, also calculated in total mass emitted by year in each traffic estimated street of Fortaleza. Thereafter, calculated emissions in streets were aggregated in grid cells of 1 km x 1 km in all Fortaleza area, in order to use as input in UBM (necessary in the model). The aggregated emission factors taking into account all vehicle technology proportions are illustrated in Table 20 used in total mass estimations. It is important to note that the Flex vehicles are the most numerous in Fortaleza fleet, however, around 90% of them uses gasoline, due to economic reasons (FORTALEZA, 2015).

Table 20 - Aggregated Emission Factors by Vehicle, Size and Fuel Type

(to be continued)

Vehicle and Fuel Type	**Total % of PassCars**	**Aggregated Emission Factor (NO_x)**	**Aggregated Emission Factor (Exhaust PM_{10})**	**Aggregated Emission Factor (CO)**
Passenger Cars_Fleet Distribution_Gasoline	0.354	0.245	0.001	2.934
Passenger Cars_Fleet Distribution_Alcohol	0.051	0.524	0.002	5.117
Passenger Cars_Fleet Distribution_Flex	0.548	0.031	0.001	0.327
Passenger Cars_Fleet Distribution_FlexLPG	0.046	0.132	0.001	0.371
Vehicle and Fuel Type	Total % of PickupSUVVans	Aggregated Emission Factor (NO_x)	Aggregated Emission Factor (Exhaust PM_{10})	Aggregated Emission Factor (CO)
PickupSUVVan_Fleet Distribution	1	1.904	0.051	0.449
Vehicle and Size	Total % of Trucks	Aggregated Emission Factor (NO_x)	Aggregated Emission Factor (Exhaust PM_{10})	Aggregated Emission Factor (CO)
Truck_Fleet Distribution_light truck	0.681	2.747	0.107	0.501
Truck_Fleet Distribution_medium truck	0.170	3.447	0.132	0.579
Truck_Fleet Distribution_heavy truck	0.149	5.631	0.214	0.961
Vehicle and Size	Total % of Buses	Aggregated Emission Factor (NO_x)	Aggregated Emission Factor (Exhaust PM_{10})	Aggregated Emission Factor (CO)

Table 20 - Aggregated Emission Factors by Vehicle, Size and Fuel Type

(conclusion)

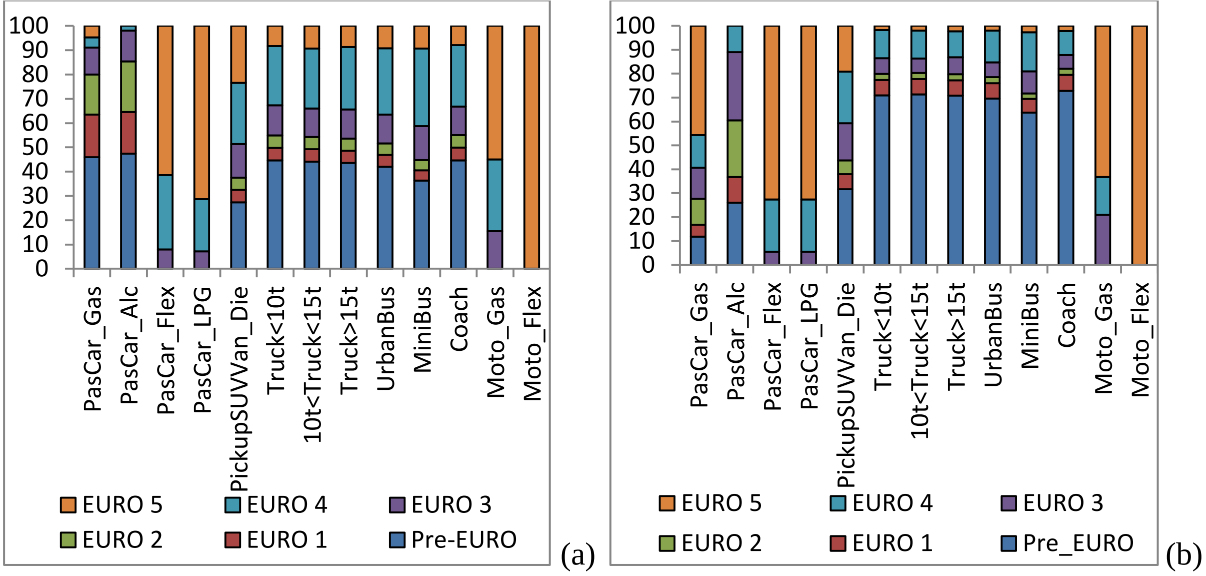
Vehicle and Fuel Type	**Total % of PassCars**	**Aggregated Emission Factor (NO_x)**	**Aggregated Emission Factor (Exhaust PM_{10})**	**Aggregated Emission Factor (CO)**
Bus_Fleet Distribution_UrbanBus	0.601	8.762	0.325	1.717
Bus_Fleet Distribution_MicroBus	0.332	4.181	0.147	0.854
Bus_Fleet Distribution_Coach	0.067	6.242	0.236	1.005
Vehicle and Fuel Type	Total % of Motorcycles	Aggregated Emission Factor (NO_x)	Aggregated Emission Factor (Exhaust PM_{10})	Aggregated Emission Factor (CO)
Motorcycle_Fleet Distribution_Gasoline	0.713	0.097	0.002	1.206
Motorcycle_Fleet Distribution_Flex	0.287	0.050	0.001	0.718

Source: Author

Even with low proportions of old technology vehicles, higher emission factors of these vehicles results in higher aggregated emission factors of each vehicle type, especially for trucks and buses, due to significant impact of old technologies in heavy duty vehicles.

The estimation in each street considered the proportions presented in Table 20 and have been aggregated in one emission factor, in order to analyze the reduction in global emission factors due to restrictions of each scenario of proposed Low Emission Zone. The emission contributions of each vehicle type and technology are shown in Figures 45a and 45b for NO_x and Exhaust PM_{10}, respectively.

Figure 45 - NO_x (a) and PM_{10} (b) Emission Contributions (%) in Real Traffic Conditions



Source: Author

Figures 45a and 45b shows the huge contributions in emissions of Pre-EURO (Pre L, PROCONVE 1 and M 1 Brazilian stages) vehicles, even considering the low vehicle number of this technology in Fortaleza fleet. The global emission factors for all fleet in each street are presented in Table 21, aggregate for all technologies and vehicles in real traffic conditions (without any proposed scenario or restriction).

Table 21 - Aggregated Global Emission Factors for All Vehicles in Each Street in Real Traffic Conditions

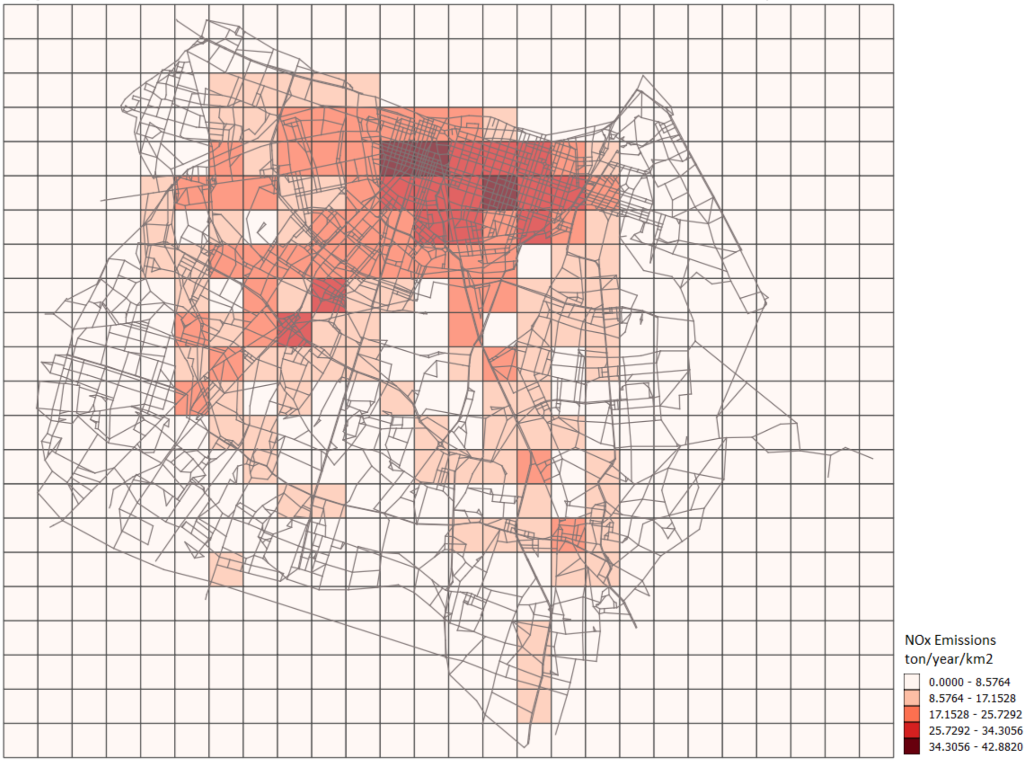
Global Emission Factor (NO_x)	**Global Emission Factor (Exhaust PM_{10})**
0.434 g/km	0.0131 g/km

Source: Author

The huge contributions in emissions of old technologies confirm that old technologies restrictions in traffic could bring huge potential in reducing air pollutant concentrations.

Knowing the vehicle contribution and global emission factors for real traffic conditions, the emission grid has been constructed to estimate the total mass of air pollutants emitted in Fortaleza, in year of 2017. The emission grid has been built in order to be used as input in urban background concentration estimations, illustrated in Figure 46 for NO_x.

Figure 46 - Emissions Grid for Non Restricted Traffic (ton/year/km^2, NO_x)



Source: Author

Figure 46 shows the northern area of Fortaleza with higher emissions for NO_x (PM_{10} follows the same pattern), confirming the area choice for pilot Low Emission Zone analysis.

The next section will present the meteorological pre-processing for calculation of complex parameters with OML pre-processor. In addition, regional background concentrations estimated with IFS model will be presented, in order to be used as input data in urban background concentrations estimation.

5.7 Meteorological Pre-Processing and Regional Background Concentrations

With the basic meteorological data collected by State company FUNCEME, OML meteorology pre-processor has been used to estimate the complex meteorological parameters, by hour, which are fundamental to air quality modelling and directly influence to air pollutant residence time in atmosphere, such as: (i) mixing height; (ii) convective velocity (wstar); (iii) friction velocity (ustar); (iv) Munin-Obhukov length and (v) air density. The calculated parameters with OML pre-processor are illustrated in Table 22 for one day of 2017.

Table 22 - Calculated meteorological parameters with OML-Highway Pre-Processor. One day of analyzed year 2017

Day	**Month**	**Year**	**Hour**	**Hmix [m]**	**Wstar (m/s)**	**Ustar (m/s)**	**Monin-Obukhov Length [m]**	**Air density [kg/m^3]**
1	1	2017	1	388	0	0.187	14	1.1637
1	1	2017	2	160	0	0.077	3	1.1635
1	1	2017	3	150	0	0.072	3	1.1635
1	1	2017	4	150	0	0.048	3	1.1642
1	1	2017	5	150	0	0.041	3	1.1652
1	1	2017	6	150	0	0.037	3	1.1654
1	1	2017	7	150	0	0.054	3	1.1634
1	1	2017	8	189	0	0.091	3	1.1594
1	1	2017	9	150	0	0.072	3	1.1563
1	1	2017	10	679	0	0.327	9998	1.1530
1	1	2017	11	806	1.006	0.388	-132	1.1497
1	1	2017	12	891	1	0.429	-201	1.1488
1	1	2017	13	924	1.136	0.445	-158	1.1462
1	1	2017	14	926	0.914	0.446	-307	1.1451
1	1	2017	15	856	0	0.412	330	1.1463
1	1	2017	16	748	0	0.36	43	1.1477
1	1	2017	17	611	0	0.294	27	1.1534
1	1	2017	18	193	0	0.093	3	1.1587
1	1	2017	19	326	0	0.157	9	1.1610
1	1	2017	20	150	0	0.065	3	1.1625
1	1	2017	21	150	0	0.06	3	1.1642
1	1	2017	22	150	0	0.054	3	1.1643
1	1	2017	23	150	0	0.068	3	1.1646
1	1	2017	24	150	0	0.07	3	1.1646

Source: Author

The calculations have been carried out for whole year of 2017, in order to analyze the two air pollution data collection campaigns. Calculated parameters presented above were used (in addition to collected by FUNCEME) as inputs in THOR-AirPAS system in first of its four steps, as regional data inputs. The regional data inputs also include regional background concentrations, which have been estimated with IFS model. IFS model was capable of estimate hourly regional background concentrations for the following pollutants: (i) Nitrogen Oxide (NO); (ii) Nitrogen Dioxide (NO_2); (iii) Ozone (O_3); (iv) Sulphur Dioxide (SO_2); (v) Carbon Monoxide (CO) and (vi) Particulate Matter disaggregated in different components, aggregated to be used as input to PM_{10} in urban background model. The particulates estimated with IFS were: seasalt (important in Fortaleza, due to littoral region; dust; hydrophobic organic matter; hydrophilic organic matter; hydrophobic black carbon and hydrophilic black carbon. The estimated regional background concentrations with IFS model are illustrated in Table 23 for one day in 2017, with PM_{10} aggregated accordingly to input in THOR-AirPAS system, in urban background modelling step.

Table 23 - Estimated Regional Background Concentrations with IFS Model. One day of analyzed year 2017

Day	**Month**	**Year**	**Hour**	**NO_X [ppb]**	**NO_2 [ppb]**	**O_3 [ppb]**	**SO_2 [ppb]**	**CO [ppm]**	**PM_{10} [ppb]**
1	1	2017	1	1.431	1.347	34.142	0.153	134.935	24.176
1	1	2017	2	1.922	1.888	34.414	0.194	132.030	27.790
1	1	2017	3	2.281	2.238	33.489	0.254	137.794	26.977
1	1	2017	4	2.641	2.589	32.564	0.314	143.559	26.164
1	1	2017	5	3.286	3.085	29.398	0.383	162.175	27.899
1	1	2017	6	3.932	3.581	26.233	0.451	180.791	29.636
1	1	2017	7	4.578	4.078	23.068	0.520	199.407	31.371
1	1	2017	8	4.163	3.613	20.013	0.419	202.594	31.706
1	1	2017	9	3.749	3.148	16.958	0.317	205.781	32.041
1	1	2017	10	3.334	2.683	13.903	0.216	208.968	32.377
1	1	2017	11	2.398	1.952	19.443	0.160	172.485	28.578
1	1	2017	12	1.462	1.221	24.982	0.103	136.002	24.780
1	1	2017	13	0.526	0.490	30.522	0.047	99.519	20.982
1	1	2017	14	0.425	0.390	32.227	0.045	92.366	20.647
1	1	2017	15	0.324	0.290	33.932	0.044	85.214	20.313
1	1	2017	16	0.223	0.190	35.637	0.042	78.061	19.979
1	1	2017	17	0.239	0.202	35.185	0.042	78.631	21.069
1	1	2017	18	0.254	0.214	34.734	0.042	79.202	22.158
1	1	2017	19	0.270	0.225	34.282	0.042	79.772	23.248
1	1	2017	20	0.535	0.487	31.725	0.061	86.648	22.620
1	1	2017	21	0.800	0.749	29.168	0.080	93.523	21.991
1	1	2017	22	1.065	1.011	26.610	0.099	100.399	21.363
1	1	2017	23	1.064	1.008	26.584	0.100	100.408	20.410
1	1	2017	24	1.063	1.005	26.558	0.101	100.417	19.457

Source: Author

NO_x concentrations used as input in Urban Background Model (UBM) is simplified as the combination of NO + NO_2, aggregated with estimated IFS air pollutants. Ozone is used as important input in Operational Street Pollution Model (OSPM, last step of THOR Air-PAS system) to calculate the proportion of NO_2 in emitted NO_x by vehicles.

Next sections will present all necessary substeps to carry out street air pollution concentrations, in order to end the Low Emission Zone Assessment experiment.

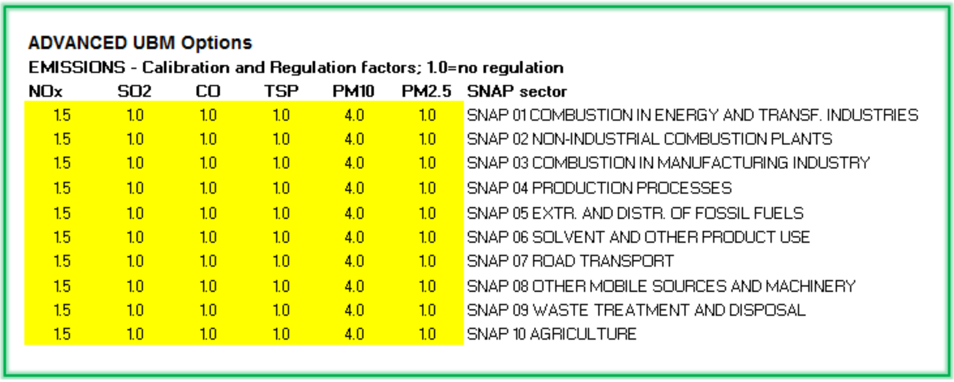
5.8 Air Quality Modelling Space and Time Analysis

With all meteorological data collected and calculated, regional background concentrations estimated (first step of THOR – AirPAS system) and aggregated mass emissions grid (second step of THOR – AirPAS system) constructed, urban background concentrations have been estimated in third step of the system, in order to finish the analysis in street levels (fourth step), which allow the Low Emission Zone Assessment.

Urban background concentrations were calculated hourly for whole year of 2017. The tool is also capable to calculate the average concentrations, aggregating all time calculated (in this case, one year).

UBM includes advanced emissions calibration and regulation options. For non-calibration in UBM, all factors should be marked as 1.0 (default configuration), however, due to uncertainties and underestimations in official emission factors, it was necessary to adjust the emission factors, after calculating the final concentrations in street levels (OSPM), the default configuration brought underestimations in air pollutant concentrations, when compared to real data collected previously presented. The calibration factors carried out to reach the final concentrations are presented in Figure 47.

Figure 47 - Advanced UBM Options Adjusted in Research



ADVANCED UBM Options

EMISSIONS - Calibration and Regulation factors; 1.0=no regulation

NOx	SO2	CO	TSP	PM10	PM2.5	SNAP sector
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 01 COMBUSTION IN ENERGY AND TRANSF. INDUSTRIES
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 02 NON-INDUSTRIAL COMBUSTION PLANTS
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 03 COMBUSTION IN MANUFACTURING INDUSTRY
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 04 PRODUCTION PROCESSES
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 05 EXTR. AND DISTR. OF FOSSIL FUELS
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 06 SOLVENT AND OTHER PRODUCT USE
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 07 ROAD TRANSPORT
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 08 OTHER MOBILE SOURCES AND MACHINERY
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 09 WASTE TREATMENT AND DISPOSAL
1.5	1.0	1.0	1.0	4.0	1.0	SNAP 10 AGRICULTURE

Source: Author

Urban background concentrations consist of regional background concentration with increment of urban emissions, estimated in emissions air pollutants mass grid. The estimated urban background concentrations with UBM are illustrated in Table 24 for one day in 2017 and average urban background concentrations of all year of 2017 in Table 25.

Table 24 - Estimated Urban Background Concentrations with UBM. One day of analyzed year 2017

Day	**Month**	**Year**	**Hour**	**NO_X [µg/m^3]**	**NO_2 [µg/m^3]**	**O_3 [µg/m^3]**	**SO_2 [µg/m^3]**	**CO [µg/m^3]**	**PM_{10} [µg/m^3]**
1	1	2017	1	11.72	11.44	60.45	0.41	172.96	27.58
1	1	2017	2	13.25	12.97	60.57	0.52	173.15	31.41
1	1	2017	3	12.9	12.66	59.58	0.68	177.93	30.2
1	1	2017	4	14.4	14.22	56.94	0.84	187.79	29.7
1	1	2017	5	16.6	16.4	49.47	1.02	209.45	31.8
1	1	2017	6	17.57	16.5	43.98	1.2	230.29	33.43
1	1	2017	7	20.73	16.94	38.49	1.39	247.57	35.9
1	1	2017	8	16.74	11.63	36.49	1.12	247.34	35.02
1	1	2017	9	20.82	12.6	29.2	0.85	258.25	37.2
1	1	2017	10	14.46	7.63	26.48	0.58	255.59	35.43
1	1	2017	11	9.05	5.02	38.25	0.43	207.66	30.26
1	1	2017	12	7.79	4.92	48.06	0.28	166.35	26.67
1	1	2017	13	5.97	3.8	58.83	0.13	124.48	22.86
1	1	2017	14	6.65	4.44	61.51	0.12	118.16	22.85
1	1	2017	15	12.77	8.96	61	0.12	120.73	24.91
1	1	2017	16	13.21	10.11	63.11	0.11	112.36	24.82
1	1	2017	17	15.06	12.42	60.1	0.11	117.98	26.6
1	1	2017	18	28.68	25.61	47.58	0.11	144.93	32.83
1	1	2017	19	21.9	21.12	50.32	0.11	131.99	31.34
1	1	2017	20	31.33	30.17	37.69	0.16	153.73	34.09
1	1	2017	21	27.94	26.95	35.84	0.21	154.8	31.99
1	1	2017	22	27.55	26.55	31.54	0.26	161.61	31.02
1	1	2017	23	19.97	19.25	37.91	0.27	146.09	27.2
1	1	2017	24	17.07	16.49	40.28	0.27	137.02	25.15

Source: Author

Table 25 - Average Urban Background Concentrations in 2017

Value	**Day**	**Month**	**Year**	**Hour**	**NO_X [µg/m^3]**	**NO_2 [µg/m^3]**	**O_3 [µg/m^3]**	**SO_2 [µg/m^3]**	**CO [µg/m^3]**	**PM_{10} [µg/m^3]**
Min	1	1	2017	1	1.5	1.4	0.4	0.0	48.8	**1.7**
Max	31	12	2017	24	182.6	93.1	222.2	4.5	528.6	82.3
Average	15.7	6.5	2017	12.5	23.2	18.3	42.8	0.3	122.7	19.9

Source: Author

Regulation factors in UBM have been adjusted, especially for particulate matter (shown in Figure 47). The underestimations in official factors have been studied by Krecl *et* *al.* (2018) for Brazilian fleet. The research carried out in Londrina observed that CETESB official emission factors for nitrogen oxides and particulate matter present different underestimations for light duty vehicles and high duty vehicles.

The increments presented in Brazilian research have been aggregated for LDV and HDV, considering nitrogen oxides and particulate matter, in order to observe the reduction in adjustments of regulation and calibration of advanced emission factors in Urban Background Model. Table 26 shows the aggregated increments added to official factors, for LDV and HDV.

Table 26 - Increments Calculated to Adjust the Underestimations in Emission Factors

Type of Vehicle	**Increment NO_x**	**Increment PM**
LDV	1.8	4.3
HDV	3.0	3.6

Source: Adapted from Krecl *et al.* (2018)

With the addition of increments in emission factors in street levels, calibration factors in UBM have been reduced to default number (1.0), and the final air pollutant concentrations estimation reached the concentration collected in field, confirming the underestimations in emission factors.

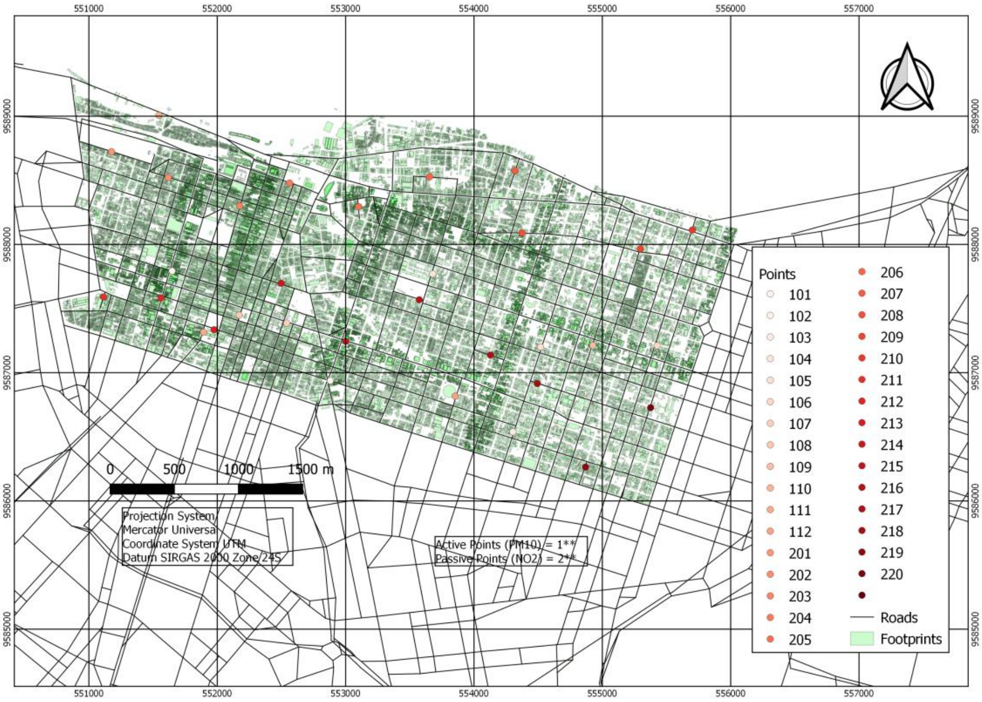
The next subsection will present the steps necessary to adjust the final simulation in proposed method, air pollutant estimation in street levels using Operational Street Pollution Model (OSPM).

5.8.1 AirGIS Street Configuration as OSPM Input

The first step to code street levels air pollution was made using AirGIS system. AirGIS was able to generate street configuration and traffic data for the OSPM model based on digital maps and national databases. This enabled estimation of air quality levels at a larger number of collection points in an automatic and effective way, in opposite to coding directly in OSPM, which allows only coding one by one data collections points.

AirGIS coding carried out in this research aimed to generate 32 street coding, due to study data collection points (20 passive NO_2 and 12 active PM). In order to code streets with AirGIS, road network, building footprints and data collection points in pilot Low Emission Zone area have been coded with QGis. The shapefiles used to code AirGIS are illustrated in Figure 48.

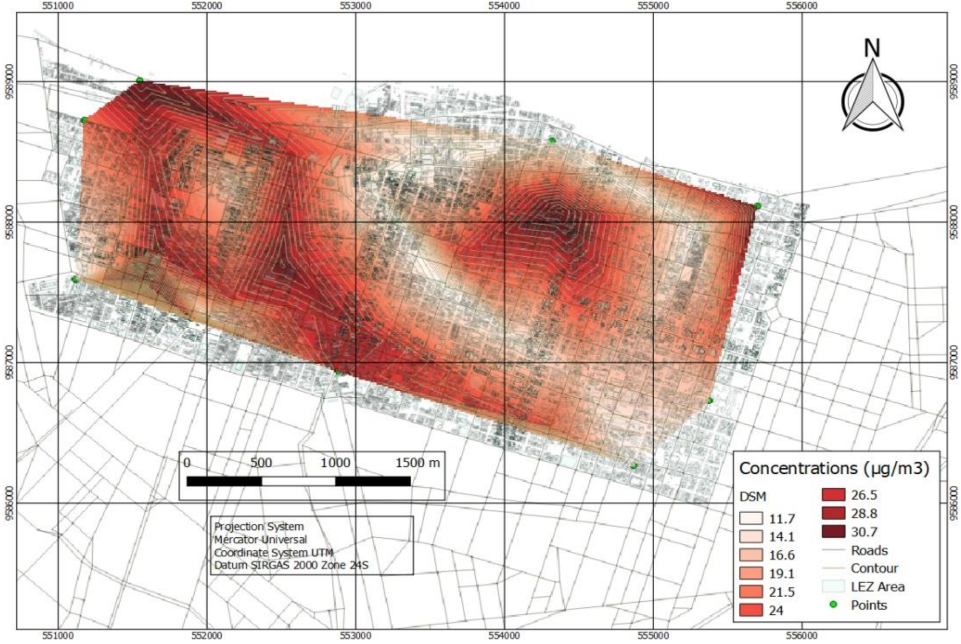
Figure 48 - Road Network, Building Footprints and Data Collection Points in QGis



Source: Author

The coding in AirGIS consider building heights, road widths and data collection point positions, in order to estimate the action of meteorological conditions to air pollution residence time. The concentrations simulated in 1º Campaign are illustrated in Figure 49 and AirGIS coding within OSPM street configuration is presented in Figure 50.

Figure 49 - Simulated Concentrations within pilot LEZ in First Campaign. Representation in Digital Surface Model



Source: Author

Figure 50 - Representation of Data Collection Points Coded with Streets and Buildings in AirGIS

Source: Author

With generated AirGIS street configuration, the final substep has been carried out with OSPM, which estimate air pollution concentrations in street levels, presented in the next subsection.

5.8.2 OSPM Street Air Pollution Modelling

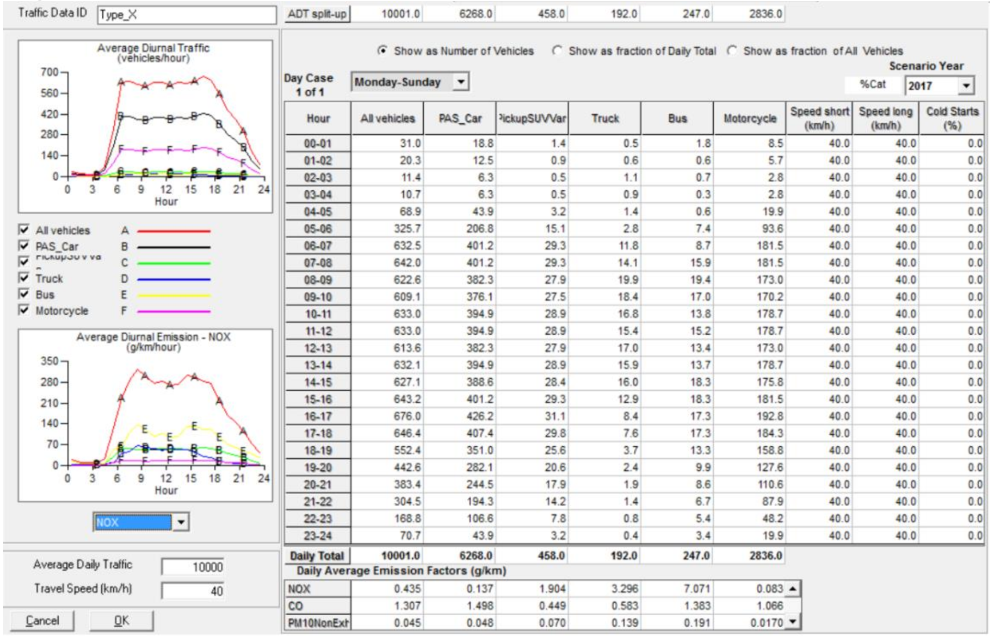
The last step in THOR-AirPAS system was carried out with OSPM modelling, in order to compare modelled street air pollution concentrations with real data collected in the field. Urban background concentrations, meteorological data, traffic distributions and emission factors have been carried on OSPM to calculate the concentrations.

In this research, OSPM simulations have been simplified, due to lack of input data, such as: (i) cold start corrections; (ii) emission factors temperature gradient; (iii) vehicle speed emission factor increment and; (iv) vehicle mileage emission factor correction. In addition, vehicle distribution has been simplified as uniform during whole week. These simplifications have not compromised the comparison between simulated and real data, due to consistence in input data in all simulations and the real data collection carried out only during weekdays, where the traffic followed the same distribution (in average).

Calculations carried out in OSPM have been coded using multi-streets mode, where all data collection points (presented in Figures 48 and 49) were simulated for whole

2017, year of data collection experiments. OSPM traffic distribution and vehicle emission factors files are presented in Figures 51 and 52, respectively.

Figure 51 - Traffic Distribution Coded in OSPM



Traffic Data ID: Type_X

ADT split-up	10001.0	6268.0	458.0	192.0	247.0	2836.0

● Show as Number of Vehicles ○ Show as fraction of Daily Total ○ Show as fraction of All Vehicles

Day Case 1 of 1: Monday-Sunday

Scenario Year: 2017

Hour	All vehicles	PAS_Car	PickupSUVVan	Truck	Bus	Motorcycle	Speed short (km/h)	Speed long (km/h)	Cold Starts (%)
00-01	31.0	18.8	1.4	0.5	1.8	8.5	40.0	40.0	0.0
01-02	20.3	12.5	0.9	0.6	0.6	5.7	40.0	40.0	0.0
02-03	11.4	6.3	0.5	1.1	0.7	2.8	40.0	40.0	0.0
03-04	10.7	6.3	0.5	0.9	0.3	2.8	40.0	40.0	0.0
04-05	68.9	43.9	3.2	1.4	0.6	19.9	40.0	40.0	0.0
05-06	325.7	206.8	15.1	2.8	7.4	93.6	40.0	40.0	0.0
06-07	632.5	401.2	29.3	11.8	8.7	181.5	40.0	40.0	0.0
07-08	642.0	401.2	29.3	14.1	15.9	181.5	40.0	40.0	0.0
08-09	622.6	382.3	27.9	19.9	19.4	173.0	40.0	40.0	0.0
09-10	609.1	376.1	27.5	18.4	17.0	170.2	40.0	40.0	0.0
10-11	633.0	394.9	28.9	16.8	13.8	178.7	40.0	40.0	0.0
11-12	633.0	394.9	28.9	15.4	15.2	178.7	40.0	40.0	0.0
12-13	613.6	382.3	27.9	17.0	13.4	173.0	40.0	40.0	0.0
13-14	632.1	394.9	28.9	15.9	13.7	178.7	40.0	40.0	0.0
14-15	627.1	388.6	28.4	16.0	18.3	175.8	40.0	40.0	0.0
15-16	643.2	401.2	29.3	12.9	18.3	181.5	40.0	40.0	0.0
16-17	676.0	426.2	31.1	8.4	17.3	192.8	40.0	40.0	0.0
17-18	646.4	407.4	29.8	7.6	17.3	184.3	40.0	40.0	0.0
18-19	552.4	351.0	25.6	3.7	13.3	158.8	40.0	40.0	0.0
19-20	442.6	282.1	20.6	2.4	9.9	127.6	40.0	40.0	0.0
20-21	383.4	244.5	17.9	1.9	8.6	110.6	40.0	40.0	0.0
21-22	304.5	194.3	14.2	1.4	6.7	87.9	40.0	40.0	0.0
22-23	168.8	106.6	7.8	0.8	5.4	48.2	40.0	40.0	0.0
23-24	70.7	43.9	3.2	0.4	3.4	19.9	40.0	40.0	0.0
Daily Total	**10001.0**	**6268.0**	**458.0**	**192.0**	**247.0**	**2836.0**			

Daily Average Emission Factors (g/km)

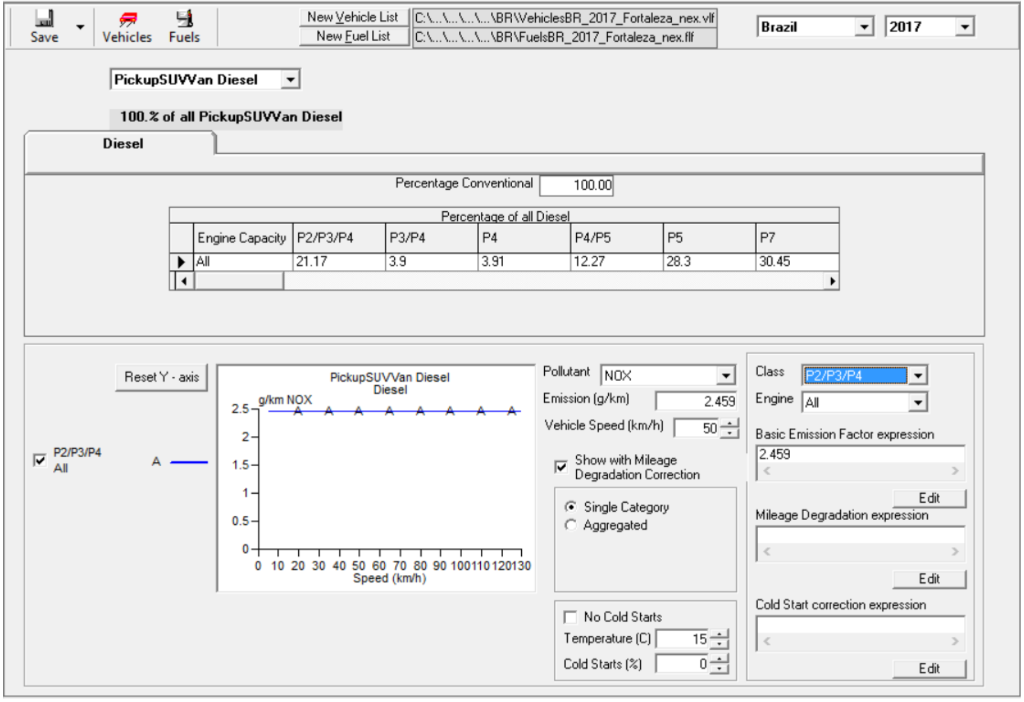
NOX	0.435	0.137	1.904	3.296	7.071	0.083
CO	1.307	1.498	0.449	0.583	1.383	1.066
PM10NonExh	0.045	0.048	0.070	0.139	0.191	0.0170

Average Daily Traffic: 10000

Travel Speed (km/h): 40

Source: Author

Figure 52 - Emission Factors Coded in OSPM



New Vehicle List: C:\...\...\...\BR\VehiclesBR_2017_Fortaleza_nex.vlf

New Fuel List: C:\...\...\...\BR\FuelsBR_2017_Fortaleza_nex.flf

Brazil | 2017

PickupSUVVan Diesel

100.% of all PickupSUVVan Diesel

Diesel

Percentage Conventional: 100.00

Percentage of all Diesel

Engine Capacity	P2/P3/P4	P3/P4	P4	P4/P5	P5	P7
All	21.17	3.9	3.91	12.27	28.3	30.45

Pollutant: NOX

Emission (g/km): 2.459

Vehicle Speed (km/h): 50

☑ Show with Mileage Degradation Correction

● Single Category
○ Aggregated

☐ No Cold Starts

Temperature (C): 15

Cold Starts (%): 0

Class: P2/P3/P4

Engine: All

Basic Emission Factor expression: 2.459

Mileage Degradation expression:

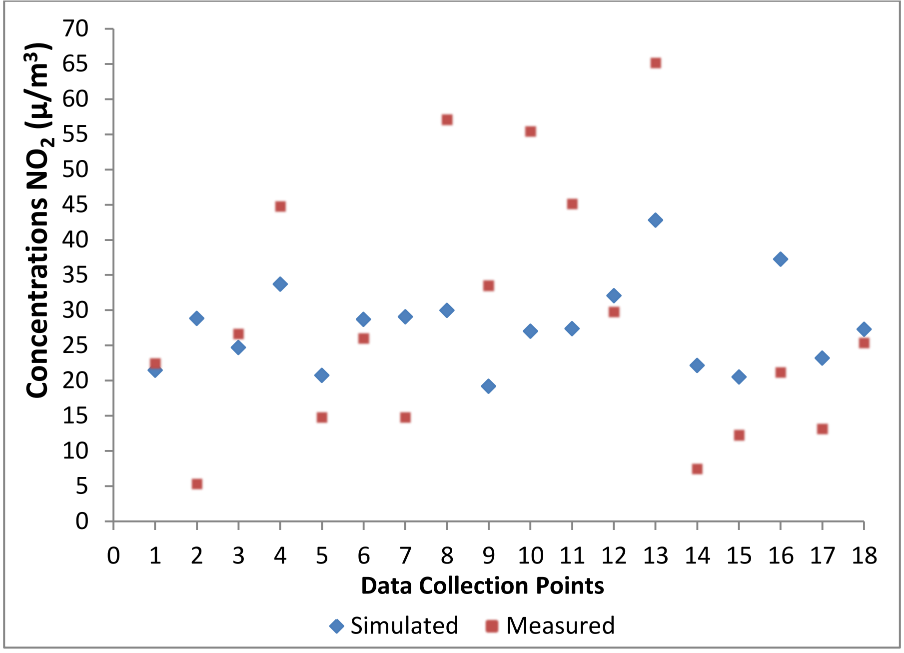
Cold Start correction expression:

Source: Author

NO_2 and PM concentrations were simulated aggregated by day (24 hours), in order to compare with real concentration data collection in street levels. Concentrations for

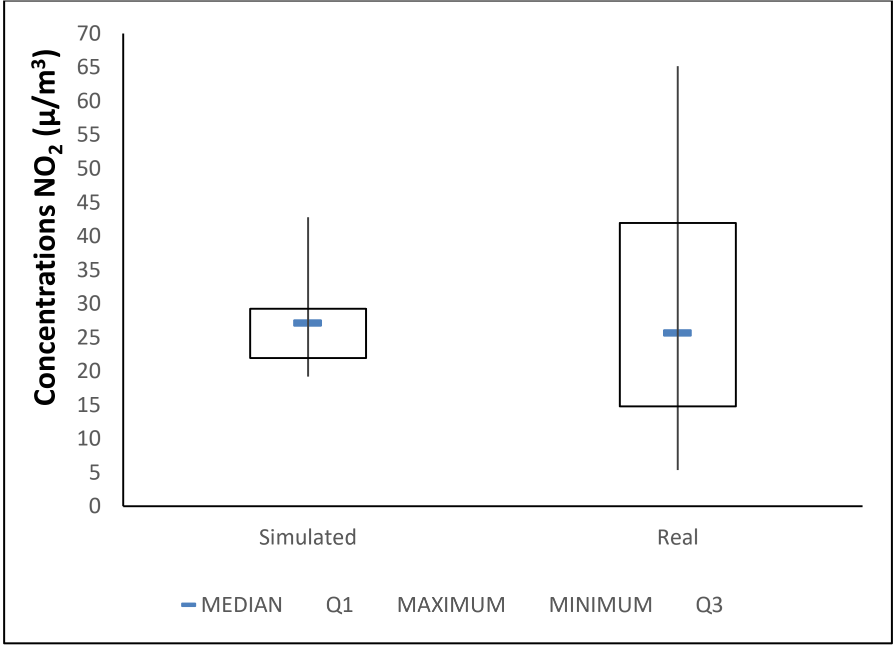
NO_2 and PM_{10} modelled in final step of THOR-AirPAS system are presented in Figures 53 to 60, respectively. Table 27 and 28 shows descriptive statystics for real and simulated data.

Figure 53 - Measured and Simulated NO_2 Concentrations (µg/m^3). 1º Campaign



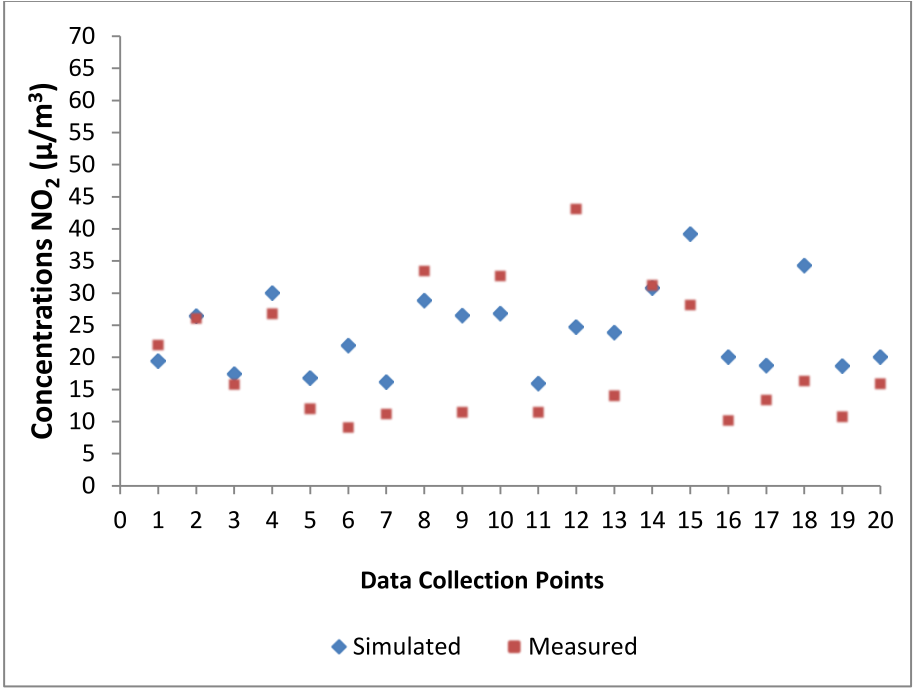
Source: Author

Figure 53 - Measured and Simulated NO_2 Concentrations (µg/m^3). 1º Campaign. Boxplot Representation



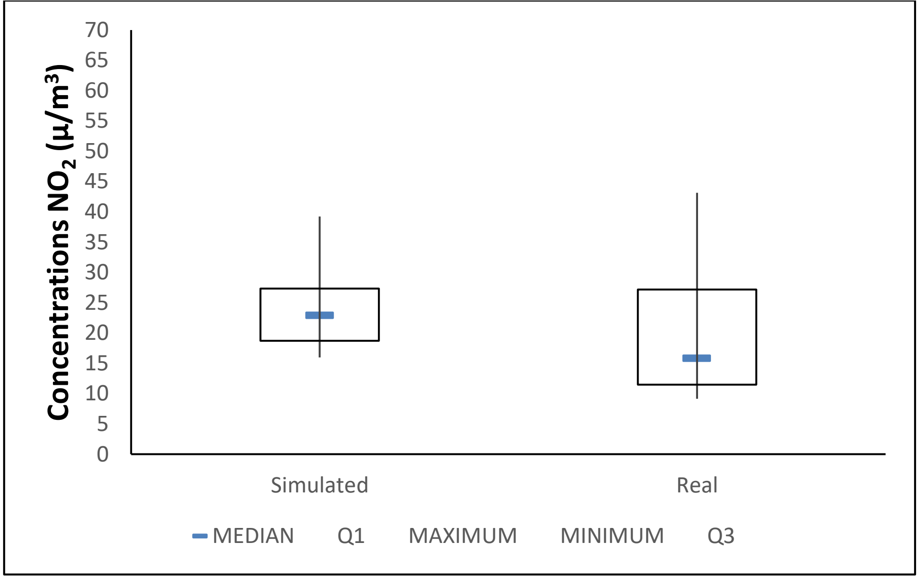
Source: Author

Figure 54 - Measured and Simulated NO_2 Concentrations (µg/m^3). 2º Campaign



Source: Author

Figure 55 - Measured and Simulated NO_2 Concentrations (µg/m^3). 2º Campaign. Boxplot Representation



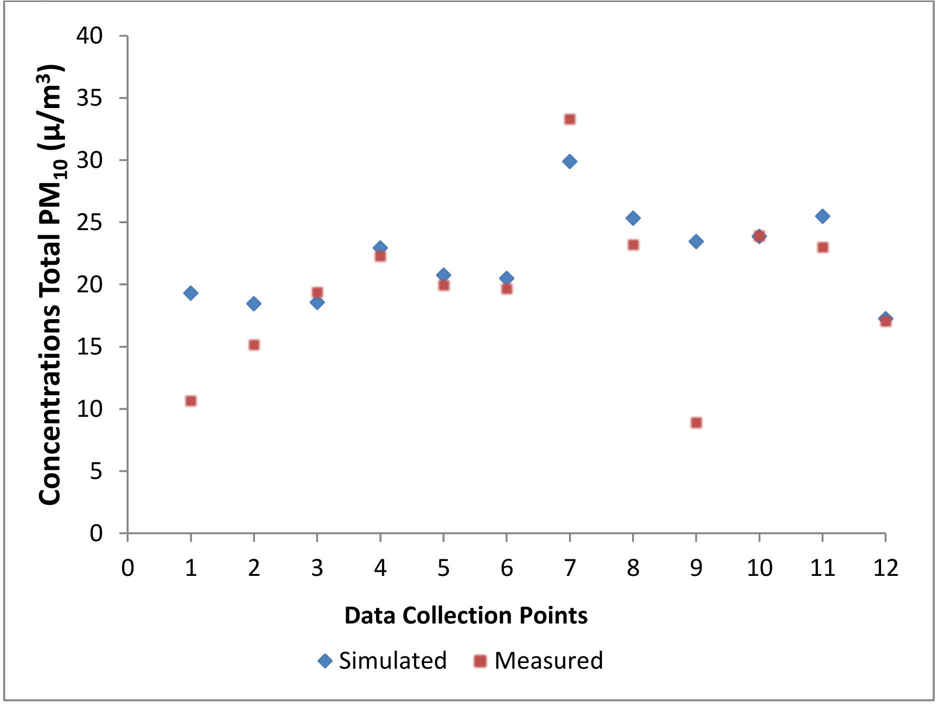
Source: Author

Table 27 - Descriptive Statystics for NO_2 concentrations (µg/m^3) in 1º and 2º campaign. Simulated and Real Data

	1º Campaign		**2º Campaign**	
	Simulated	Real	Simulated	Real
Mean	27,05686103	28,90555	23,857753	19,77183
Standard Error	1,365376028	4,20492	1,4511846	2,217909
Median	27,131793	25,68671	22,889482	15,85859
Standard Deviation	6,106147228	17,83997	6,489895	9,91879
Sample Variance	37,28503397	318,2644	42,118737	98,3824
Kurtosis	0,916452784	-0,53122	-0,007490	-0,274694
Skewness	0,948861202	0,688969	0,7549296	0,873425
Range	23,61506267	59,79469	23,298473	34,0147
Minimum	19,17081867	5,353965	15,947596	9,127641
Maximum	42,78588133	65,14866	39,246069	43,14234
Count	20	18	20	20

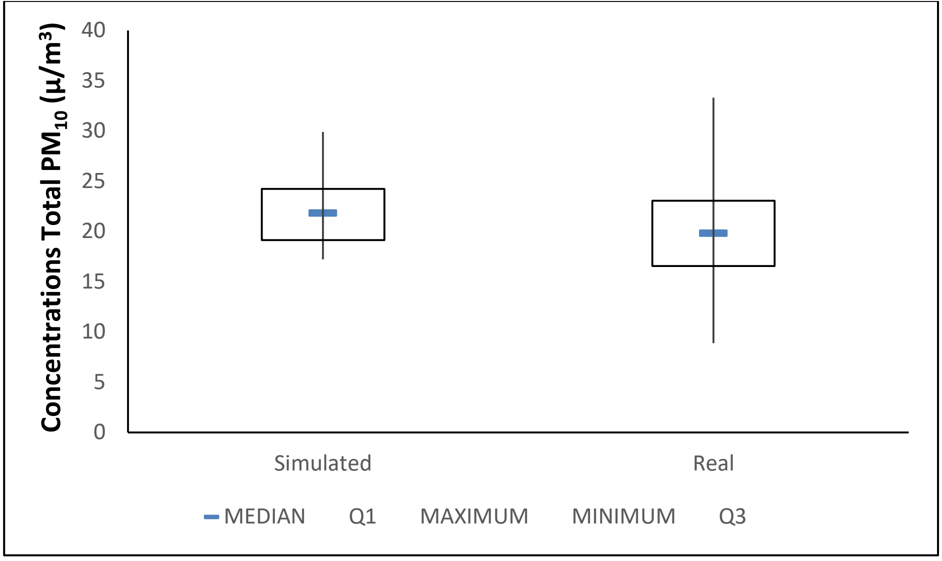
Source: Author

Figure 56 - Measured and Simulated Total PM_{10} Concentrations (µg/m3). 1º Campaign



Source: Author

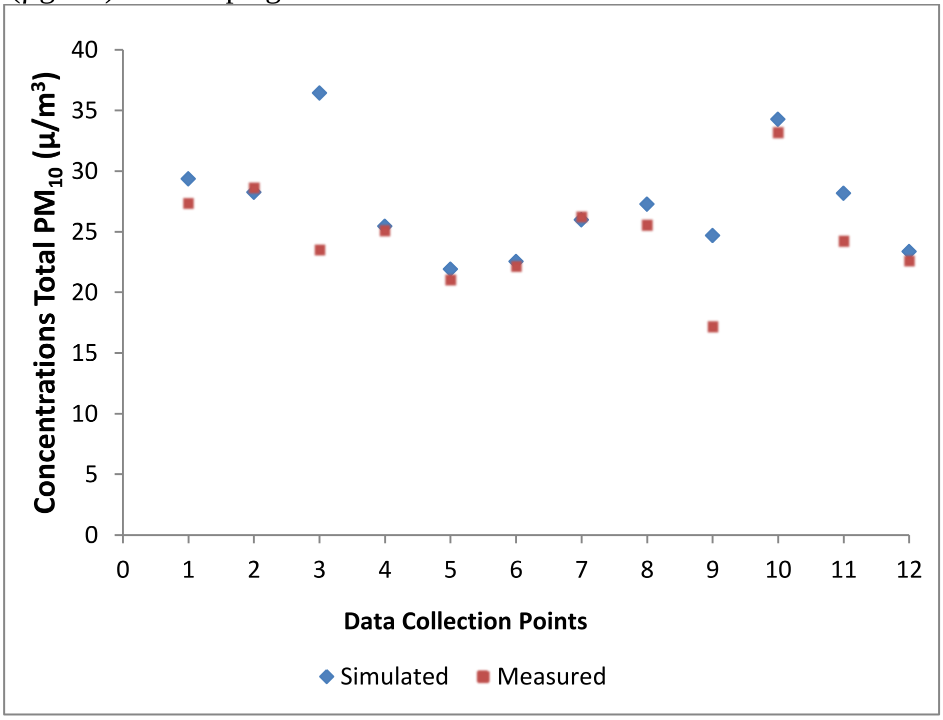
Figure 57 - Measured and Simulated Total PM_{10} Concentrations (µg/m3). 1º Campaign. Boxplot Representation



Source: Author

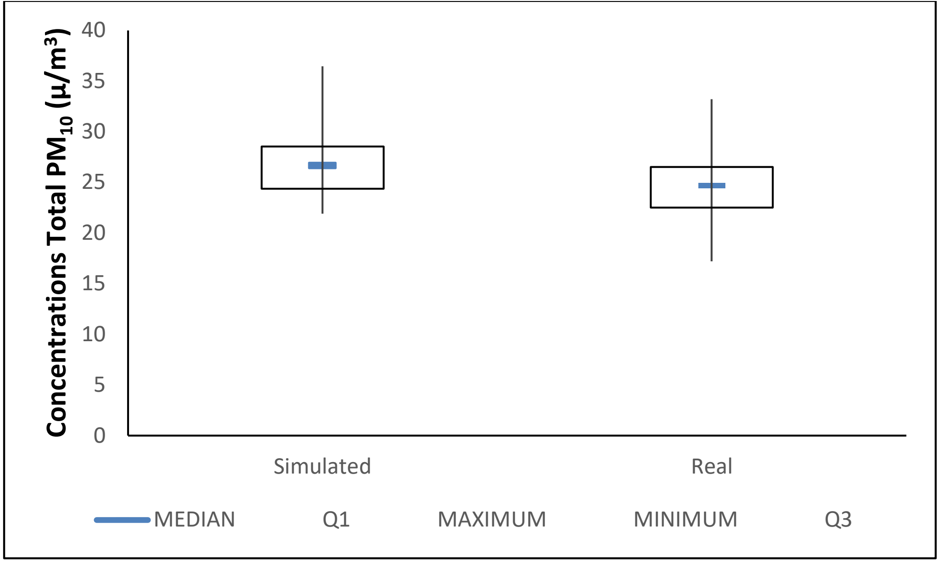
It is important to note that data collection point 7 was the observed most dense traffic street by buses in this study, what can be showed in the outlier concentrations of PM_{10}.

Figure 58 - Measured and Simulated Total PM_{10} Concentrations (µg/m3). 2º Campaign



Source: Author

Figure 59 - Measured and Simulated Total PM_{10} Concentrations (µg/m3). 2º Campaign. Boxplot Representation



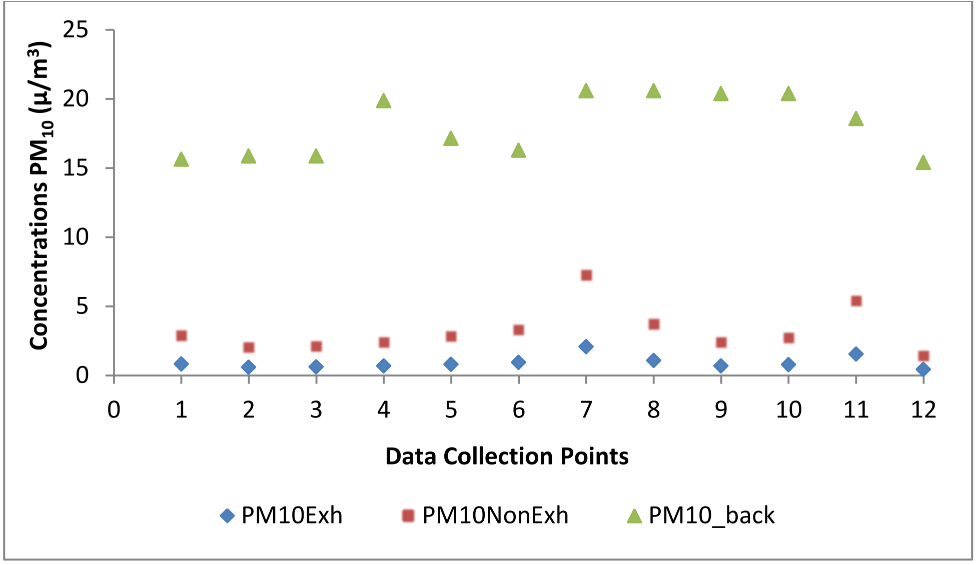
Source: Author

Table 28 - Descriptive Statystics for PM_{10} concentrations (µg/m^3) in 1º and 2º campaign. Simulated and Real Data

	1º Campaign		**2º Campaign**	
	Simulated	Real	Simulated	Real
Mean	22,14738	19,70133	27,31825	24,74445
Standard Error	1,065525	1,864745	1,283036	1,168165
Median	21,83487	19,80642	26,63939	24,67429
Standard Deviation	3,691088	6,459667	4,444566	4,046641
Sample Variance	13,62413	41,7273	19,75417	16,37531
Kurtosis	0,080997	1,003096	0,410728	1,207361
Skewness	0,646439	0,23189	0,938902	0,290429
Range	12,65381	24,40265	14,53912	16,01831
Minimum	17,2397	8,90118	21,91431	17,18904
Maximum	29,89351	33,30383	36,45343	33,20735
Count	12	12	12	12

Source: Author

Figure 60 - Source PM_{10} Contributions in Street Levels Total Concentrations (µg/m3).



Source: Author

The first NO_2 data collection campaign showed huge variety on data collections, due to uncertainties in passive collectors, however, second NO_2 data collections in field have been carried out with higher precision in data collections, which leads to lower errors when compared to simulated data in OSPM. Assessing points 1 to 4 in both campaigns, the simulated and real data can be observed with underestimations in simulated data, due to underestimations in regional background concentrations in IFS model. The points 14 to 18 (in first campaign) and 16 to 20 (second campaign, which are the same data collection points) showed overestimations in simulated data, due to overestimations in regional background concentrations in IFS model.

Observing tendencies, the simulations in street levels shows satisfactory level of accuracy, since estimated NO_2 concentrations follow tendencies and the order of magnitude are close to real data collected.

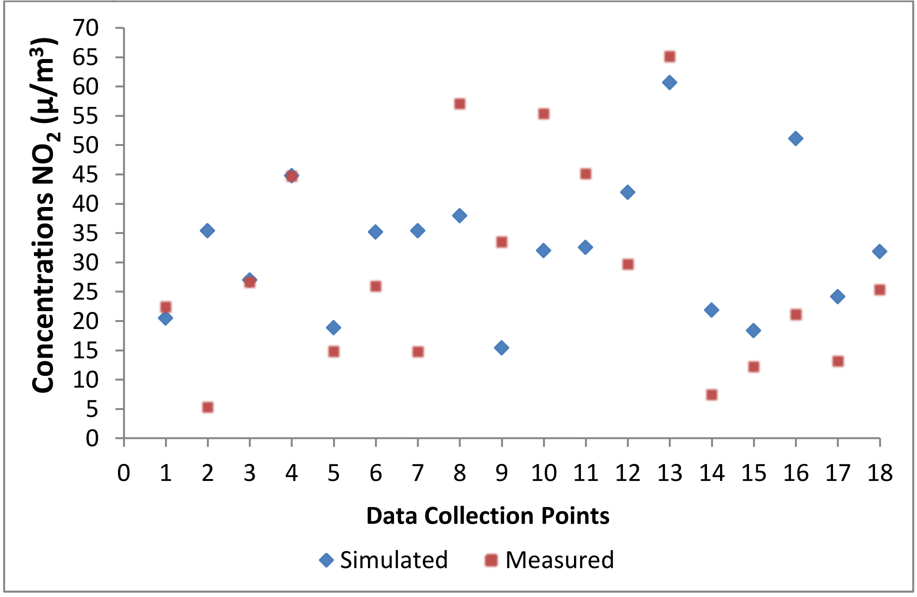
Both PM real data collections campaigns in field have been carried out with high precision method, due to active filter data collector. The results shows simulated data in OSPM close to real data collection, with exceptions in point 1 and 9 (first campaign) and point 3 and 9 (second campaign), these overestimations have been observed due to precipitation in these days. One limitation observed in OSPM is the incapability to consider precipitation in simulations, which leads to overestimations, especially in PM estimations (PM washing by rain).

Figure 60 shows that exhaust PM contributions represents low proportion (average 4%, minimum 2.4% and maximum 7%), compared to non-exhaust contributions (average 14%), which shows that the potential reduction in global air pollution by exhaust reduction is lower when compared to reduce traffic, however, this does not apply for NO_2, due to exhaust only contributions. The PM contributions in exhaust, non-exhaust and background concentrations follows state-of-art Low Emission Zones, confirmed by studies in European LEZ's, showed in Holman *et al.* (2015).

Adjusted emission factors have been introduced in OSPM model by incrementing each type of vehicle (one by one) and running the simulations within THOR – AirPAS. The adjusted emission factors were calculated to Londrina reality by Krecl *et al.*, 2018. The variation observed in data collection points 6 to 12 in first campaign can be assigned to huge presence of high duty vehicles (HDV's) in streets and their relevance in NO_x emissions in these points, increasing with the adjustments of emission factors.

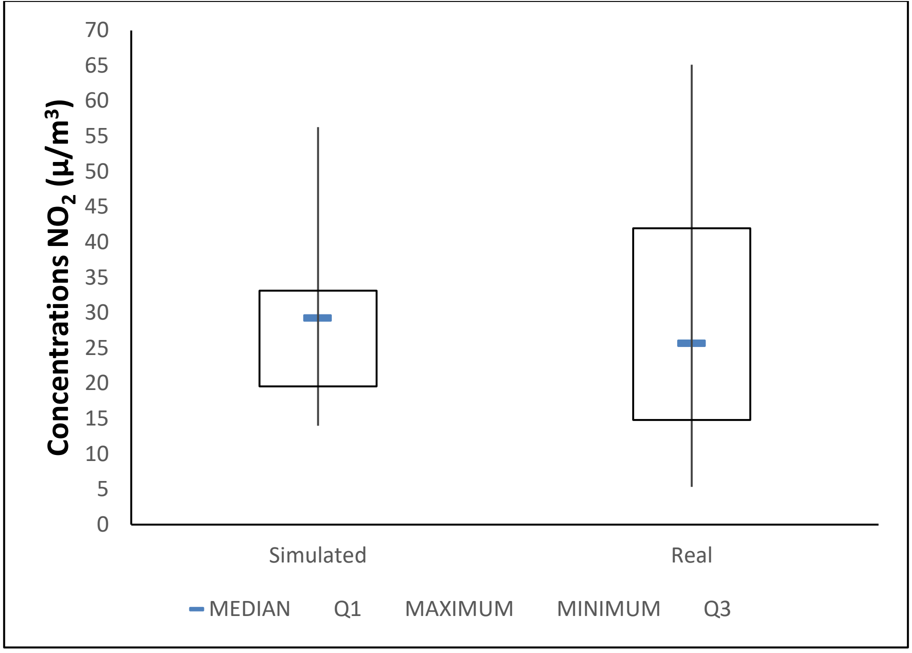
The analysis has also been carried out with adjusted emission factors, in order to use non-calibrated UBM, observing new simulated data compared to real data. Figures 61 to 68 presents the adjusted emission factors with real data collected. Table 29 and 30 shows the descriptive statystics for adjusted emission factors simulations and real data.

Figure 61 - Measured and Simulated NO_2 Concentrations (µg/m^3). 1º Campaign. Adjusted Emission Factors



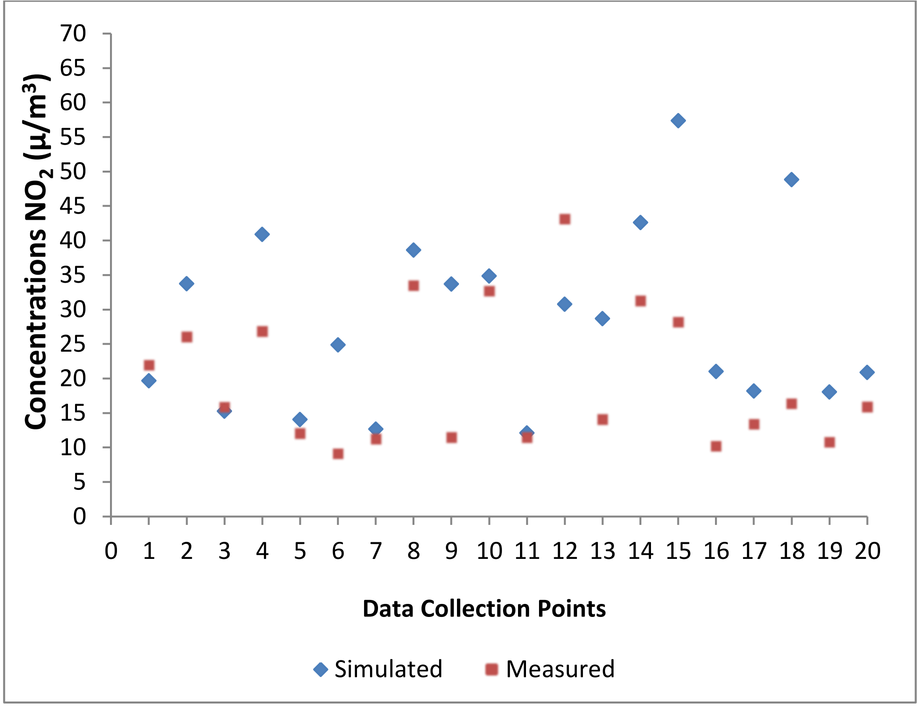
Source: Author

Figure 62 - Measured and Simulated NO_2 Concentrations ($\mu g/m^3$). 1º Campaign. Adjusted Emission Factors. Boxplot Representation



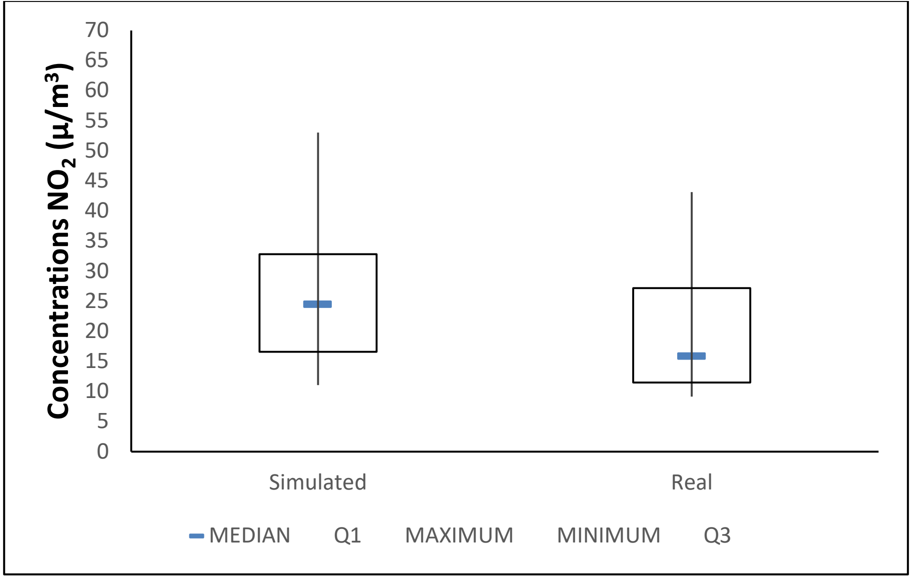
Source: Author

Figure 63 - Measured and Simulated NO_2 Concentrations ($\mu g/m^3$). 2º Campaign. Adjusted Emission Factors



Source: Author

Figure 64 - Measured and Simulated NO_2 Concentrations (µg/m3). 2º Campaign. Adjusted Emission Factors. Boxplot Representation



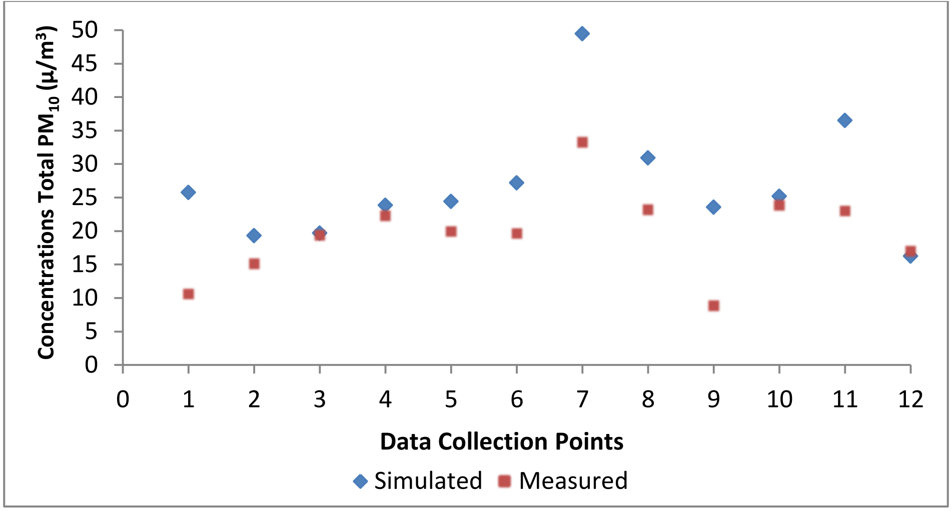
Source: Author

Table 29 - Descriptive Statystics for NO_2 concentrations (µg/m^3) in 1º and 2º campaign. Adjusted Emission Factors. Simulated and Real Data

	1º Campaign		**2º Campaign**	
	Simulated	Real	Simulated	Real
Mean	28,94345	28,90555	25,98585	19,77183
Standard Error	2,476994	4,20492	2,651184	2,217909
Median	29,28204	25,68671	24,48535	15,85859
Standard Deviation	11,07746	17,83997	11,85645	9,91879
Sample Variance	122,71	318,2644	140,5755	98,3824
Kurtosis	0,499522	-0,53122	-0,27894	-0,27469
Skewness	0,798522	0,688969	0,650371	0,873425
Range	42,31655	59,79469	41,97555	34,0147
Minimum	13,98824	5,353965	11,06038	9,127641
Maximum	56,30479	65,14866	53,03593	43,14234
Count	20	18	20	20

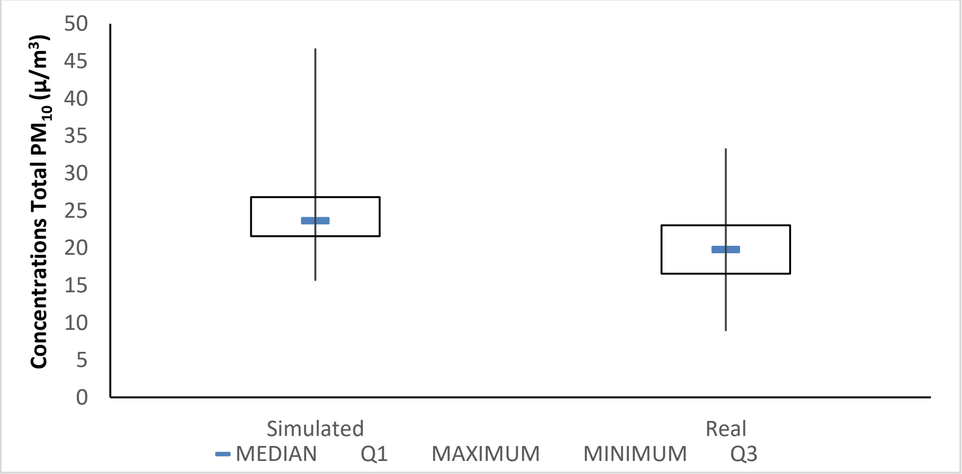
Source: Author

Figure 65 - Measured and Simulated Total PM_{10} Concentrations (µg/m3). 1º Campaign. Adjusted Emission Factors. Boxplot Representation



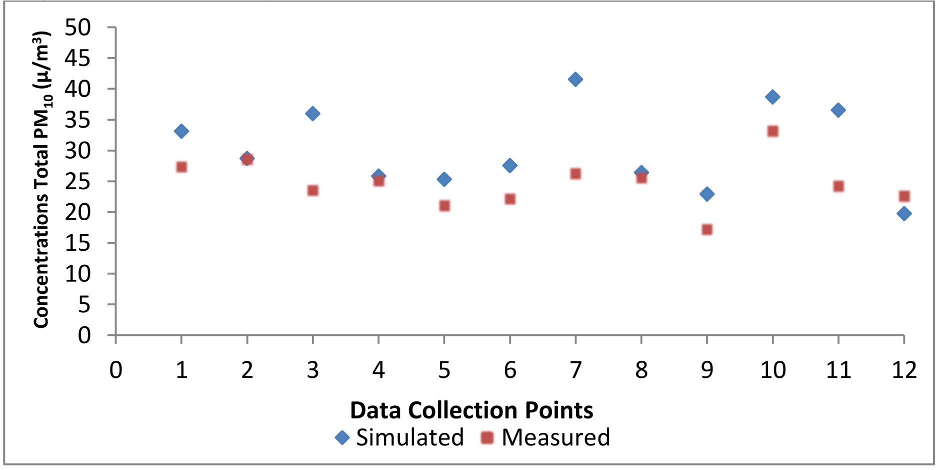
Source: Author

Figure 66 - Measured and Simulated Total PM_{10} Concentrations (µg/m3). 1º Campaign. Adjusted Emission Factors. Boxplot Representation



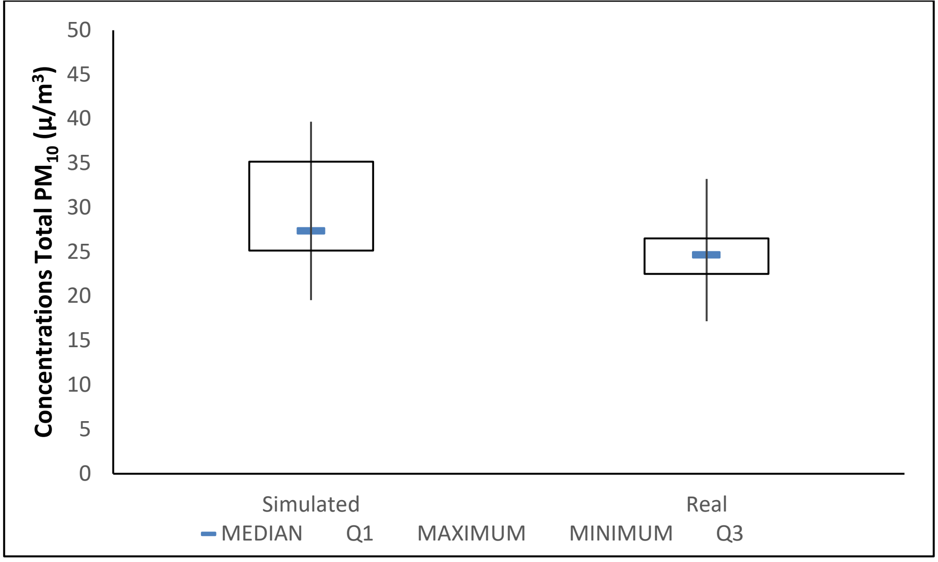
Source: Author

Figure 67 - Measured and Simulated Total PM_{10} Concentrations (µg/m3). 2º Campaign. Adjusted Emission Factors



Source: Author

Figure 68 - Measured and Simulated Total PM$_{10}$ Concentrations (µg/m3). 2º Campaign. Adjusted Emission Factors. Boxplot Representation



Source: Author

Table 30 - Descriptive Statystics for PM$_{10}$ concentrations (µg/m^3) in 1º and 2º campaign. Adjusted Emission Factors. Simulated and Real Data

	1º Campaign		**2º Campaign**	
	Simulated	Real	Simulated	Real
Mean	25,54061	19,70133	29,40199	24,74445
Standard Error	2,399133	1,864745	1,876739	1,168165
Median	23,6434	19,80642	27,37282	24,67429
Standard Deviation	8,310839	6,459667	6,501215	4,046641
Sample Variance	69,07005	41,7273	42,26579	16,37531
Kurtosis	3,257455	1,003096	-1,22341	1,207361
Skewness	1,61452	0,23189	0,231866	0,290429
Range	31,07052	24,40265	20,08879	16,01831
Minimum	15,61481	8,90118	19,57071	17,18904
Maximum	46,68533	33,30383	39,6595	33,20735
Count	12	12	12	12

Source: Author

With adjusted emission factors, patterns and tendencies in simulated concentrations follow real data collections close do default emission factors, however, errors slightly increased when compared to default EF, this could be observed due to adjustment factors been analyzed in Londrina reality, which differs from Fortaleza conditions, especially in meteorological and driving behavior parameters. The data collection point 7, which carried out higher concentrations due to strong bus traffic in the streets, also included higher errors in simulations, due to emission factors increments. Considering the non-calibration of UBM (especially for PM), the simulations shows satisfactory results when compared to real data, as can be observed in statistic analysis.

Next section presents scenario proposition and impacts in emission contributions and air pollutant concentrations reduction, for each scenario.

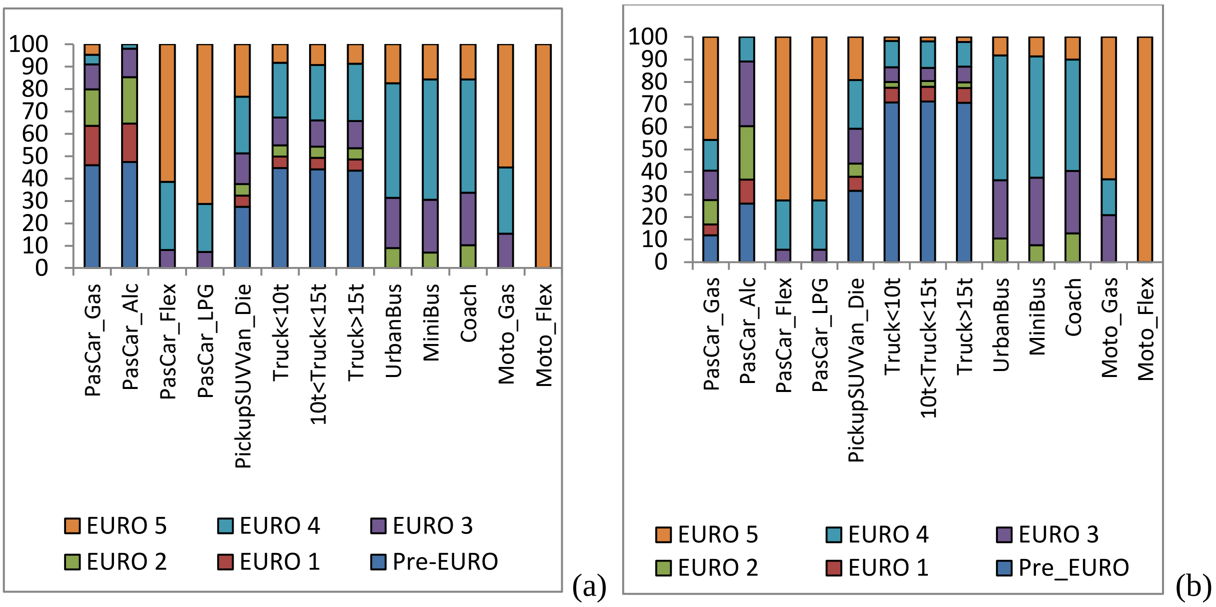
5.9 Air Quality Modelling. LEZ Performance in Different Scenarios

In order to assess impacts of proposed Low Emission Zone, seven scenarios have been suggested: (i) buses only restriction scenario; (ii) trucks only restriction scenario; (iii) pickupSUVVans only restriction scenario; (iv) passenger cars only restriction scenario; (v) buses and trucks restriction scenario; (vi) buses, trucks and pickupSUVVans restriction scenario and; Ultra Low Emission Zone (ULEZ) restriction scenario. All scenarios have been proposed following state-of-art LEZ's european scenarios, adapted for Brazilian reality. All scenarios proposes restriction to EURO2+ (Brazilian equivalent) respective restricted vehicles, with exception of ULEZ scenario, which was proposed EURO 5+ equivalent to diesel vehicles and EURO 2+ equivalent technology for passenger cars and motorcycles.

First step of analysis consisted in observe impacts in global emission factors for each scenario, compared to real traffic (non-restricted) conditions. Figure 69 shows technology emission contributions for NO_x and PM_{10} in all scenarios, in addition, Table 31 presents the global emission factors reductions in the proposed scenario. All other scenarios are presented in Appendix A.

The restrictive scenarios emission factors have been edited in both urban background concentrations model and street level model.

Figure 69 - NO_x (a) and PM_{10} (b) Emission Contributions (%) in Bus Only Euro 2+ Restriction Scenario



Source: Author

Table 31 - Global Emission Factors and Percentage Reduction Compared to Non Restricted Traffic. Bus Only Restriction Scenario

Factor	**NO_x**	**Exhaust PM_{10}**
Global Emission Factor (g/km)	0.386	0.0091
Percentage Reduction (%)	11.1	32.8

Source: Author

Global emission factor reductions shows major reductions to buses only scenario compared to trucks only scenario, due to higher bus fleet in pilot Low Emission Zone and urban buses bring higher emission factors compared to three truck types. The emission contribution histograms also indicate major contributions from Pre-Euro equivalent high-duty vehicles, especially for exhaust PM.

PickupSUVVans scenario shows low reductions in global emission factors, due to low presence in total vehicle fleet and low reductions of emission factors in technology evolution. Light duty non-diesel vehicles emits low amounts of NO_x and PM, however, technology evolution presents high levels of emission factor reductions for NO_x, what is not observed to PM. Therefore, with high fleet proportion of non-diesel light duty vehicles, passenger cars only scenario showed insignificant exhaust PM reductions, nevertheless, almost 10% of global NO_x emission factor reduction.

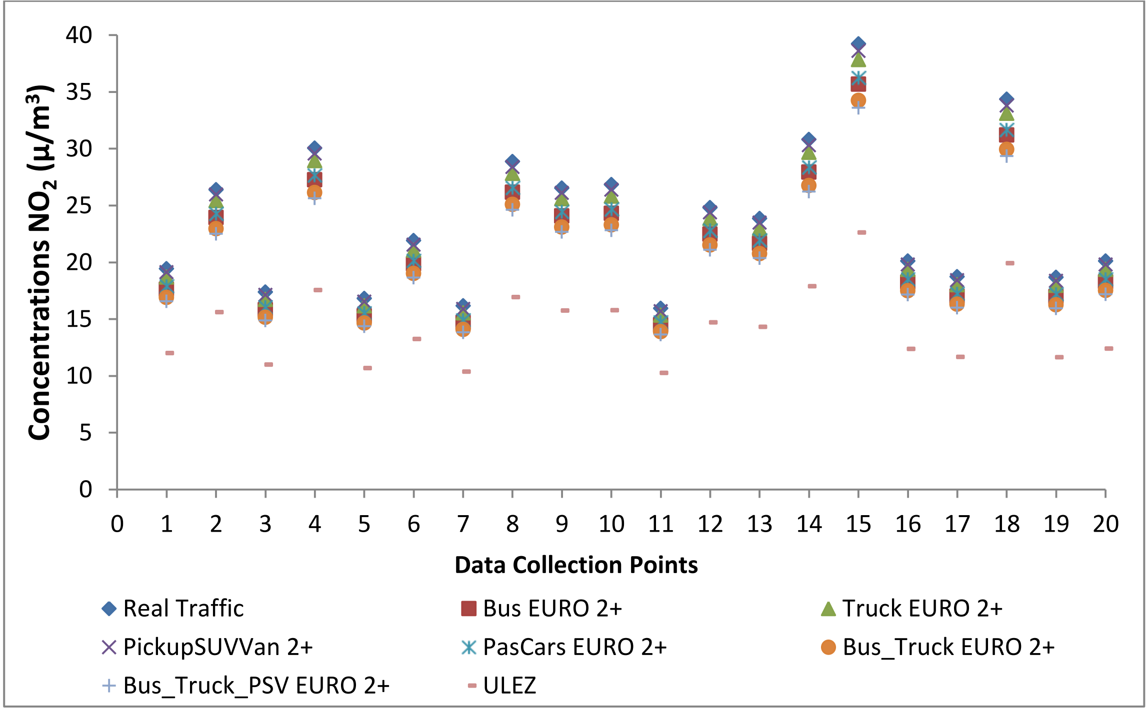
The most restrictive scenarios present gradual reduction in global emission factors, due to gradual increment in restrictions. Ultra Low Emission Zone scenario shows full potential in the restrictive measure, reducing more than 50% percent for NO_x and almost

70% for exhaust PM, and showing high potential in emission reductions with Low Emission Zones in Brazilian reality.

Considering air pollutant concentration reductions, Figures 70 to 78 and Tables 32 to 34 present reductions in concentrations for NO_2, total PM and exhaust PM for all scenarios and real traffic (non-restriction scenario). In addition, Figures 80 to 87 and Tables 35 to 37 also present concentrations reductions for the analyzed pollutants, with adjusted emission factors, in order to observe full potential in concentrations and percentage reduction in each scenario.

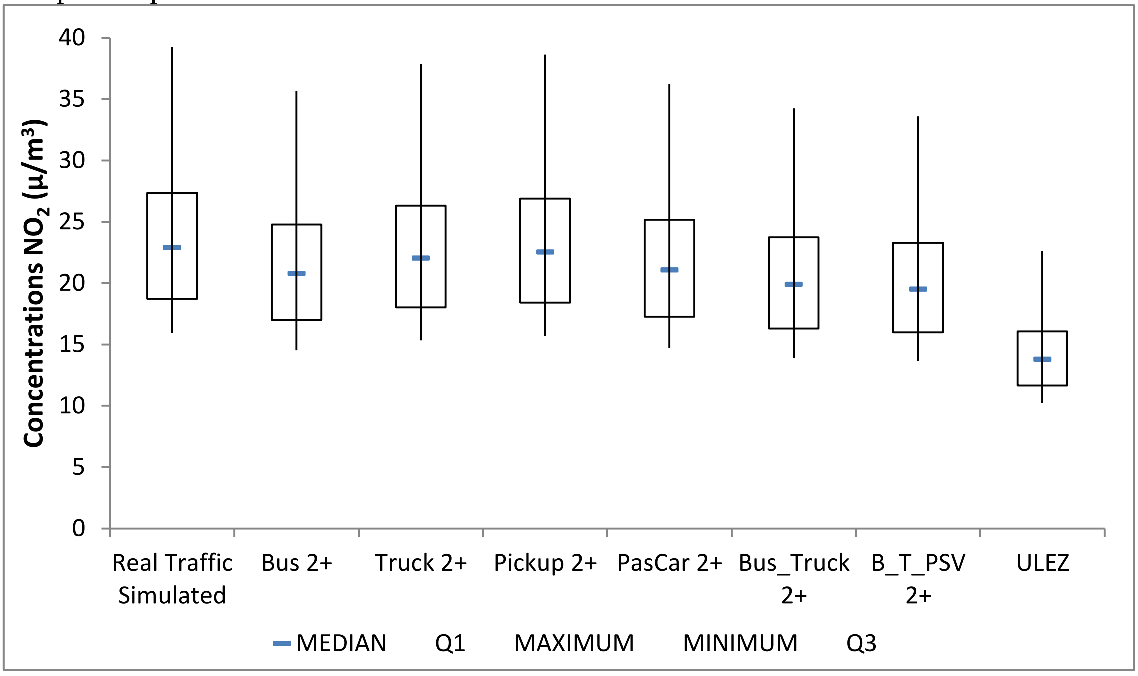
Simulations in OSPM have been carried out comparing same conditions in data collection points, day collected and traffic conditions, in order to observe consistent comparisons in air pollutant reductions. The concentration reductions in each scenario have also been calculated in urban background concentration model, which lead to reductions in urban and street levels, combining the full potential of LEZ reductions.

Figure 70 - NO_2 Concentration (μg/m3) Reductions in Different Proposed Scenarios



Source: Author

Figure 71 - NO$_2$ Concentration (µg/m3) Reductions in Different Proposed Scenarios. Boxplot Representation



Source: Author

Table 32 - NO$_2$ Average Reductions Compared to Real Traffic (Non-Restricted) Conditions

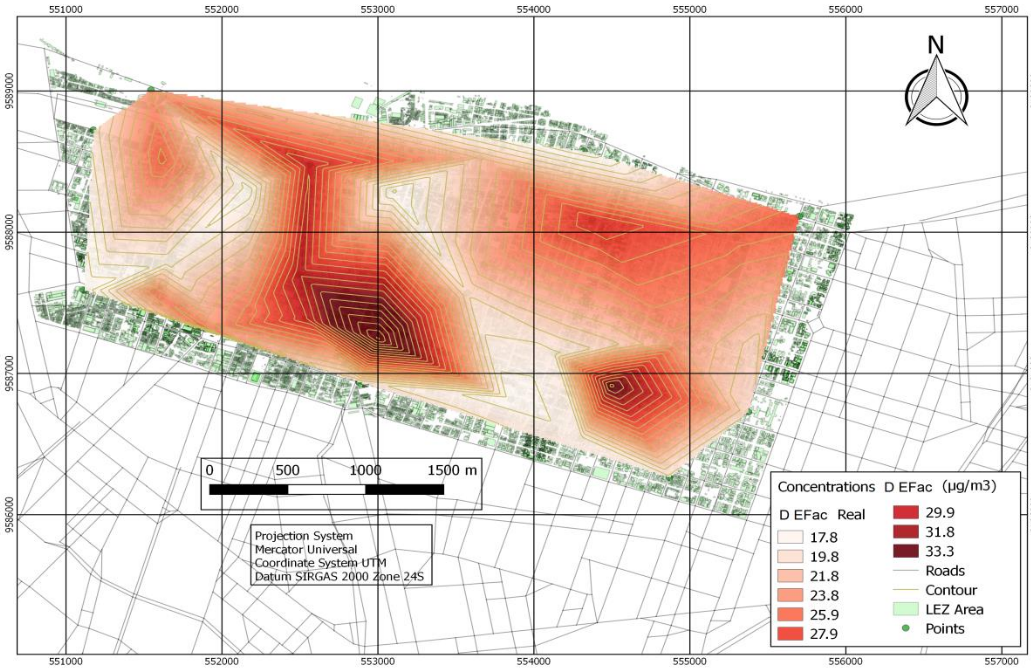
Scenario	Average Reduction (µg/m^3)	Average Reduction (%)
Bus 2+	2.2	9.22
Truck 2+	0.884	3.7
Pickup 2+	0.387	1.62
PasCar 2+	1.873	7.85
Bus_Truck 2+	3.102	13
B_T_PSV 2+	3.502	14.67
ULEZ	9.525	39.92

Source: Author

In order to visualize the real traffic data pollutant concentrations with default emission factors scenario, the Figure 73 shows the Digital Surface Modelled (DSM) for all data collection points in real traffic conditions.

The representation includes all 20 data collection points used to passive samplers (NO$_2$) and active samplers (PM$_{10}$), and describes the most polluted subareas within the established Low Emission Zone assessed.

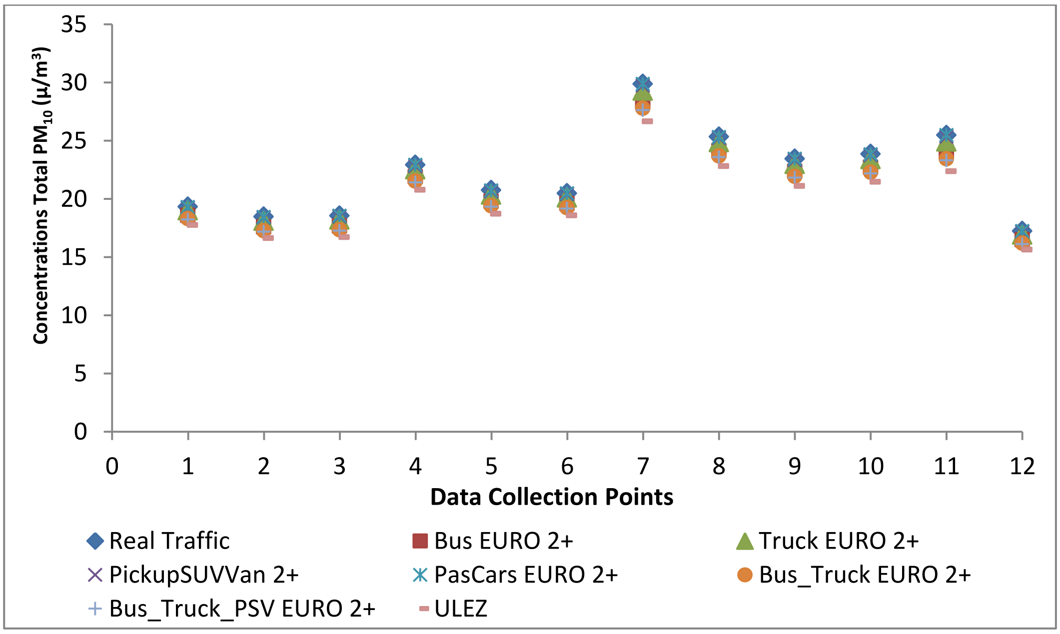
Figure 72 - Representation of air pollutant concentrations for real technology modelled with Digital Surface Model (DSM), Default Emission Factors



Source: Author

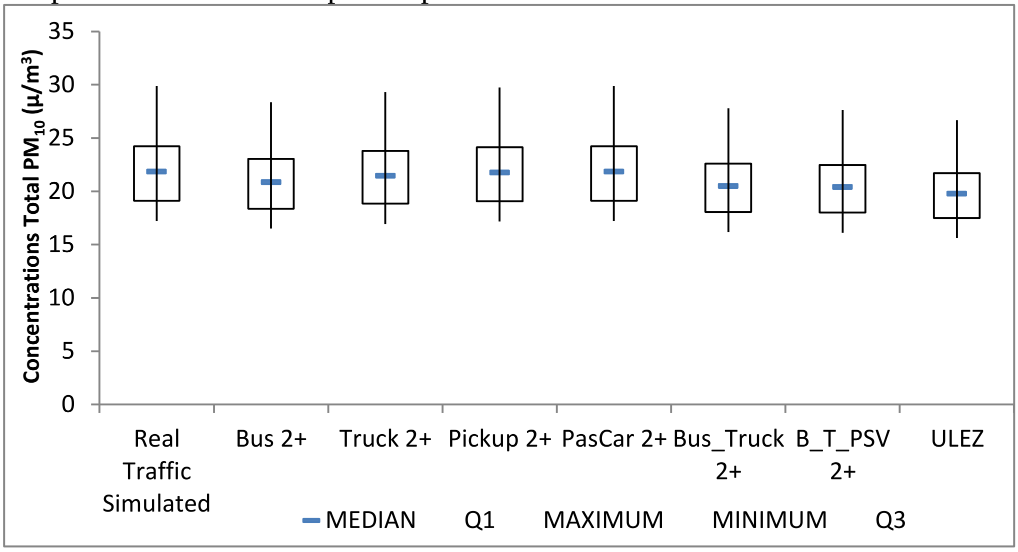
Figures 73 and 74 shows total PM_{10} concentrations reductions related to all proposed scenarios and Digital Surface Modelling (DSM) Bus2+ scenario to better visualization on reductions relatively to real traffic represented in Figure 76, respectively.

Figure 73 - Total PM_{10} Concentration (µg/m3) Reductions in Different Proposed Scenarios



Source: Author

Figure 74 - Total PM_{10} Concentration (µg/m3) Reductions in Different Proposed Scenarios. Boxplot Representation



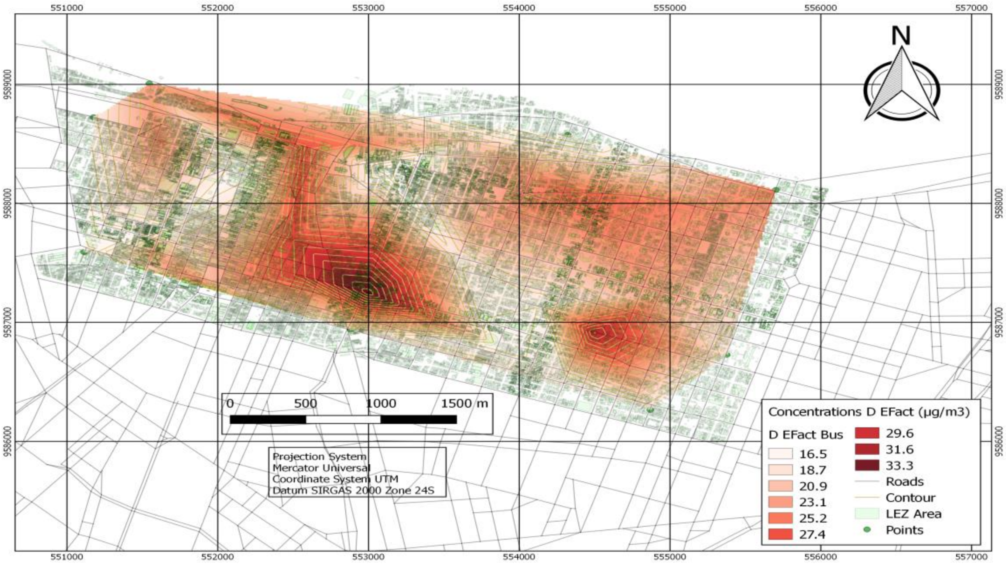
Source: Author

Table 33 - Total PM_{10} Reductions Compared to Real Traffic (Non-Restricted) Conditions

Scenario	**Reduction (µg/m³)**	**Reduction (%)**
Bus 2+	1.036	4.68
Truck 2+	0.403	1.82
Pickup 2+	0.097	0.49
PasCar 2+	0.006	0.03
Bus_Truck 2+	1.44	6.5
B_T_PSV 2+	1.537	6.94
ULEZ	2.201	9.94

Source: Author

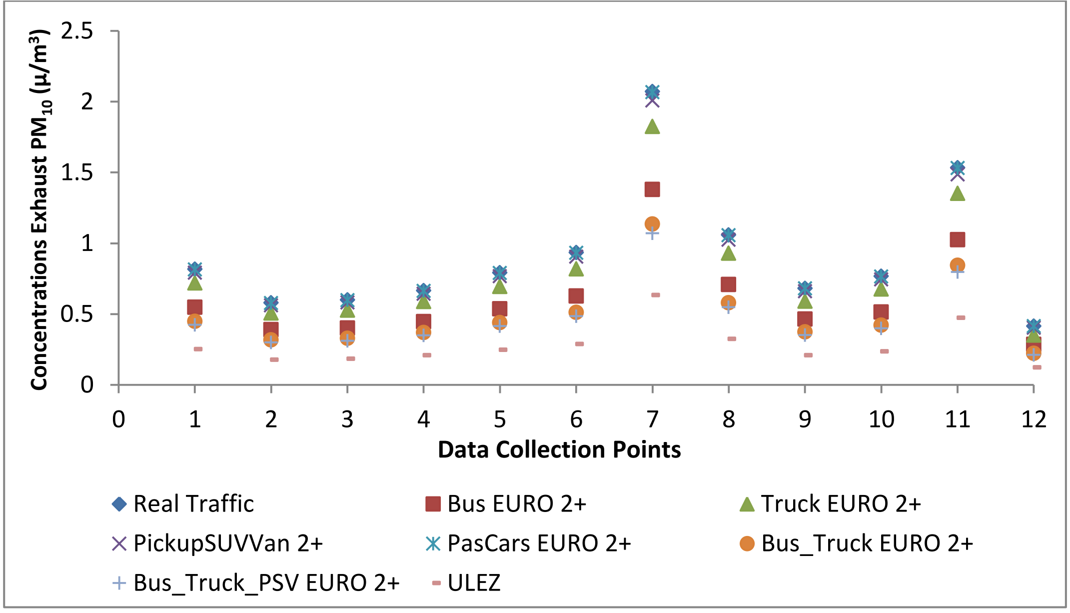
Figure 75 - Representation of air pollutant concentrations for Bus2+ scenario modelled with Digital Surface Model (MDS), Default Emission Factors



Source: Author

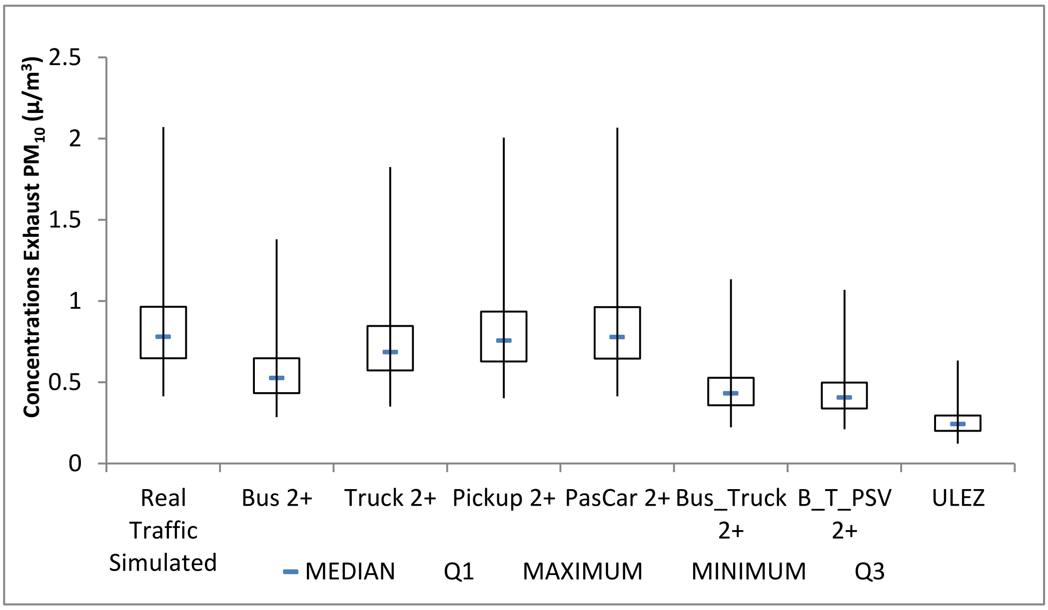
Figures 76 and 77 shows exhaust PM_{10} concentrations reductions related to all proposed scenarios and Digital Surface Modelling (DSM) ULEZ scenario to better visualization on reductions relatively to real traffic represented in Figure 79, respectively.

Figure 76- Exhaust PM_{10} Concentration (µg/m3) Reductions in Different Proposed Scenarios



Source: Author

Figure 77 - Exhaust PM_{10} Concentration (µg/m3) Reductions in Different Proposed Scenarios. Boxplot Representation



Source: Author

Table 34 - Exhaust PM_{10} Reductions Compared to Real Traffic (Non-Restricted) Conditions

Scenario	**Reduction (μg/m^3)**	**Reduction (%)**
Bus 2+	0.299	32.9
Truck 2+	0.111	12.2
Pickup 2+	0.028	3.11
PasCar 2+	0.002	0.21
Bus_Truck 2+	0.410	45.1
B_T_PSV 2+	0.439	48.21
ULEZ	0.630	69.25

Source: Author

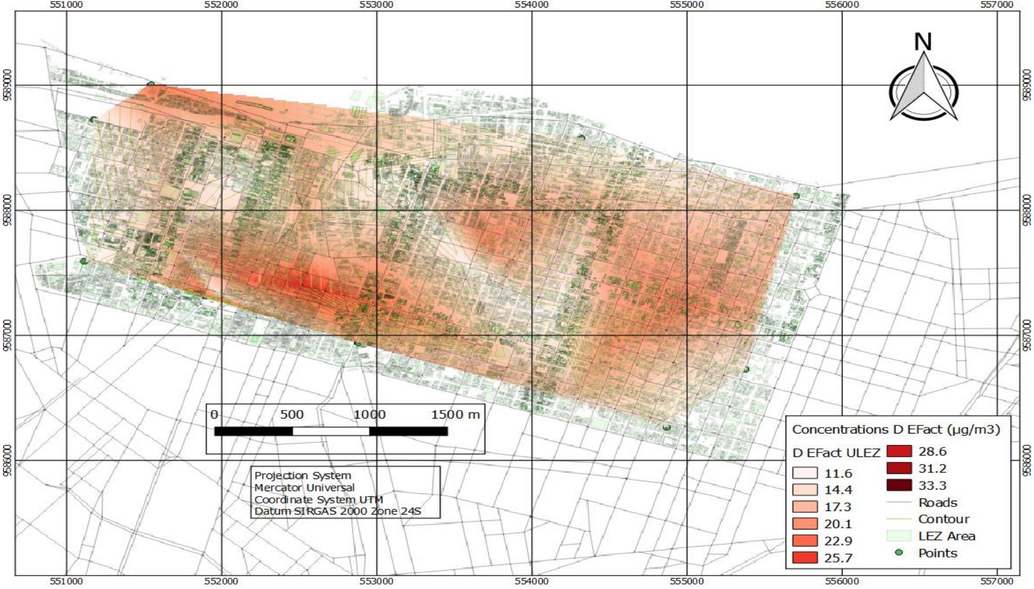
In order to visualize the most restrictive proposed scenario, the Ultra Low Emission Zone (ULEZ) concentrations with default emission factors, the Figure 79 shows the Digital Surface Modelled (DSM) for all data collection points in ULEZ high restriction conditions.

The representation includes all 20 data collection points used to passive samplers (NO_2) and active samplers (PM_{10}), and describes the most polluted subareas within the established Low Emission Zone assessed.

A DSM is an elevation model that includes the tops of everything, including buildings, treetops, and ground where there is nothing else on top of it. The surface modelled takes into account NO_2 and PM_{10} concentrations, including all 32 data collection points, 20 related to NO_2 passive data samplers and 12 related to PM_{10} active data samplers, in different places, due to operational reasons.

The ULEZ scenario shows huge reductions, which can be viewed in Figure 78, by clearer colors in red tones of Digital Surface Modelled presented in the Figure. The real technology condition presented in Figure 72 shows red tones much darker, due to higher concentrations in real scenario.

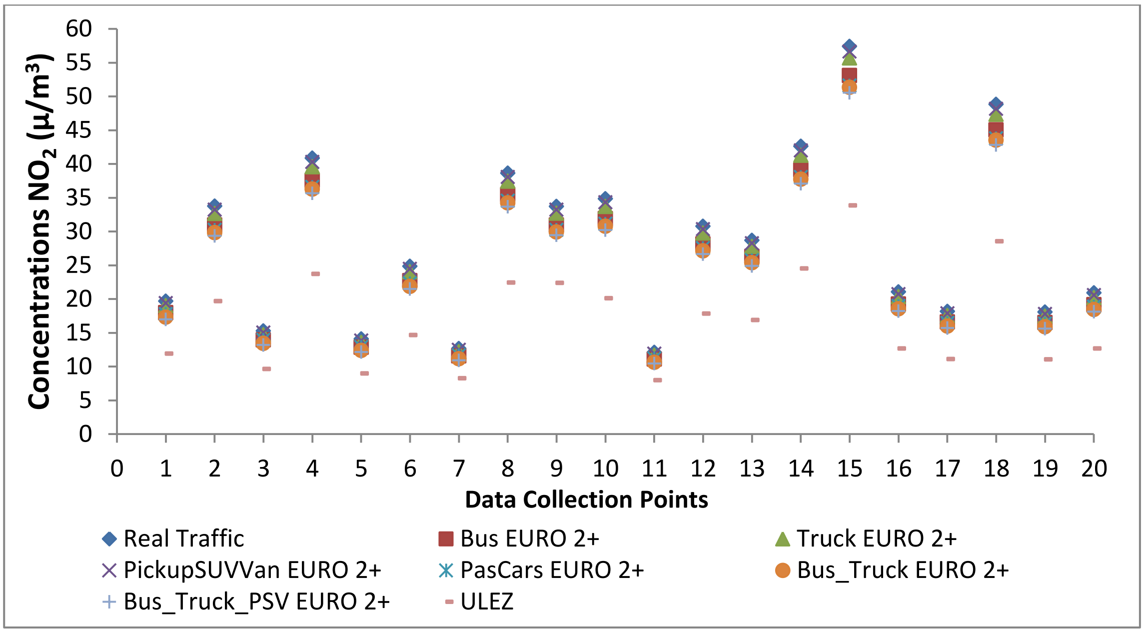
Figure 78- Representation of air pollutant concentrations for ULEZ scenario modelled with Digital Surface Model (MDS), Default Emission Factors



Source: Author

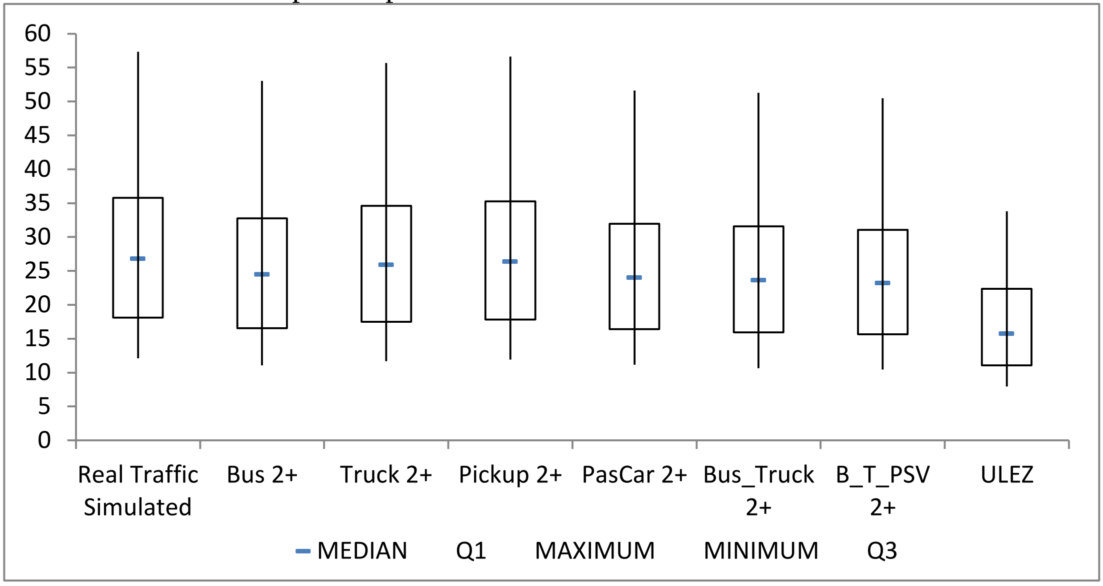
All scenarios will now be shown with adjusted emission factors modelling, in order to observe the impacts in reductions for NO_2, total PM_{10} and exhaust PM_{10}, considering the adjusted emission factors for previous Brazilian studies. Figures 79 and 80 shows NO_2 concentrations reductions related to all proposed scenarios and Digital Surface Modelled (DSM) for all data collection points in real traffic conditions, represented in Figure 81, respectively.

Figure 79 - NO_2 Concentration (µg/m3) in Different Proposed Scenarios. Adjusted Emission Factors



Source: Author

Figure 80 - NO_2 Concentration (µg/m3) in Different Proposed Scenarios. Adjusted Emission Factors. Boxplot Representation.



Source: Author

Table 35 - NO_2 Average Reductions Compared to Real Traffic (Non-Restricted) Conditions. Adjusted Emission Factors.

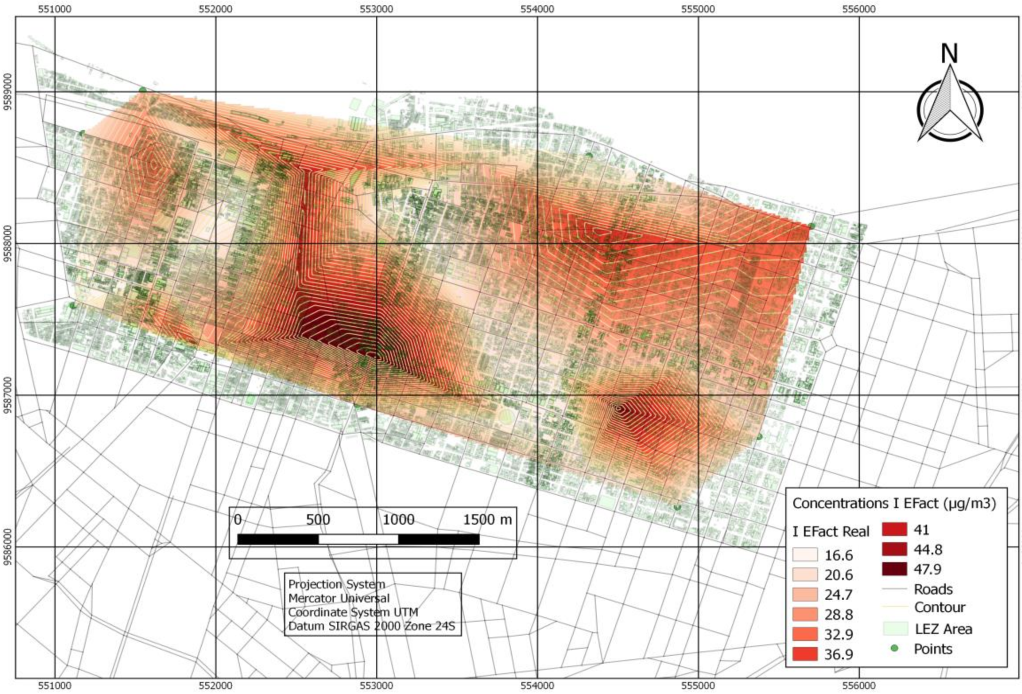
Scenario	Reduction (µg/m^3)	Reduction (%)
Bus 2+	2.336	8.25
Truck 2+	0.913	3.22
Pickup 2+	0.411	1.45
PasCar 2+	2.845	10.04
Bus_Truck 2+	3.477	12.28
B_T_PSV 2+	3.693	13.04
ULEZ	11.405	40.27

Source: Author

In order to visualize the real traffic data pollutant concentrations with adjusted emission factors scenario, Figure 72 shows the Digital Surface Modelled (DSM) for all data collection points in real traffic conditions.

The representation includes all 20 data collection points used to passive samplers (NO_2) and active samplers (PM_{10}), and describes the most polluted subareas within the established Low Emission Zone assessed.

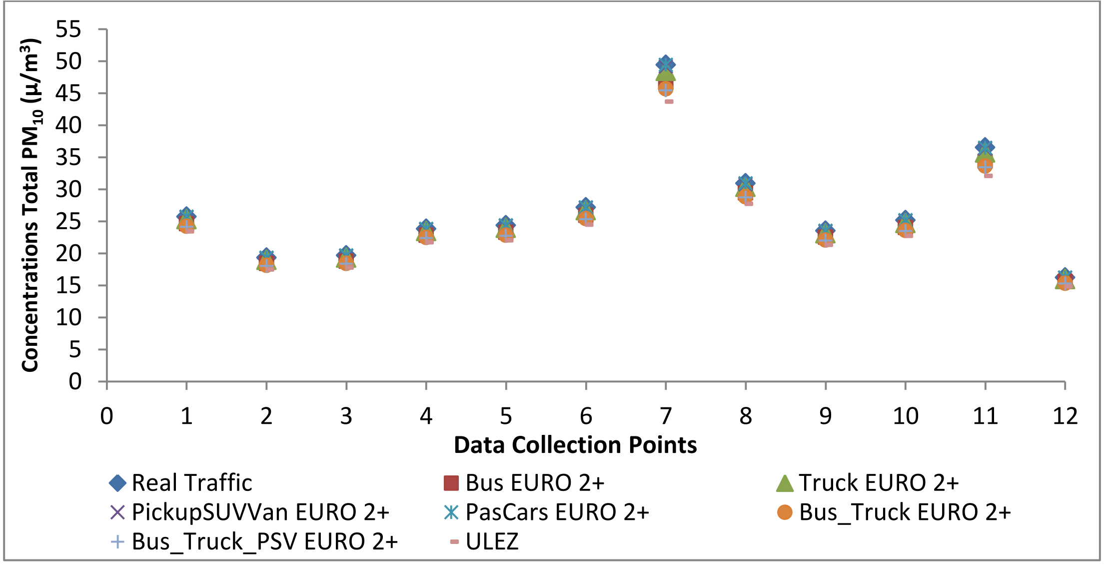
Figure 81– Representation of air pollutant concentrations for real technology modelled with Digital Surface Model (MDS). Adjusted Emission Factors.



Source: Author

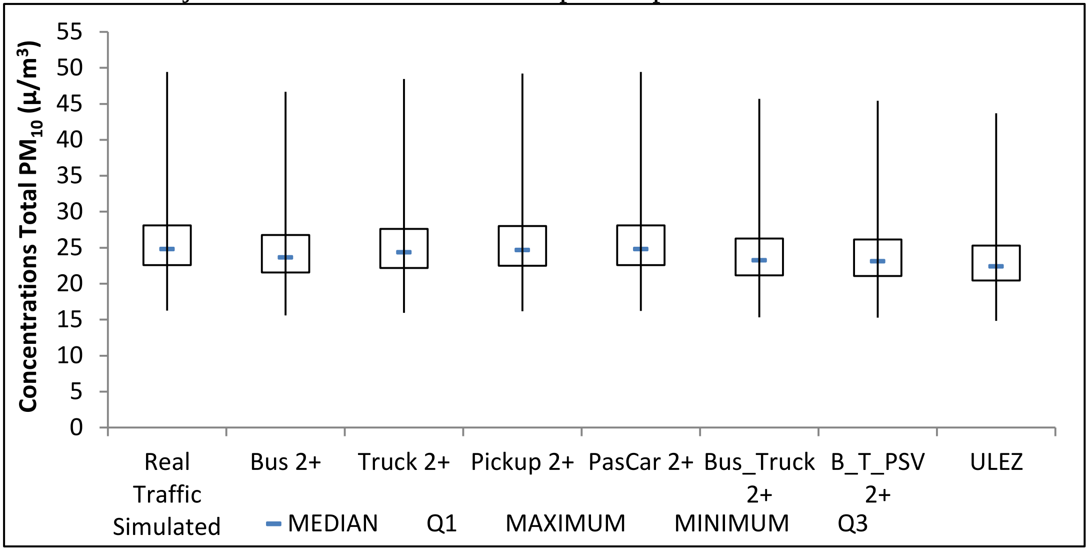
Figures 82 and 83 shows total PM_{10} concentrations reductions related to all proposed scenarios with adjusted emission factors and Digital Surface Modelling (DSM) Bus2+ scenario to better visualization on reductions relatively to real traffic represented in Figure 85, respectively.

Figure 82 - Total PM_{10} Concentrations (µg/m^3) Reductions in Different Proposed Scenarios. Adjusted Emission Factors.



Source: Author

Figure 83 - Total PM_{10} Concentrations (µg/m^3) Reductions in Different Proposed Scenarios. Adjusted Emission Factors. Boxplot Representation.



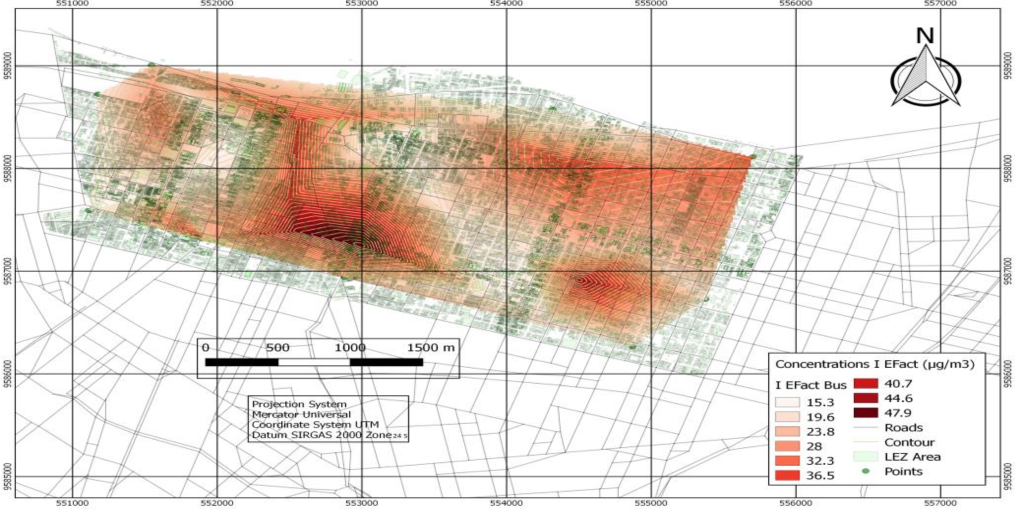
Source: Author

Table 36 - Total PM_{10} Reductions Compared to Real Traffic (Non-Restricted) Conditions. Adjusted Emission Factors

Scenario	Reduction (µg/m3)	Reduction (%)
Bus 2+	1.292	4.81
Truck 2+	0.484	1.80
Pickup 2+	0.122	0.45
PasCar 2+	0.010	0.03
Bus_Truck 2+	1.775	6.62
B_T_PSV 2+	1.897	7.07
ULEZ	2.726	10.16

Source: Author

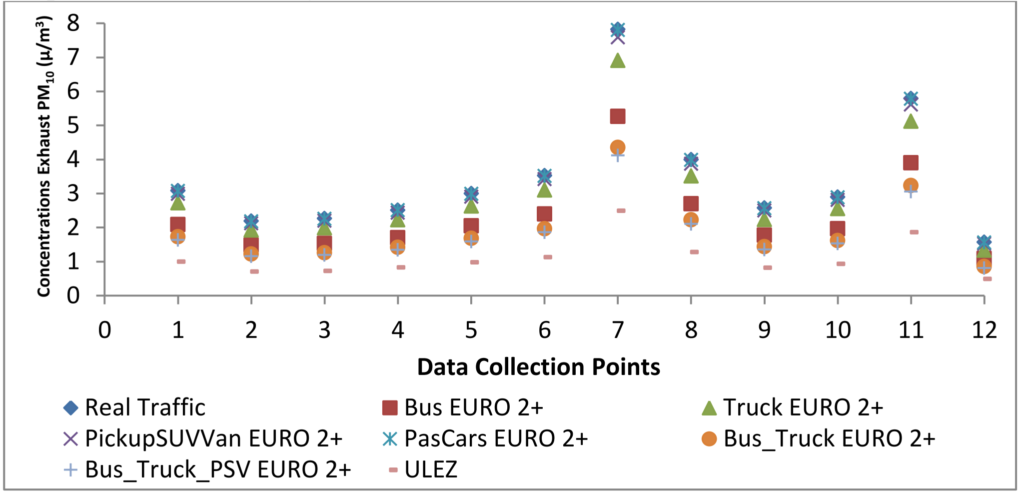
Figure 84 - Representation of air pollutant concentrations for Bus2+ scenario modelled with Digital Surface Model (MDS). Adjusted Emission Factors



Source: Author

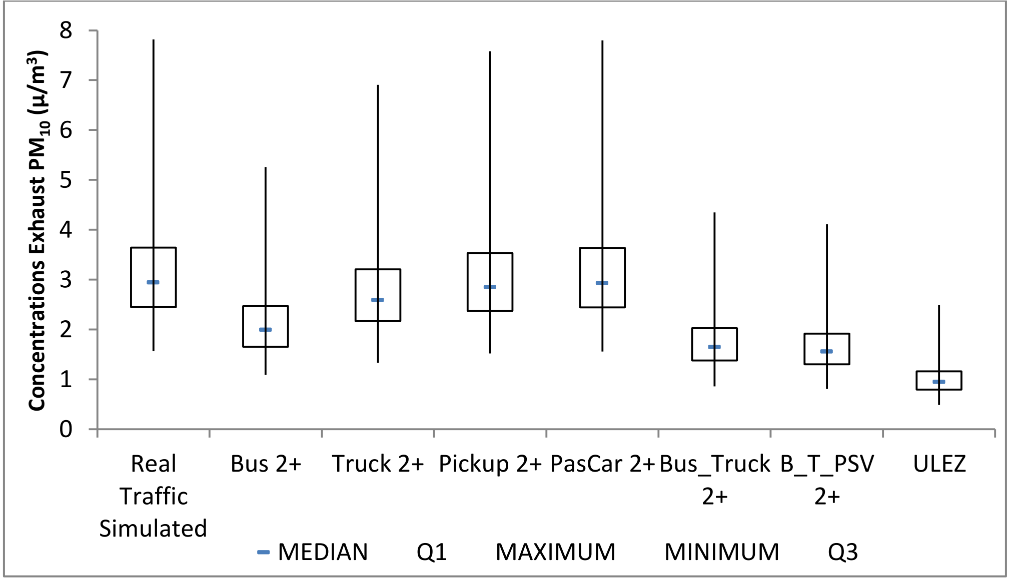
Figures 85 and 86 shows exhaust PM_{10} concentrations reductions related to all proposed scenarios with adjusted emission factors and Digital Surface Modelling (DSM) ULEZ scenario to better visualization on reductions relatively to real traffic represented in Figure 87, respectively.

Figure 85 - Exhaust PM_{10} Concentration (µg/m3) Reductions in Different Proposed Scenarios. Adjusted Emission Factors



Source: Author

Figure 86 - Exhaust PM_{10} Concentration (µg/m3) Reductions in Different Proposed Scenarios. Adjusted Emission Factors. Boxplot Representation



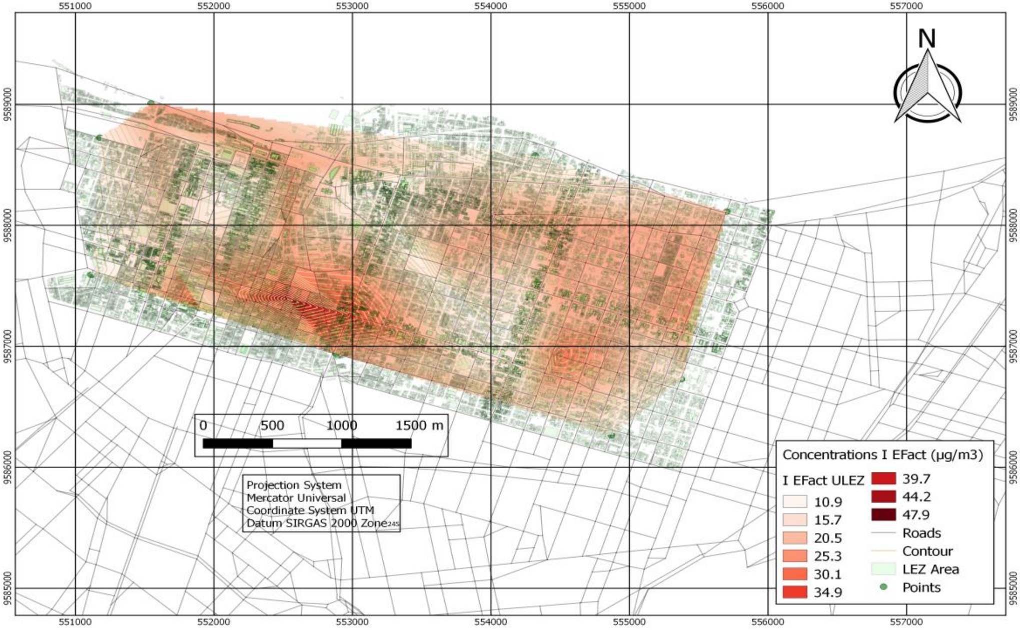
Source: Author

Table 37 - Exhaust PM_{10} Reductions Compared to Real Traffic (Non-Restricted) Conditions. Adjusted Emission Factors

Scenario	**Reduction (μg/m3)**	**Reduction (%)**
Bus 2+	1.107	32.26
Truck 2+	0.031	0.90
Pickup 2+	0.105	3.05
PasCar 2+	0.009	0.27
Bus_Truck 2+	1.518	44.22
B_T_PSV 2+	1.623	47.27
ULEZ	2.334	67.99

Source: Author

Figure 87- Representation of air pollutant concentrations for ULEZ scenario modelled with Digital Surface Model (MDS). Adjusted Emission Factors



Source: Author

First, NO_2 reductions for default emission factors shows significant improvements in global air pollution to heavy-duty vehicle restrictions, especially to buses restrictive scenario, with 2.2 μg/m^3 or 9.2% reduction, due to higher contribution by higher proportion in global vehicle fleet and higher emission factors, when compared to trucks. In addition, passenger cars, in principle, emits low amounts of NO_x, however, due to high proportion of light-duty vehicles, NO_2 concentration reduction in passenger cars scenario was observed with high percentage, higher than truck only scenario and close to buses only scenario. Ultra Low Emission Zone scenario showed around 9.5 μg/m^3, what represents around 40% of NO_2 concentration reduction, what bring high potential in most restrictive scenario.

NO_2 reductions in adjusted emission factors present even higher absolute concentration reductions, especially for passenger cars, due to high fleet proportion. In this case passenger cars only scenario present higher potential, even considering buses scenario. ULEZ scenario reduced almost 11.5 µg/m^3, representing massive concentration reduction. This magnitude of reductions could aid to make legislation limits to reach municipality goals. Potential reductions in NO_x concentrations are even higher when compared to NO_2, due to proportional exhaust related emission of NO_2 being in order of around 20% of total emissions.

Total PM concentrations in default emission factors analysis showed proportional lower reductions when compared to NO_2 reductions, due to higher contribution of non-exhaust in total PM, not changed by technology only restriction, however, buses only restriction scenario already bring high potential in concentrations, around 1 µg/m^3, with ULEZ scenario with 2.2 µg/m^3 reduction, representing around 4.7% and 10% reductions, respectively. Passenger cars scenarios presented insignificant reductions to PM concentrations, due to low impact in PM emissions for gasoline vehicle technology (Brazilian legislation does not allow diesel passenger cars). The PM concentrations in data collection points 7 and 11 shows more reductions in simulations due to high proportion of buses in respective streets, and their technology in Fortaleza (in average) is still delayed, what shows high reductions in technology enhancements in scenarios.

Total PM concentrations in adjusted emission factors present even more total PM reductions in buses only scenario and ULEZ scenario, with 1.3 µg/m^3 and 2.7 µg/m^3, which could be potentially the amount necessary to reach legislation limits or municipality goals in air pollution improvement.

Exhaust PM concentrations in default emission factors showed reductions in buses only scenario of 0.3 µg/m^3 and ULEZ 0.62 µg/m^3, which represents 33% and 70% proportional reductions. These low absolute concentration reductions considers only street level concentrations, however, impacts in urban background concentrations increases the total air pollution, which leads to higher improvements in LEZ implementation.

With exhaust PM concentrations in adjusted emission factors, absolute reductions are significantly higher when compared to default emission factors, showing 1.1 µg/m^3 and 2.3 µg/m^3, for buses only scenario and ULEZ scenario, respectively. These absolute concentrations in street levels present values with order of magnitude high enough to reach legislation goals.

ULEZ scenario presents significant higher potential in air pollutions concentrations, however, due to feasibility in economic and social criteria of Fortaleza municipality, buses only scenario could be consider as start point to implement a Low Emission Zone, with tax reductions and subsidies to vehicle fleet evolution.

The most developed countries in Europe, such as: Austria, Denmark, Germany, England, among others, suggests interventions to EURO 3+ vehicles and even EURO 4+ vehicle fleet, due to advances in EURO 6+ vehicle circulation in their fleet (briefly presented in Table 1), however, the most advanced technology in Brazilian fleet is EURO 5, therefore the restrictions are suggested starting at EURO 2+ equivalent, what make possible to even higher reductions with advances in Brazilian fleet technology in near future.

In 2023, EURO 6 equivalent technology will reach Brazilian fleet, which will bring higher potential in Low Emission Zone imposition. These concentrations and percentages could increase even more with EURO 6 technology reaching Fortaleza vehicle fleet. Next section will present conclusions taken with emissions and air pollutant concentrations assessment carried out throughout this research.

6 CONCLUSIONS

In this chapter, the last step of the proposed method is described, in order to present conclusions about this research. The inquiries, which motivated the study, presented in the first chapter, will be answered in this section. Therefore, this chapter is divided into three sections: (6.1) Brief research exposition; (6.2) Main conclusions; (6.3) Suggestions for future studies.

6.1 Brief Research Exposition

This research project is inserted in transportation environmental impacts group, within the research line developed in UFC Department of Transportation Engineering, in partnership with Environmental Sciences Department of Aarhus University and LABOMAR (Instituto de Ciências do Mar), under the guidance of Assistant Professor Bruno Vieira Bertoncini, and co-supervising of Senior Scientist Steen Solvang Jensen and Assistant Professor Rivelino Martins Cavalcante. This research line aims to understand the scale of impacts, under the viewpoint of social, economic and especially environmental sustainability that restrictive measures, in this study Low Emission Zones, may incur in densely populated urban areas, with huge presence of commercial and residential activities, such as northern region of Fortaleza municipality.

The main objective of this research was to develop a methodology to assess air pollution impacts of Low Emission Zones in Brazilian urban areas, using as study case a densely commercial and residential area of Fortaleza, by means of real data collection of air pollutant concentrations in street levels and integrating a travel demand model with an air pollution modelling system. To reach this main objective, six specific objectives have been established, in order to successfully develop the methodology.

- To explore state-of-art strategies of Low Emission Zones implementation, and how this strategy can be adapted to Fortaleza reality;
- Evaluate emission factors and air quality modelling parameters for Low Emission Zones assessment;
- To analyze methodology parameters for estimation of travel demand on a road network applicable for air quality modelling;
- Validate air pollution dispersion model against air quality measurements, and calibrate model if necessary;

- Analyze the spatial and temporal variation of different air pollutants in the selected area for Low Emission Zone;
- Evaluate criteria to define different scenarios for Low Emission Zone regulation and model the impact to emissions and air quality.

The conclusions will be briefly discussed for each of the suggested stages where the method was developed.

6.1.1 Literature Review

Through state-of-art literature review, it was possible to conclude that most Brazilian studies for urban planning process do not consider air pollution impacts caused by vehicle traffic, but mainly traffic relate issues only. Considering the absence of traffic related air pollution studies in transportation planning, it was sought to develop the described methodology.

In addition, it was possible to understand the capabilities of integrating travel demand modelling with traffic related air pollution modelling system, regarding the inclusion of air pollution impacts in urban planning process. It is important to emphasize that this effort was never carried out in Brazilian reality until this study.

6.1.2 Methodological Proposal

The advantages of the proposed Low Emission Zone assessment methodology presented in this research are: (i) development of a new approach to distribute air pollutant data collectors in Brazilian urban areas, aiming to assess pollutant concentrations in street levels; (ii) development of passive air pollutant NO_2 data collectors, making viable low cost air pollutant studies in developing countries; (iii) carry out the integration of travel demand models estimation outputs as inputs to street levels air pollution assessment; (iv) adjusts to meteorological parameters do south hemisphere air pollution analysis; (v) calibration of THOR-AirPAS air pollution modelling system to Brazilian reality; among others.

6.1.3 Experiment and Results Analysis

With the support of Labomar (Sea Sciences Institute) in UFC, Department of Environmental Sciences of Aarhus University in Roskilde - Denmark, it was possible to develop the methodology of passive NO_2 data collection and adapt the active PM data collection carried out in this research, and to code, adjust and calibrate the models within THOR-AirPAS air pollution modelling system used in this research, respectively.

It was possible to observe the capability to cover large areas with air pollution passive and active data collectors, and the possibility of expanding the analysis in theses urban areas with the air pollution modelling system. This capability is important in developing countries, due to lack of research resources and different scenarios analysis. The possibility of expanding air pollution analysis in urban areas can be used to include traffic related environmental impacts in Brazilian urban areas.

THOR-AirPAS air pollution modelling system proved to be capable of estimate air pollutant concentrations in street levels of Fortaleza, however, advantages and limitations have been observed during modelling processes, such as: (i) capability of estimate air pollution in street levels daily and hourly; (ii) capability of including traffic speeds, cold start, mileage emission factor increments, among others, making the modelling tool estimated with higher details and accuracy; (iii) NO_2 proportion in NO_x vehicles emissions, important to calibrate to each observed reality; (iv) capability of emission factors calibration by changing emission factor values or equations; (v) incapable of include precipitation increment in rain days (OSPM), which can calculate overestimations in PM concentrations in observed rainy data collected situations.

The estimations have been considered satisfactory, when compared to real data collected in field. It is important to emphasize that with literature review, studies with street air pollution Low Emission Zone analysis in Brazil have never been carried out before, therefore the method proposed has been considered successfully accurate, in order to observe air pollution reduction proportions with restrictive measure impositions, such as LEZ’s.

6.2 Main Conclusions

It was observed that outputs from travel demand models can be used as inputs to air pollution street levels modelling, however, due to observed errors from estimated concentrations compared to real data collected in the field shows that accurate models calibration processes are necessary, in addition, real data collected must be carried out during longer times and in additional points, in order to calibrate the air pollution system in a more accurate way, also the errors observed in simulated data can be attributed to far different reality of developed models, considering Danish vehicle, fuel and driving behavior reality, which reinforces the necessity of robust real data collection.

The regional and urban background concentrations modelled by IFS and UBM (respectively) showed satisfactory results that could be observed in PM background, exhaust and non-exhaust final proportional concentrations, however, in order to increase accuracy in these air pollution levels, it is necessary to carry out strong data collections, with historical series, to calibrate and validate the aggregate air pollution levels. This procedure could significantly increase accuracy in estimations, especially regarding IFS, which presents strong aggregation in estimations.

To conclude the text, the research questions suggested in the introductory chapter and that motivated the accomplishment of this project, are now answered:

- How the latest strategies of Low Emission Zone implementation can be adapted for Fortaleza reality?

The technologies of vehicles and fuel, traffic restrictions could be adapted to Fortaleza Low Emission Zone through the comparison with EURO standards and vehicle distribution analysis. Considering the delayed Brazilian technology evolution, the suggested implementation of LEZ has been decreased to start with EURO 2 equivalent technologies, with possibility to further analysis to increase technologies.

- What methodology is suitable for collection of vehicle emissions and air pollutant concentrations for assessment of Low Emission Zones?

CETESB Brazilian official emission factors could be successfully adapted to LEZ assessment, however, a previous study showed that underestimation in Brazilian emission factors could bring uncertainty to the analysis. The adjustments in emission factors have also been carried out to observe potential higher impacts in air pollutant reductions. The active (PM) and passive (NO_2) air pollutant concentration real data collection brought satisfactory results in order to calibrate the estimated concentrations in modelling stage.

- Which methodology of travel demand estimation is appropriate to Low Emission Zone road network modelling?

In order to road network air pollution modelling, THOR-AirPAS system requires Annual Average Daily Traffic, vehicles speeds, traffic distribution and vehicle technologies as input parameters. Therefore, TRANUS Integrated Land Use and Transport Model could be successfully used to estimate vehicle distribution within the area observed as pilot LEZ.

- How can an air quality tool be validated to pollutant concentrations estimation in Low Emission Zones, considering the particularities of Fortaleza?

The air quality could be validated, considering the particularities of Fortaleza using the active and passive real data collected in different urban canyon formations of analyzed area of pilot Low Emission Zone as validation data. The different average traffic, meteorological conditions and building configuration allowed including significant changes in air pollution modelling that showed consistent tendencies in estimations, compared to real data.

- How is the spatial and temporal variation of traffic and air pollutants in the area of a potential Low Emission Zone?

This study showed that land use is directly involved in air pollution in street levels, due to buildings and traffic impacts to concentration proportions and residence time. The time aggregation in analysis is important to the study, due to regional and background concentrations, which impacts significantly in street level concentrations.

- Which scenarios could be proposed, in order to assess the potential of Low Emission Zones?

The most important vehicles types have been simulated with technology adjustments, in order to assess LEZ potential, they were: (i) bus technology scenario; (ii) truck technology scenario; (iii) pickupSUVVan technology scenario; (iv) passenger car technology scenario; (v) bus and truck technology scenario; (vi) bus, truck and pickupSUVVan technology scenario and; (vii) ultra Low Emission Zone technology scenario. The proposed scenarios were capable of progressively demonstrate the potential of LEZ implementation. The last scenario (ULEZ) showed massive air pollutant concentrations reductions, however, considering Brazilian economic issues, bus technology scenario could be implemented with good results in air pollution reduction.

6.3 Suggestions for Future Studies

Air quality and Low Emission Zones are fields that still allow several different studies, especially considering Brazilian urban areas (due to lack of robust researches). The approach presented in this study observed only a specific aggregated part. Therefore, this section will list some points that could be used as future research approaches.

- Carry out solid emission factors research inventory, in order to reduce underestimations and uncertainties, which will reduce errors in air pollutant concentrations estimation in street levels;

- Carry out street levels robust air pollutants concentrations real data collections. Historical series should be constructed, within urban area, in order to calibrate the estimations accurately;
- Regional and urban background concentrations real data collections historical series. In order to calibrate and validate regional and urban background concentration models;
- Real traffic data collection inventory for observed streets in analyzed Low Emission Zone. Disaggregated traffic data collection could reduce errors in air pollution concentration estimations;
- Driving behavior and vehicle technology impacts on emission factors, such as: cold start, mileage increment and speed. For this, new driving cycles must be carried out, in order to observe the increments;
- New studies considering PROCONVE 8 (EURO 6 equivalent) technology, in order to evaluate the potential in further vehicle technologies;
- Observe the impacts of Low Emission Zone area changing. The cost in increasing area of restrictive measures in economic, social and environmental perspective;
- Assess different travel scenarios. Observe the potential in transportation modes changing within Low Emission Zone;
- Emission Factors increment specific to Fortaleza reality. In case of using CETESB emission factors, carry out a new adjustment considering Fortaleza driving and meteorological conditions.

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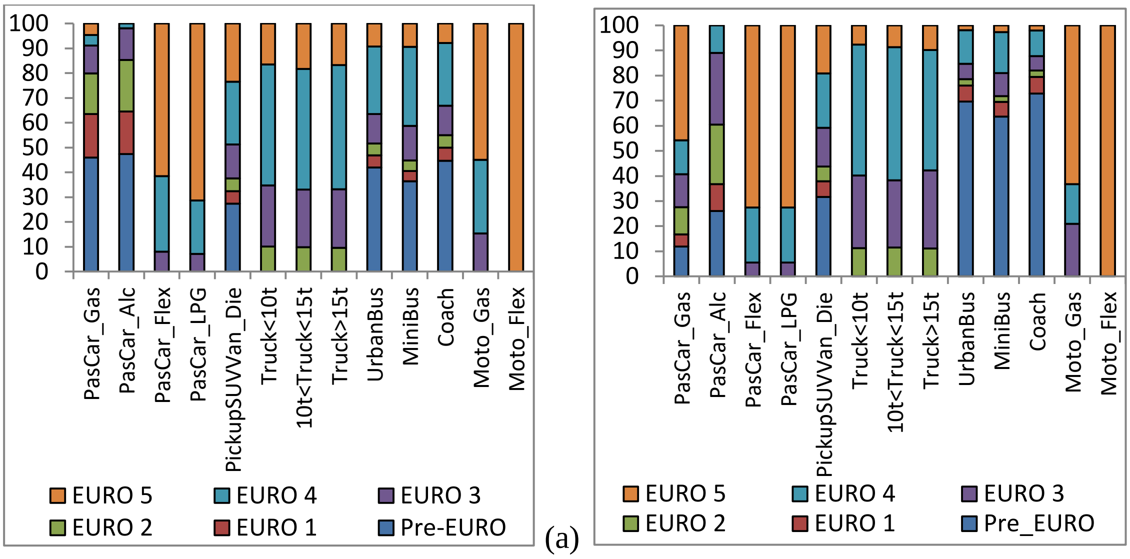
APPENDIX A

NOx (a) and PM_{10} (b) Emission Contributions (%) in Truck Only Euro 2+ Restriction Scenario



(a) (b)

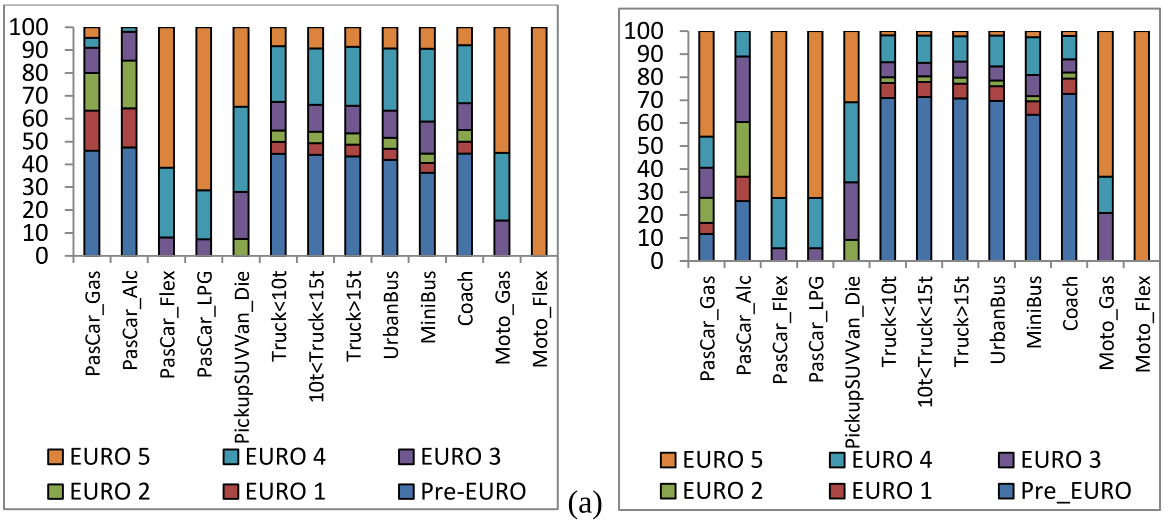
Source: Author

Global Emission Factors and Percentage Reduction Compared to Non Restricted Traffic. Truck Only Restriction Scenario

Factor	NO_x	Exhaust PM_{10}
Global Emission Factor (g/km)	0.414	0.0112
Percentage Reduction (%)	4.6	13

Source: Author

NO_x (a) and PM_{10} (b) Emission Contributions (%) in PickupSUVVan Only Euro 2+ Restriction Scenario



(a) (b)

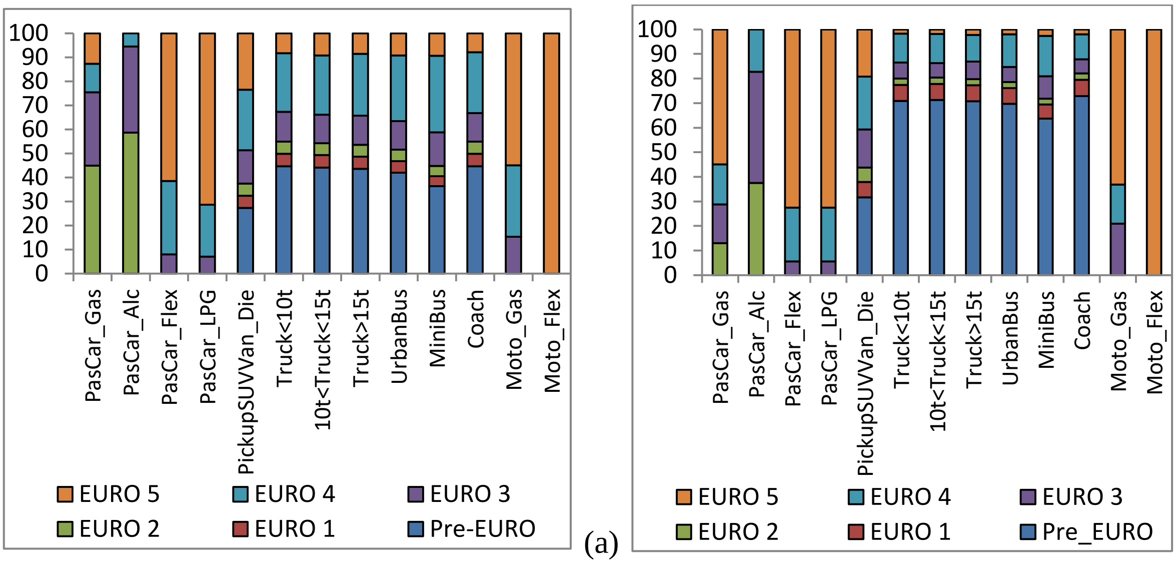
Source: Author

Global Emission Factors and Percentage Reduction Compared to Non Restricted Traffic. PickupSUVVan Only Restriction Scenario

Factor	**NO_x**	**Exhaust PM_{10}**
Global Emission Factor (g/km)	0.426	0.0130
Percentage Reduction (%)	1.9	3.1

Source: Author

NO_x (a) and PM_{10} (b) Emission Contributions (%) in Passenger Cars Only Euro 2+ Restriction Scenario



(a) (b)

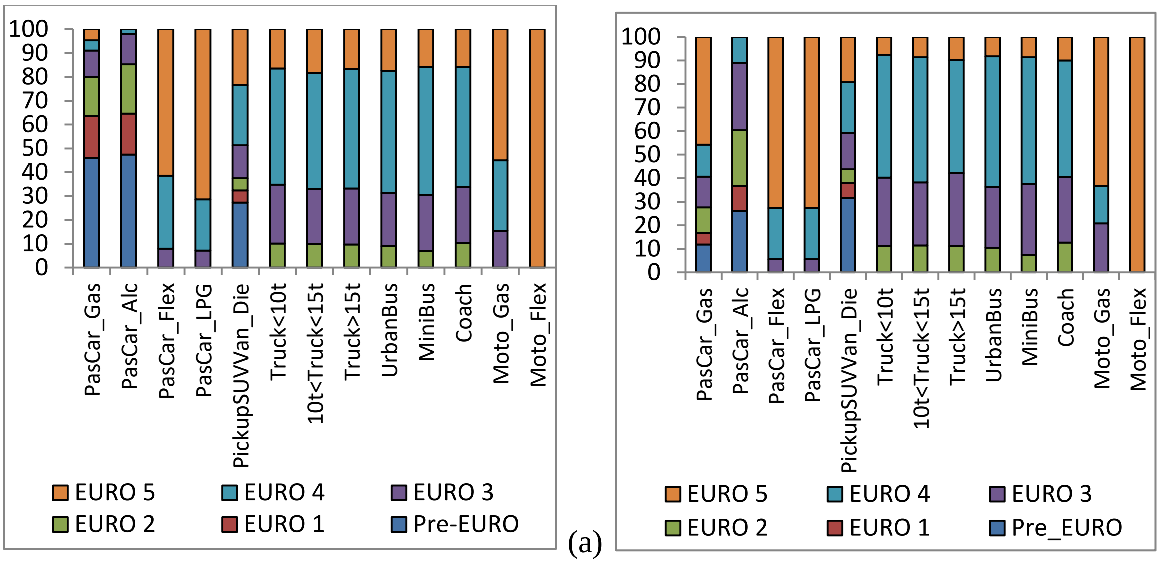
Source: Author

Global Emission Factors and Percentage Reduction Compared to Non Restricted Traffic. Passenger Cars Only Restriction Scenario

Factor	**NO_x**	**Exhaust PM_{10}**
Global Emission Factor (g/km)	0.393	0.0130
Percentage Reduction (%)	9.4	0.8

Source: Author

NO_x (a) and PM_{10} (b) Emission Contributions (%) in Bus and Truck Euro 2+ Restriction Scenario



(a) (b)

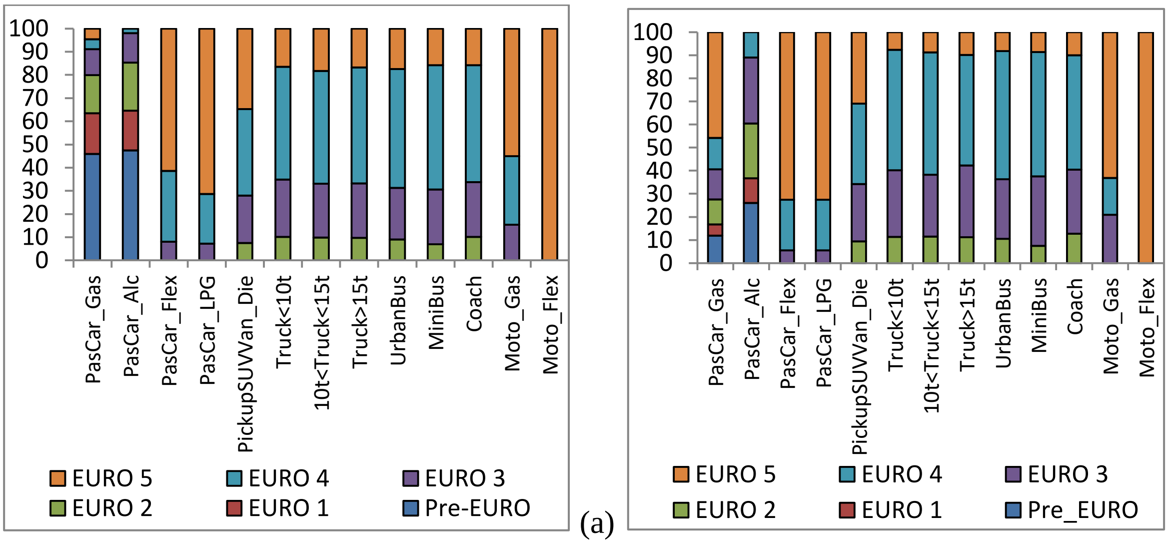
Source: Author

Global Emission Factors and Percentage Reduction Compared to Non Restricted Traffic. Bus and Truck Restriction Scenario

Factor	NO_x	Exhaust PM_{10}
Global Emission Factor (g/km)	0.365	0.0071
Percentage Reduction (%)	15.9	45.8

Source: Author

NO_x (a) and PM_{10} (b) Emission Contributions (%) in Bus, Truck and PickupSUVVan Euro 2+ Restriction Scenario



(a) (b)

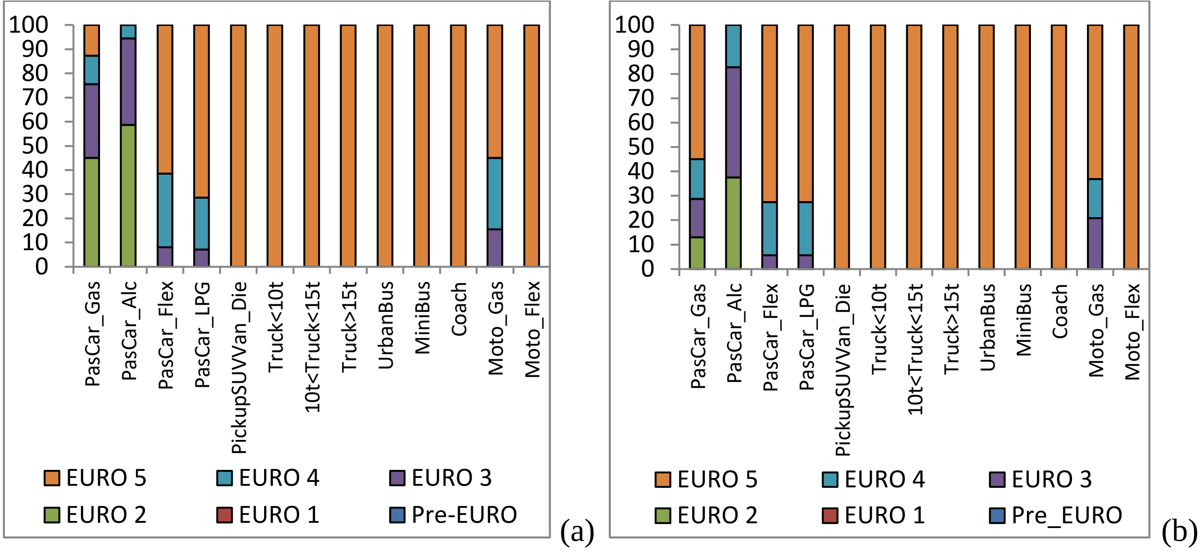
Source: Author

Global Emission Factors and Percentage Reduction Compared to Non Restricted Traffic. Bus, Truck and PickupSUVVan Restriction Scenario

Factor	**NO_x**	**Exhaust PM_{10}**
Global Emission Factor (g/km)	0.357	0.0070
Percentage Reduction (%)	17.7	48.9

Source: Author

NO_x Emission Contributions (%) in ULEZ Restriction Scenario. Buses, Trucks and PickupSUVVan Euro 5+ and Passenger Cars Euro 2+



Source: Author

Global Emission Factors and Percentage Reduction Compared to Non Restricted Traffic. ULEZ Restriction Scenario

Factor	**NO_x**	**Exhaust PM_{10}**
Global Emission Factor (g/km)	0.206	0.0040
Percentage Reduction (%)	52.5	69.5

Source: Author