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Comparison of simulators SUMO and VISSIM for measuring traffic flow interactions and vehicle emissions: a case study in Joinville, Santa Catarina, Brazil

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Thesis submitted as a requirement to obtain a bachelor's degree in the Graduate Course of Transport and Logistics Engineering of the Joinville Technological Center of the Federal University of Santa Catarina.

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COMPARISON OF SIMULATORS SUMO AND VISSIM FOR MEASURING TRAFFIC FLOW INTERACTIONS AND VEHICLE EMISSIONS: A CASE STUDY IN JOINVILLE, SANTA CATARINA, BRAZIL

This monography has been judged and approved as a partial requirement for obtaining the Bachelor of Transport and Logistics Engineering degree at the Federal University of Santa Catarina, Technological Center of Joinville.

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To my beloved Grandfather, Moasyr (*in memoriam*). From wherever you are, I know you’re proud to see me make another dream come true.

Thank you so much, I love you forever.

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“It is not the critic who counts (...).
The credit belongs to the one who is actually in the arena, whose face is marred by dust and sweat and blood; who strives valiantly; who errs, who comes short again and again, because there is no effort without error and shortcoming; but who does actually strive to do the deeds; who knows great enthusiasms, the great devotions; who spends itself in a worthy cause; who at the best knows in the end the triumph of high achievement, and who at the worst, if it fails, at least fails while daring greatly (…)”

(Theodore Roosevelt 1858 - 1919)

RESUMO

O gerenciamento urbano através de uma infraestrutura de mobilidade mais abrangente é fundamental para o desenvolvimento das cidades. A expansão urbana e seus impactos no fluxo de tráfego (poluição, ruído, congestionamentos, saúde), são questões cruciais a serem analisadas. O estudo e a proposição de melhorias em relação ao tráfego e às emissões de poluentes por meio de cenários de microssimulação são projetos de baixo custo e eficientes em termos de tempo para avaliar possibilidades e intervenções. Este trabalho, por meio do uso de duas ferramentas de microssimulação, revela, por meio de descobertas estatísticas e comparações de cenários, como a mudança de modo de transporte e a renovação da frota veicular com base nos padrões EURO/PROCONVE mais recentes podem ser soluções positivas para a melhoria da qualidade do ar e do fluxo de tráfego. Os simuladores SUMO e VISSIM foram utilizados para simular e analisar padrões de tráfego, emissões de poluentes e seus impactos na dinâmica urbana, com foco específico em uma interseção localizada na área central de Joinville, SC. Com a configuração desses simuladores, foi possível examinar as condições de tráfego da área de estudo e suas consequências associadas. Verificou-se que as políticas de mudança de modo e a implementação dos padrões EURO/PROCONVE demonstraram, operacionalmente, a capacidade de reduzir as emissões globais de veículos em 55% e o atraso da rede global próximo de 97,5%.

Palavras-chave: Mobilidade. Microssimulação. VISSIM. SUMO. Emissões veiculares. EURO Standards. mode switch.

ABSTRACT

Urban management through an integrated mobility infrastructure is a main concern for cities' health and traffic dynamics. Urban expansion and its impacts on traffic flow (pollution, noise, congestion, health) are crucial matters to be analyzed. The study and proposition of improvements regarding traffic and pollutant emissions through microsimulation scenarios are low-cost and time efficient projects for evaluating possibilities and interventions. This thesis, through the use of two microsimulation tools, reveals through statistical findings and scenario comparisons, how mode switch and fleet renewal based on newer EURO/PROCONVE standards can be positive solutions for air quality and traffic flow improvements. SUMO and VISSIM simulators were utilized to simulate and analyze traffic patterns, pollutant emissions, and their impacts on urban dynamics, specifically focusing on an intersection located in the central area of Joinville, SC. By configuring these simulators, it became possible to examine the study area's traffic conditions and its associated consequences. Mode switch policies and implementation of newer EURO/PROCONVE standards were found to be key interventions for reducing global vehicle emissions in 55% and global network delay in nearly 97,5%.

Key-Words: Mobility. Microsimulation. VISSIM. SUMO. vehicular emissions. euro standards. mode switch.

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LIST OF ACRONYMS

ABNT – Associação Brasileira de Normas Técnicas
CETESB - Companhia Ambiental do Estado de São Paulo
CO - Carbon monoxide
CO2 - Carbon dioxide
DLR - Deutsches Zentrum für Luft-und Raumfahrt
EPA - United States Environmental Protection Agency
EURO - The European emission standards
ENVIVER - Environment Vissim-Versit
GHR - Gazis-Herman-Rothery
HC - Hydrocarbons
IBGE – Instituto Brasileiro de Geografia e Estatística
MP - Particulate Matter
NOx - Nitrogen Oxides
PROCONVE - Programa de controle da poluição do ar por veículos automotores
PTV - Planung Transport Verkehr
SOx - Sulfur Oxides
SUMO - Simulation of Urban MObility
TNO - Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
VERSIT+ - TNO state of the art traffic emission model
VISSIM - Verkehr In Städten SIMulationsmodell
ZAIK - Zentrum für Angewandte Informatik der Universität zu Köln
WHO - World Health Organization

SUMMARY

1 INTRODUCTION

Constant development and expansion of urban scenarios causes many impacts for society. Traffic jams, high pollution emissions as a consequence of prioritizing individual transport towards collective, in addition to inadequate transport infrastructure, leads to an urban scenario and urban mobility that are not sustainable (BRAGA et al., 2019).

Urban mobility is characterized by three aspects: growing demand for mobility, volume and inadequate infrastructure. Given the complexity of mobility and transport, it is considered that, beyond projects, urban planning policies are a crucial tool for urban development (MATTRISCH; HOFFMANN, 2002).

Urban mobility policies are crucial for cities' development. Planning, use and accurate dimensioning of resources are imperative for a sustainable dynamic in the urban scenario, through which it is possible to have smooth interactions in traffic and, therefore, a healthy urban development.

It is estimated that up to 50% of Brazilian households own a vehicle or motorcycle, which was possible from 1930 on due to vehicle-purchase incentive policies adopted in the country (RUBIM; LEITÃO, 2013). However, urban mobility planning is not meant to prioritize individual transport, but allow conditions in which public, private and non-motorized transport can be served and and fluid altogether.

The impact caused by intense traffic is felt beyond consequences of accidents and time loss: there is also the viewpoint of health issues. According to Nieuwenhuijsen (2016), air pollution, noise and elevated temperature could be associated with health issues such as morbidity and sudden death. A United States Environmental Protection Agency (EPA) report also indicates high air pollution rates as a cause of pulmonary issues (e.g. asthma, pulmonary embolism), malformation and cardiovascular diseases (EPA, 2014).

Cities development, associated with the growth of urban traffic, lead to new issues, such as increased traffic flow and poor infrastructure to accommodate it, noises, traffic jams and queuing. Besides, traffic and highways security is another component of worry, reflected in the significant accident index and saturation of the health system.

According to Rubim and Leitão (2013), in Brazil, as a consequence of traffic accidents, data shows an average of 23 deaths per 100 thousand people. This number, when compared to countries with greater fleets, such as India (18,9), China (20,5) and USA (11,4), reveals, in average, more frequent occurrences, which could explain the high and increasing demand for rehabilitation and health services. The Brazilian health system has a health-related yearly spend of R$50 billions of reais with treatments, surgeries and paid insurances as a consequence of traffic accidents.

According to a 2013 report released by the World Health Organization (WHO, 2013), more than 80% of the inhabitants of urban areas with monitored pollution levels are exposed to worse air quality than recommended by the WHO. Although all continents are affected by this metric, poorer regions are shown to be affected the most.

The contribution of vehicle emissions to air pollution is considered a large environmental and health problem in big Brazilian cities caused, among other factors, by slow renewal of the old vehicle fleet (DIAS et al, 2020). Solid waste from burning fuel combined with poor vehicle maintenance are also components of air pollution, whose impacts are extensive to human health and air quality.

Among results of incomplete combustion of diesel and fuel engines and increase of brazilian vehicle fleet, in direct proportion, the most prominent indexes are related to incomplete combustion of fossil fuel and diesel engines, which leads to emission of toxic substances and gas, composed by Sulfur Dioxide (SO2), Carbon Monoxide (CO), Nitrogen Oxides (NOx), hydrocarbons (HC), particulate matter (PM) (CARVALHO, 2011).

While planning interventions in the urban space, in order to simulate enhanced network performance, use and implementation of microsimulation tools are crucial due to its application allowing the generation of different scenarios without the need of *in-loco* interventions. A simulation is defined as a dynamic representation of a part of the real world, built through a computer model and temporal variation (RONALDO; ISMAIL, 2012).

Swidan (2011) acknowledged that integrated emission and traffic models are essential tools for measuring pollution and vehicle emissions in urban areas. Therefore, traffic simulation tools integrated into emission models can contribute to transport planning by allowing, through findings, enhanced traffic performance and reduction in vehicular emissions.

1.1 Research problem and questions

To select a microsimulation package and understand which features are best for different kinds of analysis, it is necessary to evaluate how estimates are calculated and which parameters are taken into consideration for resultant outputs. In this research, the main estimations to be understood are related to mobile emissions and traffic estimations (delay, trip duration, behavior models).

Due to the impossibility of local monitoring in each vehicle and road of the transport network, pollutant emission models and traffic can be used as tools to estimate the emissions and pollutant concentrations impacted by vehicles (among other sources) in a traffic network.

Given the previous context, the following questions seek to answer the main points in this thesis:

- Is it possible to simulate the original conditions of a real-life network and estimate its traffic conditions?
- Is it possible to calculate vehicle emissions through microsimulation tools?
- Are traffic demands, vehicular generations and technologies, points of impact when measuring traffic delays and air conditions? Is it possible to measure it through microsimulation tools?
- Is variation of fleet technology and more restrictive pollutant emissions-related technologies able to significantly reduce air pollution rates in an urban, signalized intersection?

1.2 Objectives

The objective of this thesis is to understand how traffic flow and vehicle emissions are affected when simulated by two different microsimulation tools and its integrated dynamic emission models, through the following objectives:

1.2.1 Main Objective

This thesis aims to measure, assess and demonstrate through demand modeling and emission standards on two simulators of microscopic approach, how mode switch policies for reducing private vehicles use and increasing public transport offered by bus can impact on traffic flow performance measures and vehicle emissions. This assessment incorporates impacts between vehicle generations and technologies, as well as variations in vehicular volumes for each considered model.

1.2.2 Specific Objectives

- Estimate, by means of microsimulation tools, the traffic conditions originally found in the defined region for this case study, considering parameters as queuing and trip duration;
- Demonstrate how vehicle emissions are calculated and measured by each one of the considered microsimulation tools;
- Evaluate how variations in traffic demand, vehicle generations and technologies impact the estimations made by each one of the microsimulation tools considered.
- Demonstrate, through variation of fleet technology and more restrictive legislations, how the most recent technologies can contribute to a significant reduction in air pollutant products derived from vehicular activity.

1.3 Justification

Through a comparative analysis between two traffic microsimulation tools, it became possible to analyze the impacts of the reduction in demand and evolution of fleet modernity in Joinville, assess the improvement in fluidity and environmental impacts related to traffic, as well as the reasons for the estimations given by each tool by building the chosen study scenario, the implementation in each of the tools, and the subsequent generation of data for comparison.

Both the microsimulation tools considered for this thesis are built in a microsimulation approach. One of the main analysis to be addressed is to understand how an open source software (SUMO) and a licensed, state-of-the-art (VISSIM) are comparable in terms of data generation, outputs' quality and potentialities; as well as understanding which software is most adequate for each kind of proposed analysis and why.

Once data was generated, the main goal was to pursue and identify the differences in the results from each defined microsimulation tool that could be derived from mathematical models intrinsic to its construction. The findings are related to vehicles' model, technology generation, type of vehicle and type of fuel for its function.

This case-study was performed in Joinville, a highly populated city with an estimated fleet of 439.615 vehicles for 597.658 inhabitants (IBGE, 2020), which portrays an average 1,35 inhabitants/vehicle. This index, when compared to metropolis as São Paulo, with a population of 12.325.232 inhabitants and 8.761.213 vehicles (average 1.41 inhabitants/vehicle), demonstrates that Joinville, despite its smaller population when compared to a big city as São Paulo, portrays a high vehicular density.

1.4 Thesis structure

This document is divided into five sections, starting with this introduction, whose main objective is to give the reader an overview and context regarding traffic interactions and its consequences to environment and human life.

The literature review stands as explanations for the proposed interventions and studies hereby proposed, in order to back up the conclusions and discoveries made throughout the work, as well as to expose in a concise and direct way the emission problematic, its consequences for society, and how traffic simulation tools can help, among the several available, and each with its own particularities, in the construction and improvement of the urban environment.

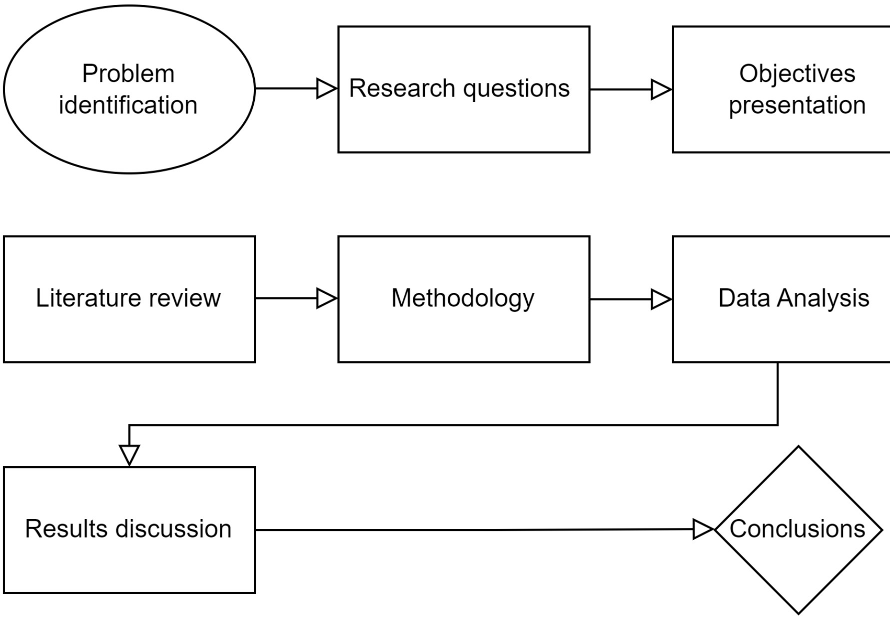
In the methodology section will be presented a comparative structure between the two considered tools for this analysis. With the help of statistical tools, this thesis aims to understand how each tool functions, in order to a better understanding of why its outputs are displayed as is. Infrastructure, mode switch and vehicular generations will also be considered for this analysis.

In the results section, the results derived from VISSIM and SUMO will be confronted, in order to understand the intrinsic influences of mathematical models and how their formulation affects the final results of each estimation per tool.

At last, in the conclusions section, there will be presented the final results and conclusions regarding why each tool functions differently, discussions on best applications for each set, as well as recommendations for future studies.

A summary of this structure is presented in figure 1.

Figure 1 - Thesis structure



Source: Author, adapted from SANTOS, 2022

2 LITERATURE REVIEW

In chapter 1 - Introduction - were introduced the main components of traffic issues, which reveals there is not a single cause for the urban motorized chaos, but a combination of problems, exemplified as health, air pollution and poor infrastructure.

In this chapter there will be presented more evidence regarding the main traffic issues, in order to justify their existence, as well as expose its agents, whether derived from incomplete combustion of fossil fuels, traffic volumes greater than the given infrastructure and its capacity, health problems and/or urban mobility issues.

Chapter 2 will also present traffic microsimulation tools, equipped with emission models and behavior models, through which it is possible to generate data for further comparison.

2.1 Traffic simulation

Traffic simulation in microscopic approach refers to the description of the movement of each vehicle that composes the traffic flow, which implies modeling the actions of each driver in response to the surrounding traffic, for example: acceleration, deceleration, and lane changes (BARCELÓ, 2010).

Defining a study area for microsimulation requires a careful and previous analysis. In a traffic simulation study, formulation of the aims and scope of the study involves determination of the traffic system and the alternative solutions to be analyzed. The delimitation, period and study area’s coverage are also defined in the first step of a traffic study (OLSTAM; TAPANI, 2011).

Traffic simulation studies are usually built and generated using traffic simulation software packages. The model construction task consists of building a software representation of the traffic system to be analyzed using an adequate traffic simulation software package. Network codification, traffic volumes, control and fleet characteristics are parts of this step (OLSTAM; TAPANI, 2011).

2.2 Traffic models

According to Araújo (2003), traffic models can be classified regarding traffic flexibility characteristics, divided into interrupted and uninterrupted flows.

Trajectories are interrupted by wait points, placed at the stop line positions, where vehicles are required to stop or give way. This may be at traffic signals, or to wait for a suitable gap in other streams of vehicles. These wait points will normally coincide with the physical markings on the road where vehicles must stop (BARCELÓ, 2010).

Uninterrupted flows refer to traffic flows that are neither controlled by stationary traffic controllers nor affected by fixed elements on the road that can forbid traffic flow from happening. An example of this road classification are rural traffic and freeways (e.g. German Autobahn, BR101).

Counterpart, interrupted flow classification suits roads that are affected by stationary traffic controllers and other obstacles capable of traffic interruptions, such as roundabouts and traffic lights. This classification is appropriate for urban traffic flow representation. Besides flow-related divisions, traffic models are also sub-divided into aggregation levels: macroscopic, mesoscopic and microscopic.

Macroscopic models are appropriate for representing traffic flows with low detail level, meaning it is not appropriate for representing vehicle-to-vehicle interactions, but a more aggregated representation of a vehicle platoon (DIAS, 2014).

In mesoscopic models, considered mid aggregation level, its interactions are analyzed per vehicle platoons. Mesoscopic analysis takes into consideration elements as lane density, not vehicle-to-vehicle interactions (LIEBERMANN;RATHI,1997).

Lastly, for microscopic models, the richest in detail-level among aggregation classes, vehicle-to-vehicle aspects are incorporated in such a way that allows more complex analysis and, for so, demands a great amount of data for its processing. In microsimulation each vehicle is analyzed individually inside the traffic network, from the moment it enters until it reaches its final destination (MATHEW, 2019).

2.2.1 Behavior models of microscopic approach simulation

Given the possibility to analyze the conductors' behavior and its interactions with the traffic environment around its trajectory, there are several mathematical models built-in microsimulation tools capable of describing it, in order to demonstrate how vehicle-to-vehicle interactions are perceived and translated into behavior's demonstration. In this section, there will be exposed three behavior models for traffic microsimulation: car following, lane changing e gap-acceptance.

2.2.1.1 Car Following

According to Treiber and Kesting (2013), Car following models are the most important ones when it comes to microscopic modeling of traffic flows. This model describes the individual longitudinal perception of each vehicle, and it is considered complete once capable of describing all traffic situations, including acceleration and free flow conditions, which directly affects roads' density and free flow speed (LACERDA; CASTRO NETO, 2014). By definition, car following models refer to a vehicle pursue parameter and the safety distance perceived longitudinally by the drivers.

Car following models calibration can take into consideration different inputs, such as speed, acceleration and perception from the follower of the leader vehicle rear's area. Car following models can be classified into different approaches:

I) Gazis-Herman-Rothery (GHR) model, where the acceleration of the follower vehicle is proportional to the speed of the leader vehicle and the relative spacing and speeds between the leader and the follower (BRACKSTONE; MCDONALD, 1999), classified a stimulus-response model,

II) Safety distance or collision avoidance models, where leader-follower vehicle relationship does not describe a stimulus-response type function as proposed by the GHR model, but tries to emulate a safe following distance in which a collision would only be unavoidable if the driver of the lead vehicle in front were to act in an unpredictable/reckless style driving (BRACKSTONE; MCDONALD, 1999),

III) Psychophysical or action point models (AP), where drivers would be able to tell they were approaching a vehicle in-front due to changes in the apparent size of the vehicle, by perceiving relative velocity through changes on the visual angle subtended by the vehicle ahead and its rear's area (BRACKSTONE; MCDONALD, 1999).

For car following models, this thesis will focus on two main contributions: Krauss Model (KRAUSS, 1984) and Wiedemann Model (WIEDEMANN, 1974), classified as collision avoidance and psychophysical, respectively.

2.2.1.1.1 Krauss model

Krauss' car-following model, developed in 1997 by Stefan Krauss, is classified as a microscopic, space-continuous, safe-speed based model. The model is based on a derivation of a safe gap: a vehicle, the EGO, needs to stop behind a leading vehicle, the LEADER, without colliding with him (BARCELÓ, 2010). This safe speed is computed as follows:

$$vsafe(t) = -\tau \cdot b + \sqrt{}((\tau.b)^2 + vleader(t-1)^2 + 2.b.gleader(t-1)) \quad (1)$$

Where:

vsafe(t) is the safe speed for time t (m/s);
τ is EGO's reaction time (s);
b is the maximum deceleration ability (m/s²);
vleader(t) is LEADER's velocity at time t (m/s);
gleader(t) is the gap (between EGO's front and LEADER's back) at time t (m).

Krauss' car-following model operates by default in the SUMO microsimulation tool (DLR, 2023).

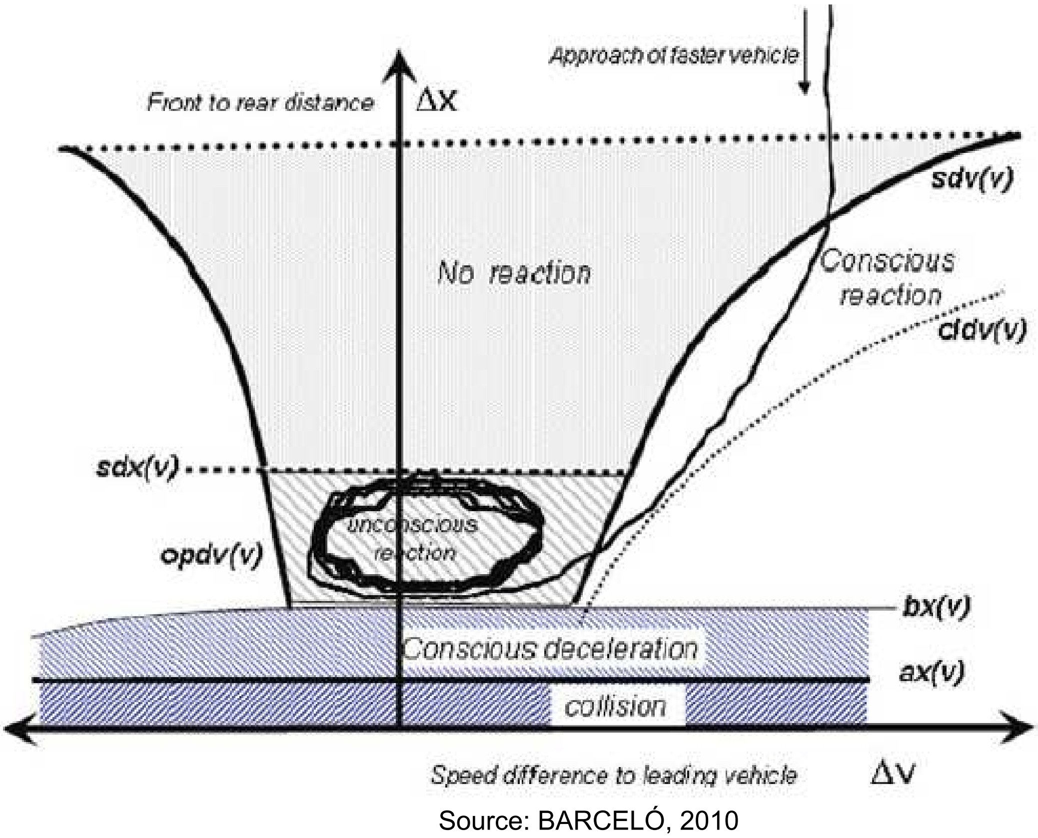
2.2.1.1.2 Wiedemann model

The Wiedemann car-following model, developed by Rainer Wiedemann in 1974, is classified as a psychophysical model. These models consider that if a faster vehicle is approaching a slower leading vehicle, it will start to decelerate until it reaches its individual threshold. The threshold is a function of speed difference and spacing (BIEKER-WALZ et al., 2017).

The faster vehicle responds to the leading vehicle based on the rear area's appearance: the closer to the leader, the bigger the rear area's appearance. Due to the distance perception, the following vehicle will accelerate/decelerate in order to maintain a safe speed (LACERDA; CASTRO NETO, 2014).

According to Barceló (2010), there are four different stages of following a lead vehicle. Figure 2 demonstrates the oscillating approach process, where thresholds are explained in an abbreviated form:

Figure 2 - Psychophysical car-following model by Wiedemann



Source: BARCELÓ, 2010

- *ax* is the desired distance between the fronts of two successive vehicles in a standing queue. ax := VehL + MinGap + rnd1·axmult with rnd1 normally distributed N(0.5, 0.15).
- *abx* is the desired minimum following distance which is a function of ax, a safety delta distance bx, and the speed with abx := ax + bx·v.
- *sdv* is the action point where a driver consciously observes that he approaches a slower leading car. sdv increases with increasing speed differences v.
- *opdv* is the action point where the following driver notices that he is slower than the leading vehicle and starts to accelerate again. The variation of opdv is large compared to cldv - a delta closing speed.
- *sdx* is a perception threshold to model the maximum following distance which is about 1.5–2.5 times abx.

Wiedemann's car following model has two variations: Wiedemann 74 (W74) and Wiedemann 99 (W99). W74 is used for urban traffic and merging areas and operates according to three parameters (average standstill distance, additive part of safety distance, and multiplicative part of safety distance). W99 is used for highways and freeways with no merging areas, and features nine parameters (standstill distance, headway time, and seven other parameters related to deceleration), and allows a finer calibration if enough data is obtained.

Wiedemann is the default car-following model for PTV Vissim microsimulation tool (LACERDA; CASTRO NETO, 2014).

2.2.1.2 Lane Changing

Fitch (2009) describes a Lane changing behavior as a maneuver envisioning lane change in a one-way traffic situation. This behavior comprehends side-to-side movement of the vehicle. A lane change is defined as a segment in which the vehicle starts moving towards another lane and continues, without reversal, through to that lane. The starting and ending point of the lane change process (time window) has a significant impact on lane changing dynamics (CHAUHAN; KANAGARAJ; ASAITHAMBI, 2022).

The lane changing maneuver is a fundamental driver behavior that determines vehicle distribution across lanes. These maneuvers are commonly classified as free, mandatory or discretionary. Free lane changes happen once the subject vehicle attempting a lane change finds sufficient gap in the target lane for it to complete the process without interaction with other vehicles.

Mandatory lane changes are executed when the driver must change lane (e.g., merging through an on-ramp to the freeway). Discretionary lane changes are performed when drivers are not satisfied with the current driving conditions and desire to change lanes to gain speed (CHAUHAN; KANAGARAJ; ASAITHAMBI, 2022).

2.2.1.3 Gap-Acceptance

Besides the lane change model, there is an additional side parameter to be analyzed, Gap-Acceptance, which estimates the gap acceptance to enable the vehicle waiting outside the lane to enter it safely in order to avoid collisions (BAGGIO, 2021). This gap is a physical space, expressed either in time or distance (TUDelft, N.A).

Gap acceptance models are used to represent the decision making process of drivers on secondary roads wishing to cross or join the main traffic stream, or to change lanes of traffic on the main road. The events modeled by this type of algorithm can result in high-severity crossover interactions/conflicts due to the speed difference between the vehicles involved (CUNTO; LOUREIRO, 2011).

For gap acceptance theories, models assume that each driver has his/her own critical gap, which is the minimum space-perception for the driver to execute the lane entrance maneuver safely. The required space is dependent on characteristics of the driver, the vehicle and the road. Hence humans have different perception capabilities, the space/distance can vary (TUDelft, N.A).

2.3 Air pollution

Air Pollution is defined by the World Health Organization (WHO) as the contamination of the external or internal environment derived from any chemical, physical or biological agent able to modify the atmosphere's natural characteristics. Among the main sources of air pollution are manufacturing activities, forest fires and presence of combustion fed engines.

As one of the greatest environmental harms, air pollution affects human health and quality of life. The WHO estimates that over 4 million people die prematurely due to air pollution related health issues. Over 90% of Earth’s global population is exposed to higher pollutant concentrations than recommended by the WHO (CETESB, 2023).

The parcel of air pollution derived from vehicular activity is composed by particulate matter, carbon monoxide, ozone, nitrogen dioxide and sulfur oxides, whose impact is harmful beyond air quality viewpoint, resulting in health issues for humankind such as cancer, heart and respiratory diseases and allergies (WHO, 2022).

2.3.1 Main mobile exhaust emissions

According to CETESB, pollutants can be classified into two categories: (i) primary, that are emitted directly by the emission sources, or (ii) secondary, that are formed as a consequence of chemical reactions between the primary pollutants and natural components found in the atmosphere. In this thesis, the main focus will be regarding pollutants emitted from primary sources - vehicles.

Incomplete combustion process is responsible for CO, HC, SOx and PM. (VASCONCELOS, 2020 apud. CONEMA 43, 2012).

In the following section will be detailed the main pollutants derived from combustion process and vehicular activity:

2.3.1.1 Carbon Oxides - CO and CO_2

Carbon Monoxide (CO) is a poisonous, odorless gas, a product derived from incomplete combustion of fossil fuels. This compound is harmful to human health because, once inhaled, it reduces the oxygen-carrying capacity of the blood cells and can cause death by asphyxiation. High concentrations of this gas can cause cardiovascular and psychomotor disorders. (CETESB, 2022; MMA, 2022).

$$CO_2 \rightarrow CO + O \qquad (2)$$

Continuous exposure to CO can lead to health consequences, especially in elderly, child and pregnant women, who are considered at-risk population groups and highly sensitive to developing heart and physical issues (WEAVER et. al, 2002).

Regarding traffic impacts, passenger cars are responsible for over 70% of CO emissions in urban areas. Although CO emissions in the Brazilian context are trending low in the last decade due to fleet modernization in PROCONVE standards, pollution numbers tend to stabilize because decrease in emission rates are associated with fleet modernization and not vehicle usage reduction (SANTOS, 2022).

Carbon Dioxide (CO_2) is the main product derived from complete combustion of fossil-fueled engines, and although it is naturally present in the atmosphere, it is not considered a pollutant. The importance of CO_2 is for being a gas that generates the greenhouse effect, a phenomenon that contributes to global warming (DIAS, 2014).

$$2C + O_2 \rightarrow 2CO \qquad (3)$$

$$2CO + O_2 \rightarrow 2CO_2 \qquad (4)$$

2.3.1.2 Hydrocarbons - HC

Hydrocarbons (HC) are the portion of unburned or partially burned fuel that is expelled from the engine, as well as fuel vapor emitted from the different sections of the vehicle or expelled during tank filling. HC deserves special attention regarding its control, since it reacts in the atmosphere promoting the formation of photochemical smog. Because of their reactivity, it is common to treat HC as Volatile Organic Compounds (VOC) (CETESB, 2023).

The harmful effects of this compound are the formation of tropospheric ozone and subsequent formation of Methane (CH4), which is a potential cause of the greenhouse effect (CETESB, 2022). Regarding human health, hydrocarbon ingestion and inhalation are of increased risk for pulmonary absorption and can lead to central nervous system (CNS) depression (CURTIS; METHENY; SERGENT, 2022).

2.3.1.3 Nitrogen Oxides - NOx

Nitrogen oxides (NOx) is the generic term for a group of highly reactive gasses. They form when fuel is burned at high pressure and temperature conditions, which induce the dissociation and subsequent recombination of atmospheric N_2 and O2 that generate NOx .

Nitrogen oxides can be divided into two main compounds: monoxide (NO) and dioxide (NO_2) (DIAS, 2018), and are formed due to fuel combustion in high temperature and pressure conditions. When reagent to ammonia and humidity, NOx compounds are capable of resulting into nitric acid: a toxic compound, responsible for severe respiratory damage when inhaled. NOx contributes with SO_2 to the formation of acid rain and of particulate matter. It also causes eutrophication (nutrient overload in water bodies) and contributes to the formation of smog (CAPPIELLO, 2002).

$$N_2 + O_2 \rightarrow 2NO \qquad (5)$$

$$2NO + O_2 \rightarrow 2NO_2 \qquad (6)$$

2.3.1.4 Particulate Matter - PM

Particulate matter (PM) is composed of solid or liquid air-suspended particles that feature a diameter up to 100 μm (BERINGUI et. al, 2021) and can be released by different emission agents from either natural (forest fires, volcanic emissions) or anthropogenic sources (vehicular emissions, biomass or fuel burning and industrial activities). Regarding its origin, PM can be I) primary, when directly emitted into the atmosphere or II) secondary, when the primary pollutants react with air and gas, producing new substances (BERINGUI et. al, 2021).

In traffic sources, such particles originate mainly from diesel. 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 (DIAS, 2018).

Regarding human health, PM is a harmful compound when found in diameters smaller than 10µm due to its capacity to penetrate in the respiratory system. This phenomenon occurs due to the inability of the lungs to filter particles smaller than 10µm, which can cause respiratory and cardiovascular diseases, since they settle in the deeper regions of the lung (lung alveoli and bronchioles) (OKUBO, KUWAHARA, 2020).

The following chart (table 1) summarizes all aforementioned pollutants and their impacts in environmental-level and health-related problems:

Table 1 - Emission compounds and effects to environment and human health

Emission parcel	**Origin**	**Impact to environment and human health**
Particulate Matter (MP)	Mainly derived from diesel's incomplete combustion	Acid rain formation, atmosphere visibility reduction;
Carbon monoxide (CO)	Incomplete combustion by automotive vehicles	Cardiovascular diseases, respiratory problems;
Carbon dioxide (CO2)	Main product from fuel incomplete combustion	Greenhouse effect gas and contribution to global warming;
Hydrocarbons (HC)	Fuel incomplete combustion and/or evaporation	Carcinogenic effects, photochemical smog formation;
Nitrogen oxides (NOx)	Fuel combustion in high temperature and pressure conditions	Contribution in ozone (O3) formation, cause of respiratory diseases
Sulfurous oxides (SOx)	Fossil fuel incomplete combustion	Harmful compound for plants' growth, respiratory diseases

Source: Adapted from Dias, 2018.

2.3.2 Vehicle emission standards

As previously exposed, pollutant products derived from mobile sources, fossil fuels, incomplete combustion and evaporation, especially from vehicles, are harmful for both human health and Earth's environment.

In 1986, Programa de Controle da Poluição do Ar por Veículos Automotores (PROCONVE) was created by the Brazilian Government as a program for reducing the level of pollutant emissions by motor vehicles in the country. This program also envisioned an encouragement for the national technological development in automobile engineering and pollutant measurement fields, as well as the promotion of improvements in the technical and chemical characteristics of fuels, resulting in a reduction of combustion-derived emissions (CETESB, 2023).

PROCONVE program has evolved since its first implementation in 1986 and, as of 2023, has 8 different phases (generations) and covers all vehicle types found in the Brazilian fleet (CETESB, 2023). These phases' requirements and admissible emissions have become stricter over the years, in order to encourage the development of vehicle technology and thus assist in reducing the emission limits of pollutants from light and heavy duty vehicles (PROCONVE, 2023).

PROCONVE generations are based on The European emission standards (EURO, the first rules covering air pollution from motor vehicles, introduced in 1970 by The Council Directive 70/220/EEC, who first introduced tests for carbon monoxide, and hydrocarbons (EEA, 2012). All EURO standards are amendments that have introduced tougher limits and testing over time.

In table 2 can be verified the equivalence between EURO and PROCONVE standards.

Table 2 - EURO and PROCONVE equivalence

EURO Standard	**PROCONVE Heavy Duty**	**PROCONVE Light duty**
Pre-EURO	P1 (1989)	PP (1982)

Pre-EURO	P2 (1996)	L1 (1988)
EURO I (1991)	P3 (2000)	L2 (1992)
EURO II (1996)	P4 (2002)	L3 (1997)
EURO III (2000)	P5 (2006)	L4 (2005)
EURO IV (2006)	P6 (skipped)	L5 (2009)
EURO V (2008)	P7 (2012)	L6 (2015)
EURO VI (2014)	P8 (2023)	

Source: BAGGIO, 2021 (adapted from DIAS, 2018)

2.4 Microsimulation tools

The modeling of individual vehicle movements on a second or sub second basis for the purpose of assessing the traffic performance of highway and street systems, transit and pedestrians is called microsimulation (FHWA, 2004);

Microsimulation tools are crucial for simulating adjustments and scenario construction as a way of improving road architecture and traffic flows. One way of selecting a microsimulator, according to Freitas et al. (2005), is by analyzing the following criteria: road size, network representation, traffic operation and representation, traffic control, model outputs, data availability, being easy to use and having all necessary features for the proposed analysis.

Two microsimulation softwares were used for this study: I) SUMO, an open source, non-commercial software, developed by the Deutsches Zentrum für Luft-und Raumfahrt (DLR) and II) VISSIM, developed by PTV, a state-of-the-art, commercial interface, marketed as world's leading multimodal traffic simulation software.

Both microsimulators are integrated with models that allow traffic analysis regarding saturation and vehicular emissions. This section will give better understanding upon traffic simulation context and the two chosen softwares.

2.4.1 SUMO - Simulation of Urban Mobility

SUMO - Simulation of Urban Mobility, developed by Deutsches Zentrum für Luft-und Raumfahrt (DLR) in a partnership with Zentrum für Angewandte Informatik der Universität zu Köln (ZAIK), is an open source, microscopic, space-continuous, and time-discrete traffic flow simulation suite (DLR, 2021).

SUMO application allows service level evaluation in traffic intersections through queuing, speed, delays and time loss, trip duration, among other performance measures and parameters, whose data can be helpful when it comes to traffic lights implementation, mitigation measures for traffic flow interruptions and environmental-level analysis (FILHO, 2019).

According to DLR (2021), SUMO is not only a microsimulation tool, but a series of applications that allow a project's preparation and performance, such as NETEDIT for network editions, general infrastructure addition (e.g., traffic lights, public transport, vehicles and routes) and NETCONVERT for converting network files derived from third-party sources (e.g OpenStreetMaps - OSM) into compatible files for SUMO's workspace (.net.xml, .sumocfg). The suite also allows customizations by its users, resulting in a wide range of applications.

When evaluating SUMO's potential in accessibility and usability features, its open-source nature stands out as a great advantage towards similar microsimulation tools. SUMO has solid and easy-to-use documentation (e.g. DLR Website, ELib), as well as an online forum - Eclipse Sumo community forum - for collaboration between its users and SUMO's main developers, which allows a faster and wider knowledge spread. SUMO is available for use in a variety of platforms (Windows, Linux or macOS) and it is implemented in C++ and Python, which allows, in parallel to use of portable libraries, a much more customizable work environment.

Although there is help from editing tools such as NETEDIT, SUMO has a high complexity level for creating each of the elements of the traffic network, flows, trips, signs, crosswalks and bus stops, which must be created manually and individually. According to Meng et. al (2022) converting OpenStreetMap data to a road network suitable for microscopic traffic simulation keeps being a challenging task: both missing information and excessive details, as well as wrong typologies present in the data set, which frequently confuses automatic converters.

In addition to the aforementioned models, SUMO has built-in logics for evaluating microscopic traffic sub-models: car-following, lane-changing, and gap-acceptance.

SUMO car-following operation, following Krauss' modified model implementation, considers that vehicles drive as fast as possible while maintaining perfect safety, therefore becoming collision-free if the leader starts braking within leader and follower maximum acceleration bounds (DLR, 2023).

This modified model differs from Krauss' original proposition in terms of allowing different deceleration capabilities among the vehicles, that are handled without violating safety and therefore ensuring models' collision-free characteristic. Another allowance is related to safe speed's formulation since SUMO offers the ballistic update (opposed to Krauss's original, that considers eulerian update), which considers the acceleration constant during one time step (DLR,2023).

For lane-changing metrics, SUMO operates natively with the “LC2013” model, based on the model developed by Treiber and Kesting (2013). This model is designed to simulate the lane-changing behavior of drivers on multi-lane roads.

SUMO's LC2013 model considers factors such as desired lane position, current speed, surrounding vehicles' speed, distance to next lane change opportunity and current lane's congestion level for determining whether a driver should change lanes or not. These factors are used to calculate a "lane-change desire" value for each available lane, and the driver will choose the lane with the highest desired value. These parameters can be set in the SUMO configuration file or through the TraCI API (DLR, 2023).

2.4.2 VISSIM - Verkehr In Städten SIMulationsmodell

Developed by *Planung Transport Verkehr* (PTV), VISSIM is a traffic microsimulation tool widely used for urban traffic simulation scenarios. This software allows different traffic modes, lane distribution, vehicular composition, settings for traffic light intersections, vehicle speed, acceleration and deceleration rates, lateral distance between vehicles, among other features (REDDY; MURTHY, 2021).

VISSIM, instead of a classical representation of a road network as a graph of nodes (vertices) and links (edges), has a structure of one-way links connected with connectors. This approach enables modeling of road systems of almost any structure, including roundabouts, which is practically impossible to be done precisely by means of the classical graph representation (MACIEJEWSKI, 2010).

It can also simulate the interactive behavior of vehicles, trucks, trams, and pedestrians in a simulation scenario. VISSIM's simulation can achieve high accuracy, including microscopic individual car-following behavior and lane change behavior, as well as group cooperation and conflict (FANG; TETTAMANTI, 2022) (DIAS, 2014).

One of VISSIM’s great features is that vehicles’ diving behavior can be modeled separately for each simulated link, allowing more aggressive scenarios and inputs near high waiting times zones, which leads to a higher level of impatience by drivers (SALGADO, et. al, 2016). For traffic representation models, VISSIM uses the WIEDEMANN model, combining perception models with traffic performance models (LACERDA, 2016).

VISSIM lane change model is based on Willmann and Sparmann (1978) work. This model is rule-based, where lane changing behavior is motivated by moving to a faster or slower lane (FRANSSON, 2018). For a lane change in a queue, the model equally assesses the lead time to collision between the subject and the preceding vehicles in the target lane. These parameters are deemed critical for model LC behavior through VISSIM (MOHAMED et. al, 2021).

This lane change model argues the following questions to justify the maneuver: I) is there a desire to change lanes?, II) are the driving conditions improved by the lane change maneuver? and III) is it possible to safely perform the desired lane change maneuver?. Also, there are two types of motivations for lane change in VISSIM: I) necessary and II) free (FRANSSON, 2018). Both parameters are dependent on the distance to the emergency stop position of the next connector of the route.

Despite being user-friendly in terms of interface, variety of implementation parameters, fast and direct usability, when evaluating traffic parameters, especially those related to behavior models, it is found that one drawback of such increase in complexity is, among others, the multiplicity of parameters contained within VISSIM. The huge number of parameters has made the model calibration rather difficult. In addition, when the spatial scope of the modeled network is quite large, the calibration will usually be very time consuming (STRC, 2012).

2.5 Dynamic modeling of vehicle emissions

The integration between traffic and emission models can be done at various levels e.g. Spatial aggregation, temporal scale and vehicle aggregation. The choice regarding detail level depends on the objective behind the use of the models (i.e.regional transportation planning vs. design of local traffic control measures), and on other constraints such as data availability and computational time requirement.

According to Cappiello (2002), the spatial distribution of vehicle emissions can be negatively affected by measures that improve congestion. For example, the use of traffic signals may prevent congestion from forming, but their introduction leads to a higher concentration of emissions in the proximity of the signals due to deceleration and higher acceleration of vehicles. Therefore, this scenario demands that both emissions and congestion are taken into consideration during the process of traffic development, optimization, and allocation.

Most traffic models are integrated with emission models, however, the generated data can show discrepancies. Car-following and lane change models are the main responsible factors for variation in stats from emission models due to its nature: some tend to generate a most significant instant acceleration for a similar traffic pattern. Variation fuel consumption and emissions derived from incomplete combustion are directly impacted by acceleration and speed, which justifies the discrepancy in emission stats (IMASATO, 2007).

2.5.1 SUMO, PHEMLight and HBEFA v3.1

For environmental-level analyses performed with the SUMO tool, PHEMLight stands out. This is a simplified model, derived from the PHEM model, and has been implemented to operate natively in SUMO (HAUSBERGER; KRAJZEWICZ, 2014). In SUMO version 1.9.2 the emission factors used, calculated using PHEMLight, are extracted from the HBEFA base (BAGGIO, 2021).

The Handbook Emission Factors for Road Transport (HBEFA, 1994), was developed by environmental protection agencies of European countries such as Germany, Switzerland and Austria. HBEFA is a database of emission factors for all vehicle classes (cars, freight, heavy duty, buses and motorcycles), in which every vehicle class is divided into different classes and generations, allowing a variety of possible scenarios and traffic environments (HBEFA, 2021).

SUMO emissions are estimated through the PHEMlight model which uses characteristic emission curves to define the emission amount [g/h] as a function of the actual engine power of the vehicle, being able to measure CO_2, CO, HC, NOx, PM and fuel consumption for each vehicle (DLR, 2023), as well as featuring all available EURO-standards (EURO 0 to EURO 6).

These characteristic curves are computed using PHEMLight with representative dynamic real word driving cycles, PHEM itself provides basic emission factors for HBEFA 3. The amount of emissions and fuel consumption produced by a vehicle during a simulation step is determined by computing the power needed by the vehicle to move (P) (KRAJZEWICZ et. al, 2015).

According to Erdağı, Silgu and Çelikoğlu (2019) in Eclipse SUMO, the power demand of the vehicle is calculated as follows:

$$P = c0 + c1va + c2va2 + c3v + c4v2 + c5v3 \quad (1)$$

In the Eq-1, coefficients of cn are dependent on vehicle type and engine type of the vehicles and from HBEFA database the emission factors are chosen for the calculated power demand.

2.5.2 VISSIM, Versit+ and EnViver

VISSIM features an interface called Environment Vissim and Versit+ (EnViver), which combines traffic simulation and vehicular emission models. VERSIT+, developed by the TNO, is constituted by a suite of models used to predict emission factors and energy use factors that are representative for vehicle fleets in different countries.

This model is capable of modeling emissions of NOx, MP and CO_2 for all kinds of vehicles, based on the speed findings through its trajectories (TNO, 2022). VERSIT+ is based on the HBEFA database, derived from 12,000 measured driving cycles, reproducing all aspects of real time driving behavior. Using advanced statistical modeling techniques, VERSIT+ finds a suited emission factor equation for a given driving pattern (iCET, 2015).

According to Dias (2014), VISSIM can estimate traffic emissions through an integrated emission model called ENVIVER (Environment Vissim and Versit+), based on the microscopic emission model VERSIT+ (+LD for light vehicles, +HD for heavy duty vehicles). According to Quaassdorff (2018), VERSIT+ total traffic exhaust emissions (TE) (g/h) for a pollutant j are computed considering a vehicles’ emission class k, average speed l and sections of the road m as shown in equation 2:

$$TEj \ = \ \sum k, m \, (E^{f} j, k, l \, * \, TVk, m \, * \, Lm) \qquad (2)$$

Where:

$E^{f} j, k, l$ is the mean factor factor for pollutant j, vehicle class k and average speed l

TVk, m is the traffic volume (vehicles/hour) for a section of the road m

Lm is the length of the section (km).

The mean emission factor $E^f j, k, l$ (g/km) is defined by equation 3:

$$E^f j, k, l \;=\; (Ej, k, j \;+\; (Ej, k, j(CFairco - 1)Pairco \;+\; (CFage, h \;-1)) \\ +\; (Cj, k * Ncold * \; CFage, cs)/d \quad (3)$$

Where:

$E^f j, k, l$ is the predicted hot running emission factor
$CFairco$ is the correction factor for air conditioning use
$Pairco$ proportion of vehicle kilometer time traveled with air conditioning operating
$CFage, h$ correction factor for aging
Cj, k cold start emission factor
$Ncold$ number of cold starts
$CFage, cs$ cold start correction factor for deterioration
d average trip distance

Following context given in sections 2.5.1 and 2.5.2, table 3 features a summary on on SUMO and VISSIM main features to be observed throughout this study:

Table 3 - SUMO and VISSIM main features

Tool	**Availability**	Approach	Native Car Following Model	Car Following Model classification	Native emission model
SUMO	Open-source	Microscopic	Krauss	Safety-distance	Modified PHEM
VISSIM	Licensed	Microscopic	Wiedemann	Psychophysical	Versit+

Source: Author

Given all models, context and references aforementioned, the following chapter presents the methodology for this thesis' development.

3 METHODOLOGY

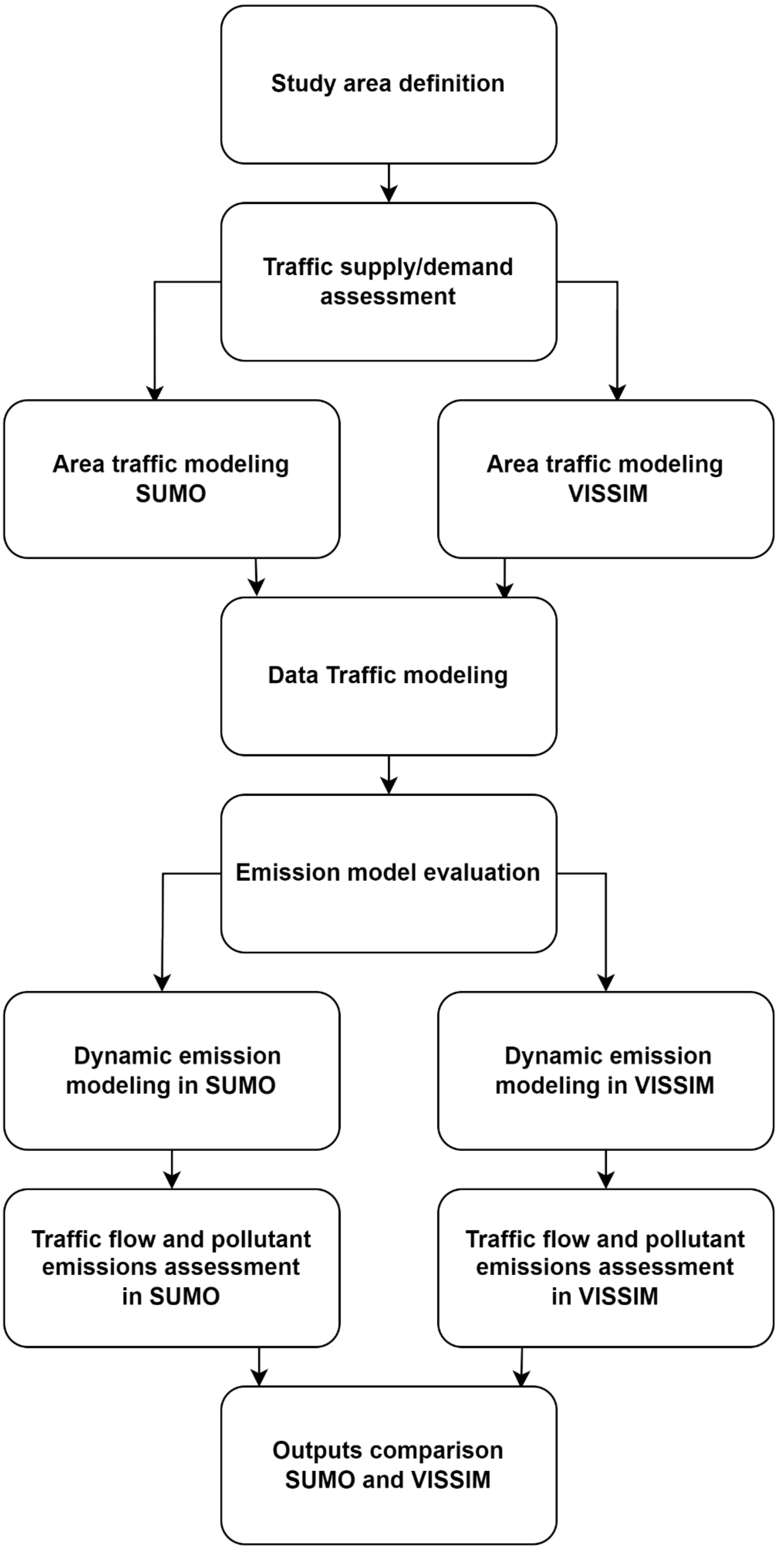
The methodology of this thesis started with an introduction and background on traffic-related issues, covering environmental, social and infrastructure issues caused by traffic dynamics. The consequences of traffic must be addressed in order to allow a fluid and well-balanced urban dynamics, where urban mobility is qualified with measures to reduce travel times and vehicle emissions, resulting in improvements towards the quality of life and health of its users.

Traffic microsimulation tools allow experiments and new scenario generations without need of real-world interventions, which saves valuable resources as time and money. In order to fulfill all proposed objectives aforementioned, traffic and emissions-related, the first step was to define, measure and calibrate a real-life scenario using two microsimulation tools: SUMO and VISSIM.

Once microsimulation models had an identical set of information input and calibrated, the next step was to generate scenarios for comparison with the area of study’s original features.

Figure 3 presents a flow chart for the considered methodology:

Figure 3 - Methodology flow chart



Source: Author (2023)

3.1 Study area definition

For Santos (2022), a traffic study region must have enough data available for its codification, such as traffic lights standards, public transport lines, allowed traffic movements, lanes' width and length, traffic volumes and possible routes. An area's configuration data can be obtained from cities' traffic management division, by visual inspection, on-site data collection or from public reports, for example.

This thesis' study area (figure 5) was chosen due to having available data for its codification, as well as its major contribution for Joinville's central area in terms of complexity and high traffic volumes, that can be justified by the presence of a bus terminal, shopping centers, school, walk-in stores, hospitals, supermarkets and other trip generators that impact directly in daily traffic flow volumes, delay and demanded infrastructure. Besides, this is a key intersection for connecting Joinville's south and north regions.

3.2 Traffic supply/demand assessment

Demand for transport represents a scale in which mobility services are used and/or required. This representation aims to understand traffic origins, destinations, motivations, socioeconomic factors and how travel generator poles affect the daily traffic distribution.

According to Ortúzar and Willumsen (2011), traffic demand modeling process starts with data collection from trips' origins and destinies and can comprehend socio economic aspects, as well as land use and occupation characteristics. This collected data is summarized into a matrix, called origin/destination (OD) matrix, on which can be verified offer and demand between two nodes in a network.

This case study's OD data was released by Joinville traffic management division in a summarized spreadsheet, containing traffic directional counting, vehicle routes, allowed movements/conversions, modal division and pedestrians counting. All data was collected during the morning rush hour, between 7:00:00 and 7:59:59.

3.3 Area traffic modeling and calibration

A correct interpretation, data collection and calibration are crucial for an accurate traffic modeling process, which is aimed at recreating traffic as observed and measured on the street, without any preliminary changes. These models are developed based on integration between mathematical models and traffic systems (AZLAN; ROHANI, 2018).

Area’s traffic modeling is a crucial and careful step for either the base-scenario or the proposed interventions. Correct data inputs as network measures, infrastructure (e.g. Traffic lights, stop signs), traffic flows and related routes are the main elements for a well calibrated and built model. Besides all correct data, it is mandatory to have on-site calibrations as a way of assuring a traffic simulation model’s accuracy.

In this step, the network model was built inside the microsimulation packages according to its original traffic conditions, resulting in a baseline scenario:

- Infrastructure: links, connectors, public transport stops, zebra crossings, waiting areas, stop signs;
- Traffic: Vehicle compositions, routes, traffic lights standards, public transport lines.

Once built, the simulation model must be calibrated. The current calibration process was performed as parameters were adjusted to portray, both visually and numerically, the observed on-site reality. Due to its microscopic nature, with a higher complexity level, this type of model has a greater amount of parameters to be calibrated since it is able to represent users’ individual behaviors.

Because of the stochastic nature of VISSIM and SUMO, this research has applied a 15min (900sec) warm-up time and 60min (3600sec) simulation period (KIM et. al, 2020), running 10 simulations per scenario, using random seed numbers on each.

These repeated model runs, due to the stochastic nature of VISSIM and SUMO models, are essential because the output of a single traffic microsimulation model run is a slight sample from an unknown distribution (HOLLANDER; LIU, 2008).

Once all models ran, its outputs were grouped and each scenario had an arithmetic mean of ten runs taken (VILARINHO, 2008). This resultant average was considered for traffic calibration.

3.4 Traffic flow modeling

Traffic supply and demand modeling can be adapted according to different proposed scenarios. This thesis' scenarios aim at two main approaches: first is mode switch, that refers to the process of encouraging travelers to use alternative modes of transportation, such as public transport, bicycling or walking, instead of driving alone in a personal vehicle. Mode switch propositions aim to reduce traffic congestion, improve air quality, and promote sustainable transportation options. According to the EEA:

> "Vehicle occupancy rates can be used to explain changes in levels of vehicle ownership and to illustrate changes in the efficiency of mass passenger transport. Efficient usage of passenger vehicles results in the need for less vehicle-kilometers to transport the same number of passengers. Utilization efficiency is one of the main parameters that determine energy and emissions efficiency, meaning that the vehicle occupancy indicator is important in relation to the environmental impact of different transport modes (EEA, 2015)".

This thesis' occupancy rates refer to average occupied seats per vehicle. The present mode switch from car to bus factor considers vehicle transport capacities according to table 4:

Table 4 - Occupancy rates and capacity of buses and cars

Vehicle Type	**Vehicle Capacity (seats)**	**Average Occupancy (seats)**
Passenger Car	5	1.5
Urban Bus	50	30

Source: Author (2023)

Considering a car’s occupancy rate at 1.5 seats (EIONET, 2020) and a bus capacity of 50 seats per vehicle (RODRIGUES et.al, 2008), the mode switch rate was from approximately 35 passenger cars to 1 bus occupied at full capacity.

3.5 Dynamic emission modeling

Dynamic emission modeling aggregates traffic metrics and emissions per vehicle in order to estimate the individual emissions from users in a traffic network. Vehicular emissions originate mainly from incomplete combustion of fossil fuels.

This thesis, through dynamic emission models and simulation of scenarios with vehicles from different EURO standards, proposes a comparison between generations and the pollutant concentrations for each. A combination of improved engine technology, exhaust after-treatment systems and the use of cleaner fuels such as diesel with lower sulfur content, allowed improvements from the first EURO generations (EU0) until nowadays (EU8).

The promotion of alternative modes of transportation, such as public transit, cycling, and walking, can also help to reduce traffic emissions by reducing the number of vehicles on the road. By combining these efforts with the continued evolution of EURO/PROCONVE standards, it is possible to create a cleaner and more sustainable transportation system for the future.

For this thesis, all buses and HDV were considered diesel-fueled and all LDVs and motorcycles fuel-fueled, as exposed in table 5:

Table 5 - Fuel types per vehicle

Vehicle Type	**Fuel Type**
Bus	Diesel
LDV	
Passenger Car	Gasoline
Motorcycle	

Source: Author (2023)

Once vehicle and fuel types were defined, data was generated and extracted from SUMO and VISSIM ‘s native dynamic emission models: modified PHEM and VERSIT+LD/+HD, respectively.

3.6 Traffic flow and pollutant emissions assessment

Traffic flow and pollutant emissions assessment can be evaluated from different perspectives and scenarios e.g fleet renewal, implementation of low emission zones, traffic calming zones and mode switch.

Mode switch policies refer to strategies that encourage travelers to switch from high occupancy vehicles, such as private cars, to low occupancy modes, such as public transit or active transportation, in order to reduce congestion and improve travel times. These policies can take various forms, such as providing incentives for using alternative modes, increasing the availability and quality of public transit, and implementing road pricing or congestion charges.

This thesis’ scenarios will focus on mode switching by increasing the availability of public transport, switching from cars to buses in order to understand how lower traffic volumes and newest EURO standards can improve urban mobility in terms of delay times, as well as improvements on vehicle emission rates.

For achieving the objectives mentioned in section 1.2 and proposed changes based on mode switch through microsimulation runs, table 6 summarizes the proposed scenarios of mode switch from cars to buses following traffic demand reductions due to higher capacity of buses according to Eionet (2015) and Rodrigues (2008).

Table 6 - Proposed mode switch from cars to buses

PROPOSED SCENARIOS						
GENERATION	MODE SWITCH FROM CARS TO BUSES					
EURO 1	100%	90%	80%	70%	60%	50%
EURO 2	100%	90%	80%	70%	60%	50%
EURO 5	100%	90%	80%	70%	60%	50%

Source: Author (2023)

3.7 Outputs comparison

SUMO and VISSIM were configured using a common data set and simulation scenario to ensure uniform output data in both tools. Once this data was generated it became possible to evaluate several performance measures by varying model parameters such as aggressivity in behavior models, traffic volumes and emission standards, similar to those performed by Burgard and Schmaus (2019).

For travel times, an on-site calibration was performed by the author in its private vehicle (probe vehicle), performing a driving style seeking no purposeful rush or delay, in order to compare these on-site measures with the ones derived from SUMO and VISSIM models.

For emission standards, due to lack of resources to perform on-site data collection, HBEFA and ENVIVER outputs were compared through a critical analysis based on each model’s considered parameters to calculate its emission curves and a further comparison to the most recent emissions report released by Cetesb (2021). By comparing simulation outputs with real-world data, it becomes possible to assess simulation models’ accuracy and identification of any biases or errors in their outputs.

4 DATA ANALYSIS AND RESULTS DISCUSSION

This chapter presents the main findings and results regarding aforementioned methodologies. Outputs' analysis and explanations will follow the methodology presented in figure 3 (methodology flow chart).

4.1 Study area definition

The study area defined for this thesis was chosen due to its location and expressive traffic volume. Besides being a busy location, this study area is a main connection between Joinville's southern, central and northern zones, which implicates expressive traffic volumes throughout the day, especially during morning and afternoon rush hours (7am to 9am and 17pm to 19pm). This intersection is located near Colégio Santos Anjos (school), Terminal Central (Central Bus Station), Catedral de Joinville (religious location) and two mid-sized supermarket branches.

This intersection features three traffic light compositions and four stages: one of them being dedicated to pedestrians and three for controlling the intersection's conflict areas and movements.

Traffic volumes for this study were disclosed by Joinville urban planning division (Secretaria de Planejamento Urbano e Desenvolvimento Sustentável - SEPUD). Vehicle counting was performed between the 10th and 12th of march, 2020. Traffic lights standards were disclosed by Joinville signaling and transport division (Departamento de trânsito - DETRANS). Both divisions belong to the Joinville city hall administrative area. Intersection's map and sketch (Figure 4) and extension (Figure 5) can be verified below:

Figure 4 - Intersection’s map and sketch

Source: Prefeitura de Joinville (2020)

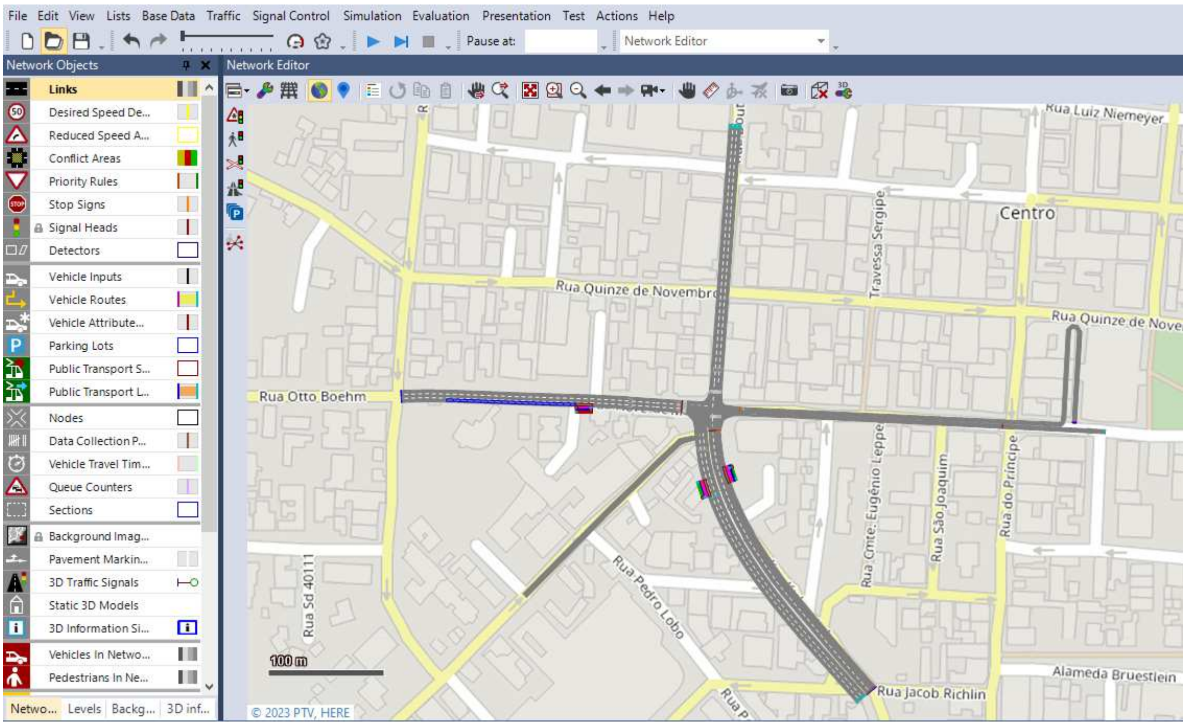
Figure 5 - Intersection’s extension

Source: Google Earth (2023) (Adapted)

4.2 Traffic supply/demand assessment

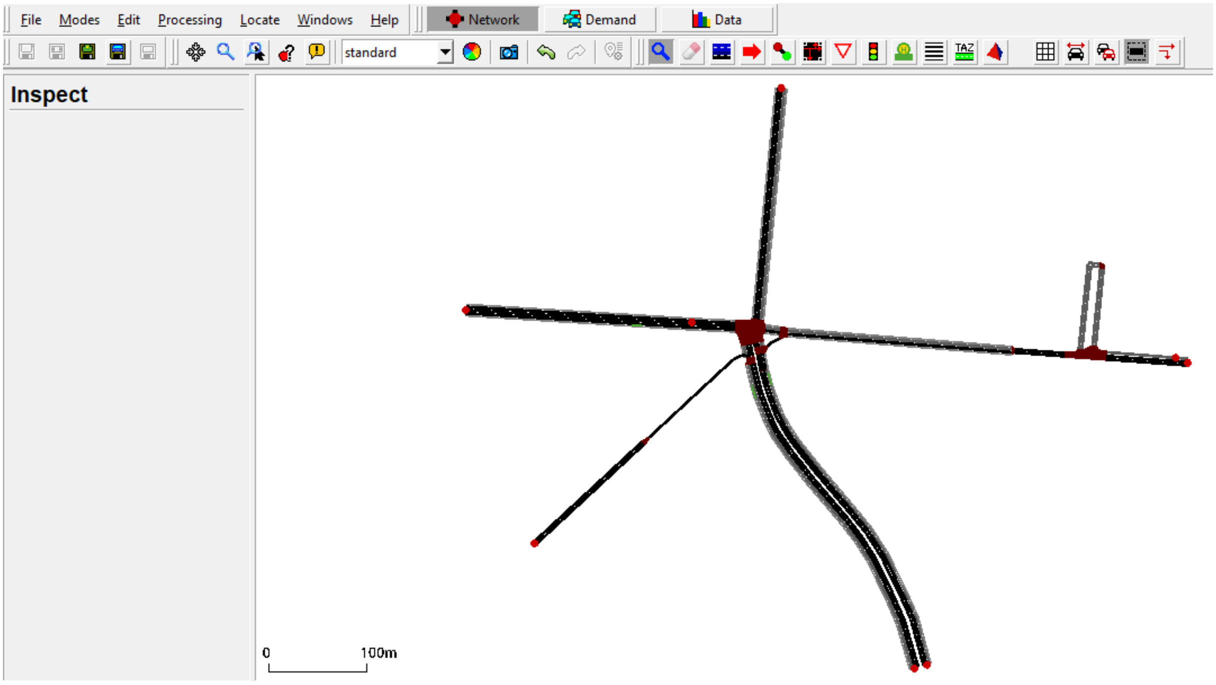
Supply and demand assessment was a crucial step for building the models in both microsimulation suites. This data was carefully inputted and revised in order to avoid mistakes that could lead to scenarios' inaccuracy. This assessment was performed using Google Maps and on-site visual inspection for verifying number and length of lanes, zebra crossing position, routes and other intersection elements. Once observed the models (figure 6 and figure 7), on-site infrastructure and current routes (table 7) were identical, OD data (table 8), released by Joinville's traffic management division, was inputted in SUMO and VISSIM models.

Figure 6 - Traffic network represented in VISSIM



Source: Author (2023)

Figure 7 - Traffic network represented in SUMO



Source: Author

Table 7 - Intersection’s vehicle routes

Route	From - To
AB	R. Nove de março - Leste → Av. Juscelino Kubitschek - Sul
AD	R. Nove de março - Leste → R. Doutor João Colin - Norte
BA	Av. Juscelino Kubitschek - Sul → R. Nove de março - Leste
BD	Av. Juscelino Kubitschek - Sul → R. Doutor João Colin - Norte
CA	R. Nove de março - Oeste → R. Nove de março - Leste
CB	R. Nove de março - Oeste → Av. Juscelino Kubitschek - Sul
CD	R. Nove de março - Oeste → R. Doutor João Colin - Norte

Source: Prefeitura de Joinville (2020)

For traffic lights standards (table 9), even though it is acknowledged the region has a high pedestrian flow and a current traffic stage for their crossing, both VISSIM and SUMO models had limitations for pedestrian representation (input limit and pushbutton implementation) and, for this reason, green time for pedestrian crossing was omitted from the general TLS cycle.

Table 8 - Traffic counting per defined route

Time interval	Route	Motorcycle	Passenger car	Bus	HDV
from 7:00:00h to 7:59:59h	AB	0	0	41	0
	AD	0	1	35	0
	BA	1	11	56	2
	BD	219	843	14	15
	CA	5	149	26	2
	CB	29	377	12	2
	CD	15	231	1	2
	Totals	**269**	**1612**	**185**	**23**

Source: Prefeitura de Joinville (2020)

Table 9 - Traffic lights standards

Origin	Green (s)	Yellow (s)	Red (s)
Rua 9 de Março	19	3	1
Corredor 9 Março	16	3	1
Rua JK	24	3	1
R. 9 Mar x R. do Príncipe	30	4	30

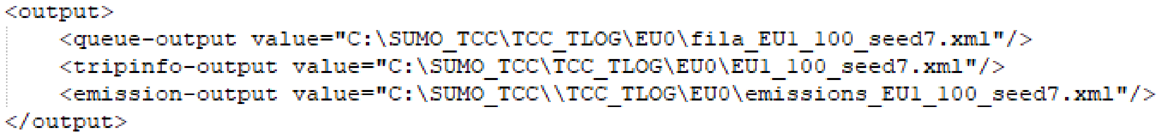
Source: Prefeitura de Joinville (2023)

4.3 Area traffic modeling and calibration

For traffic modeling parameters, it was crucial that the baseline scenarios in both tools featured as identical elements as possible, to cite: network length, traffic lights standards, flows and routes.

After initial assessment of traffic supply and demand, area traffic modeling and calibration involved collecting data on traffic flow in the study area. The calibration was performed considering the travel times between two points on each route of the simulated network: by including a flag for simulation outputs in SUMO configuration file (Figure 8), and through data collection points (1, 2 and 3) for VISSIM (Figure 9); its data was collected from driving rounds in a probe vehicle during typical days in the morning rush hour (7:00:00h-7:59:59h).

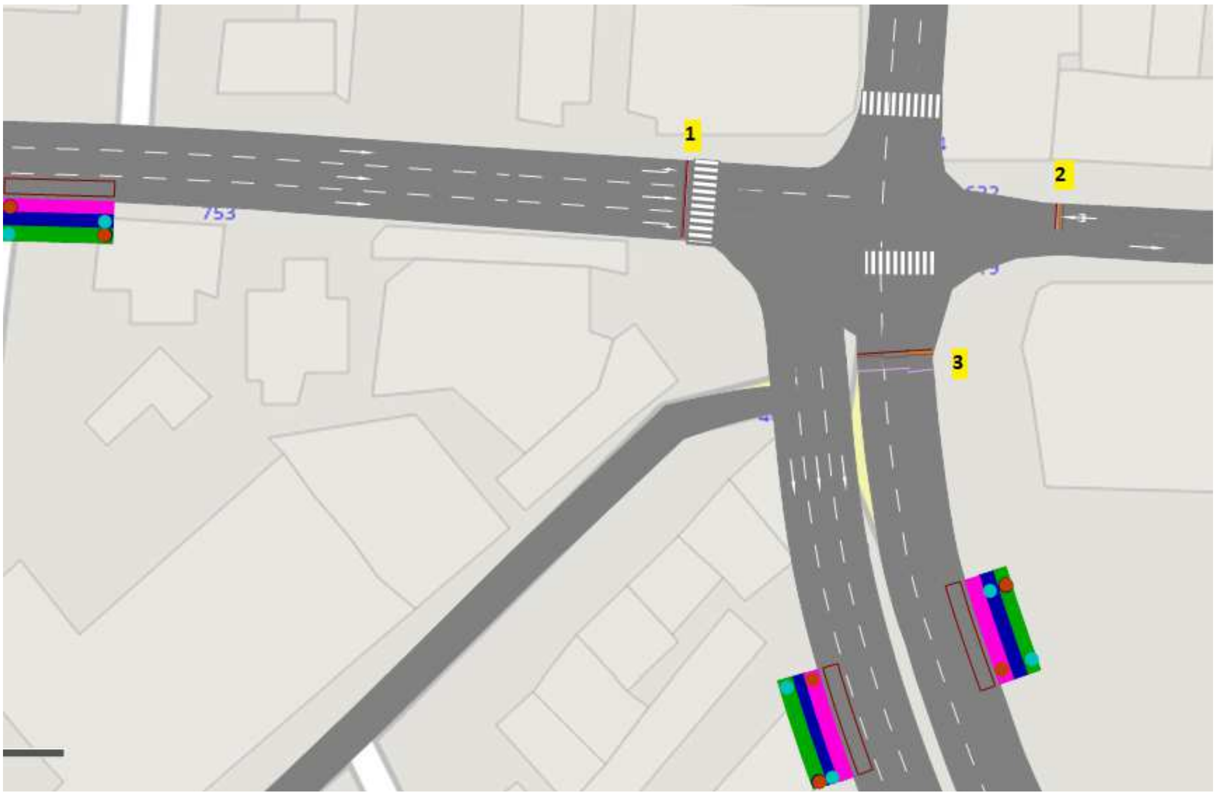
Figure 8 - Traffic data collection points in SUMO



```
<output>
    <queue-output value="C:\SUMO_TCC\TCC_TLOG\EU0\fila_EU1_100_seed7.xml"/>
    <tripinfo-output value="C:\SUMO_TCC\TCC_TLOG\EU0\EU1_100_seed7.xml"/>
    <emission-output value="C:\SUMO_TCC\\TCC_TLOG\EU0\emissions_EU1_100_seed7.xml"/>
</output>
```

Source: Author (2023)

Figure 9 - Traffic calibration data collection points in VISSIM



Source: Author (2023)

Calibration data was collected in typical days (Thursday, March 16th and 23rd, 2023), in the same hourly interval considered in traffic counting, for ten times per route to ensure as stochastic scenarios as possible (Table 10). Each route, then, has its average travel time calculated for further comparison with SUMO and VISSIM’s baseline scenario and errors evaluation. The use of probe vehicle collection methods allowed a more detailed perception of the area’s network features, both for infrastructure and traffic patterns, as well as for its practical, efficient approach and being a low-cost solution.

Table 10 - Trip durations per route

Travel times probe collection (s)										
Route/ Date	**16/03**	**16/03**	**16/03**	**16/03**	**16/03**	**23/03**	**23/03**	**23/03**	**23/03**	**23/03**
BA	99	150	188	97	95	97	112	150	98	96
CA	100	100	95	160	162	95	100	98	158	115
CB	73	62	83	101	51	47	65	94	96	58

Source: Author (2023)

Errors' evaluation was made through comparison between probe measures and simulation outputs regarding time travels. Based on Santos' (2022) study in a similar study area, the admissible tolerance for errors was at 10% maximum per route, resulting in the following route duration times (Table 11):

Table 11 - Results and errors per route

Travel times and errors (s)					
Route	**Probe Average**	**SUMO Average**	**SUMO Error %**	**VISSIM Average**	**VISSIM Error %**
BA	98.5	106.73	-8.36%	106.35	7.97%
CA	118.3	106.61	-9.88%	116.86	1.22%
CB	73	75.34	-3.21%	68.32	6.41%

Source: Author (2023)

According to delay metrics calculated in table 11, measures estimated by VISSIM are more accurate towards probe averages, evidenced by average global error around 1.2%.

Despite both microsimulation packages featuring an identical set of network length and traffic inputs, particularities such as native behavioral models of different classifications (Krauss as collision avoidance and Wiedemann as psychophysical), and different reference for vehicle account (front and rear reference) can be identified as contributing factors for different simulation outputs, therefore, impacting on calibration results.

For calibration purposes, after finishing the models' codification and running a first simulation round, its resulting outputs were compared to the collected probe measurements. Once realized the initial error was greater than the admissible tolerance of 10%, it was necessary to select and iterate one of the simulation parameters to allow the convergence of the results to a tolerable error range. The simulation parameter chosen for this operation was related to car following behavior.

Calibration process started with SUMO. Its car following parameter, sigma, ranges from 0 to 1, in which 1 refers to perfect driving conditions, while 1 is the most aggressive and reckless driving behavior. By default, sigma is set as 0.5, which was the condition for the first simulation run aforementioned. For convergence matters, sigma was iterated from 0.5 (standard) to 0.4 for cars and motorcycles and 0.3 for buses, in order to converge to admissible limits of 10%, while the same parameters were kept as standard in VISSIM.

4.4 Traffic modeling

After careful network configuration, followed by calibration and visual inspection, which are crucial steps for avoiding errors during traffic allocation and infrastructure addition due to its high influence in traffic conditions, it became clear that sharp corners, curves and wrongful construction of links caused infrastructure related delays, resulting in long queuing times and count, as well as impacts on trips' delay. This wrongful configuration, proven to be inaccurate through visual inspection made in the study area, was crucial for a later adjustment of the network file; that led to a coherent representation of the traffic pattern.

For traffic modeling measures as speed, queue length, trip duration and average delay per route, it is known that VISSIM and SUMO are built with different logics for each, therefore, the main objective once outputs were extracted became to understand why there were such differences since all basic traffic parameters inputted were the same.

Following calibration results described in section 4.3 and table 11, mode switch scenarios were built according to the aforementioned methodology: for occupancy switch, 1 fully occupied bus equals 35 passenger cars, resulting in a significant fleet increase from the baseline scenario to the final step proposed in this thesis - 100% to 50%. Lane “Avenida JK” (Routes BA, BD) had the most significant mode switch policy, increasing the public transport fleet by 21,28% (table 12).

Table 12 - Mode switch - Cars

Volumes per scenario (cars/per/hour)						
	Passenger Car			Urban Bus		
Origin	**100%**	**50%**	**Delta %**	**100%**	**50%**	**Delta %**
Rua 9 de Março - West	802	434	**-45,89%**	63	75	**19,05%**
Avenida JK	941	526	**-44,10%**	47	57	**21,28%**

Source: Author (2023)

Due to an increase in public transport fleet and exclusive lane for bus travels, the maximum speed of vehicles was negatively impacted by mode switch propositions. When evaluating the baseline scenario versus best reduction case (table 13); results show that decreasing individual transport in this case may not be the best for maximum speed improvements, as found in both simulators.

Table 13 - Network and routes’ maximum speed

MAX SPEED (km/h)				
Traffic Flow and Route	**SUMO**		**VISSIM**	
	100%	50%	100%	50%
BA	48,67	28,74	56,12	29,03
CA	48,06	20,44	58,53	21,17
CB	47,87	25,24	63,72	25,52

Source: Author (2023)

Even though public transport capacity for mass travels is greater than an average passenger car, its occupancy area leads to increase in road occupancy area, which affects directly queuing (table 14), travel delays (table 15), and therefore speed.

Table 14 - Maximum queue count and length

MAX QUEUE (m)				
Traffic Flow	**SUMO**		**VISSIM**	
	100%	50%	100%	50%
Rua 9 de Março - Bus Lane	82,00	81,59	86,98	86,98
Av Juscelino Kubitschek	139,78	58,09	164,80	99,64
Rua 9 de Março	109,65	56,12	101,80	54,91
Rua 9 de Março x Rua do Príncipe	126,52	158,07	120,33	156,49

Source: Author (2023)

Table 15 - Average delay per route

AVERAGE DELAY (s)				
Traffic Flow and Route	**SUMO**		**VISSIM**	
	100%	50%	100%	50%
BA	50,74	37.06	71,54	27,94
CA	54,51	39,15	57,08	42,33
CB	32,56	35,59	28,48	27,82

Source: Author (2023)

When evaluating results derived from each simulator, VISSIM and SUMO scenarios portray fairly similar outputs. While analyzing possible impacts for diverse outputs in an identical scenario, besides calibration errors, both simulators are built differently in terms of network construction, discovered to be a crucial simulation layer.

SUMO has a graph directed map, composed of nodes, for representing intersections, and edges, for road and lanes representation. This graph representation implicates in a slightly more complicated mechanism for network editions due to its clusterized behavior, therefore being advised by SUMO development team as not meant to be edited by hand, but on NETEDIT or similar applications.

VISSIM, however, rather than intersections as nodes, has lane connections represented by connectors, meant to connect two network links. This network representation type implicates in a less complex codification step, as well as not generating clusters, but individual lane connections. This road behavior type allows a higher level of detail and disaggregation per lane for both traffic and emission-related studies.

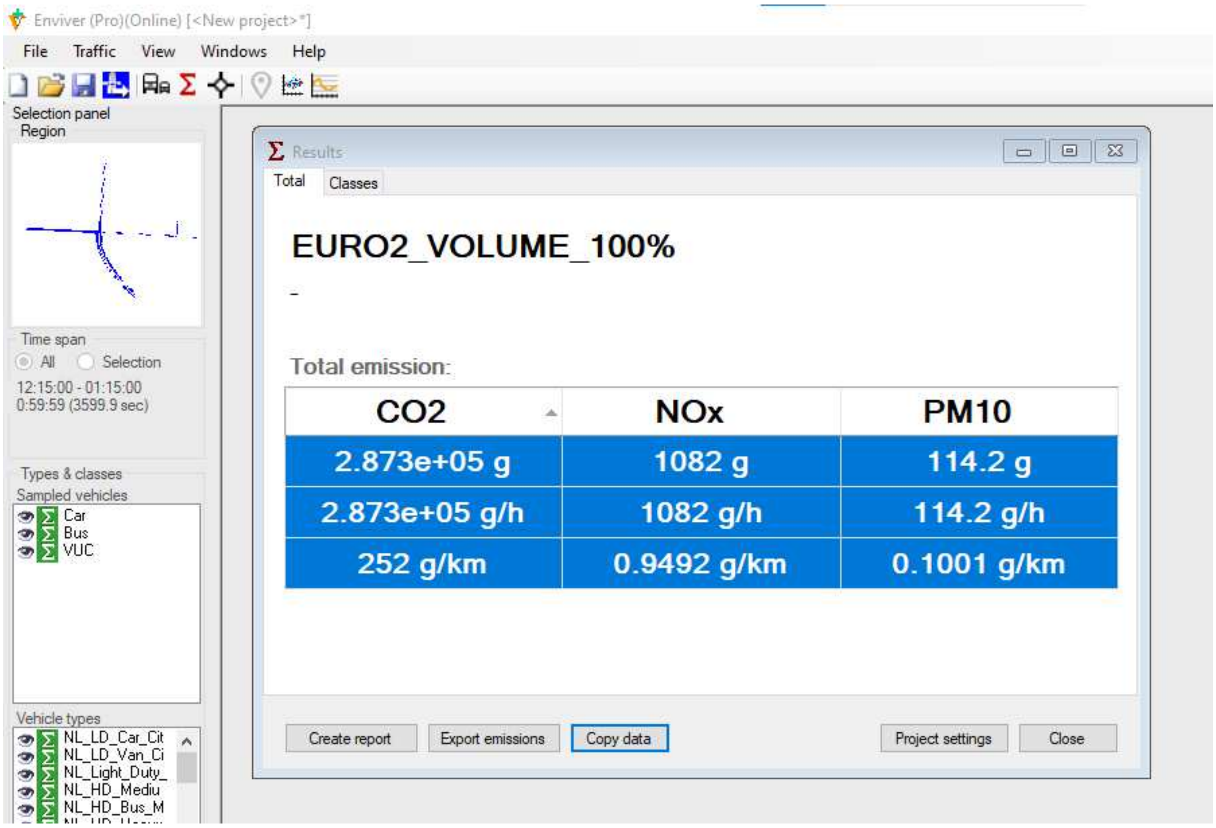
4.5 Dynamic emission modeling

Even though SUMO and VISSIM emission factors both derive from HBEFA database, each microsimulation package's logic for emission modeling is different in terms of extraction, complexity and variety of estimations. These aforementioned differences demanded a few assumptions for ensuring data convergence as explained below.

In PHEM-Light’s (SUMO) emission outputs, even though HBEFA V4.1 version featuring motorcycle emissions was already released, emission class HBEFA V3.1 was chosen to be linked to each vehicle class due to a software limitation in the currently used SUMO V1.9.2 version, therefore excluding emissions derived from motorcycles in general emission outputs. In ENVIVER (VISSIM) motorcycles were set as “emission class = none”. Therefore, all emission-related info considers only LDV, bus and cars’ derivatives.

For operation purposes, SUMO featured a less complex process for data extraction once it was linked with trip info XML output files, previously set in the main configuration file (figure 8). For VISSIM dynamic emission modeling, it was necessary to first generate outputs, then follow with their upload in EnViver+ program, in which it became possible to set different emission standards and extract the emission outputs for each generation through the VERSIT(+LD,+HD) model. All simulation outputs regarding emissions can be verified in ANNEX A (Table AA, AB).

Figure 10 - Enviver representation of baseline scenario



12:15:00 - 01:15:00
0:59:59 (3599.9 sec)

EURO2_VOLUME_100%

-

Total emission:

CO2	NOx	PM10
2.873e+05 g	1082 g	114.2 g
2.873e+05 g/h	1082 g/h	114.2 g/h
252 g/km	0.9492 g/km	0.1001 g/km

Source: Author (2023)

In terms of dynamic emission modeling estimations, output data revealed that SUMO’s PHEM-light is able to compute instantaneous fuel consumption along with CO2, NOX, CO, HC, PM emissions and fuel/energy consumption for a given speed and acceleration combination. Meanwhile, VISSIM’s ENVIVER outputs features only CO2, NOX and PM10. Therefore CO and HC estimations were omitted from general emission results. Even though CO2 is not considered a health-related pollutant, its impact is crucial for emissions due to its classification as a Greenhouse Gas. Since the European Union fleet is the biggest emitter of CO2, with road transport contributing to about 20% of global emissions, it is crucial for simulators to calculate its emissions.

For a baseline scenario considering fleet’s average emission standard as EURO 2 and traffic volumes in 100% (without mode switch or motorcycles), table 16 features the global emission outputs:

Table 16 - Global vehicle emissions per dynamic emission model

	CO2	**NOx**	**PMx**	
Modified PHEM-Light	753987	4292,33	106,30	**g/h**
ENVIVER	287300	1082	114,2	

Source: Author (2023)

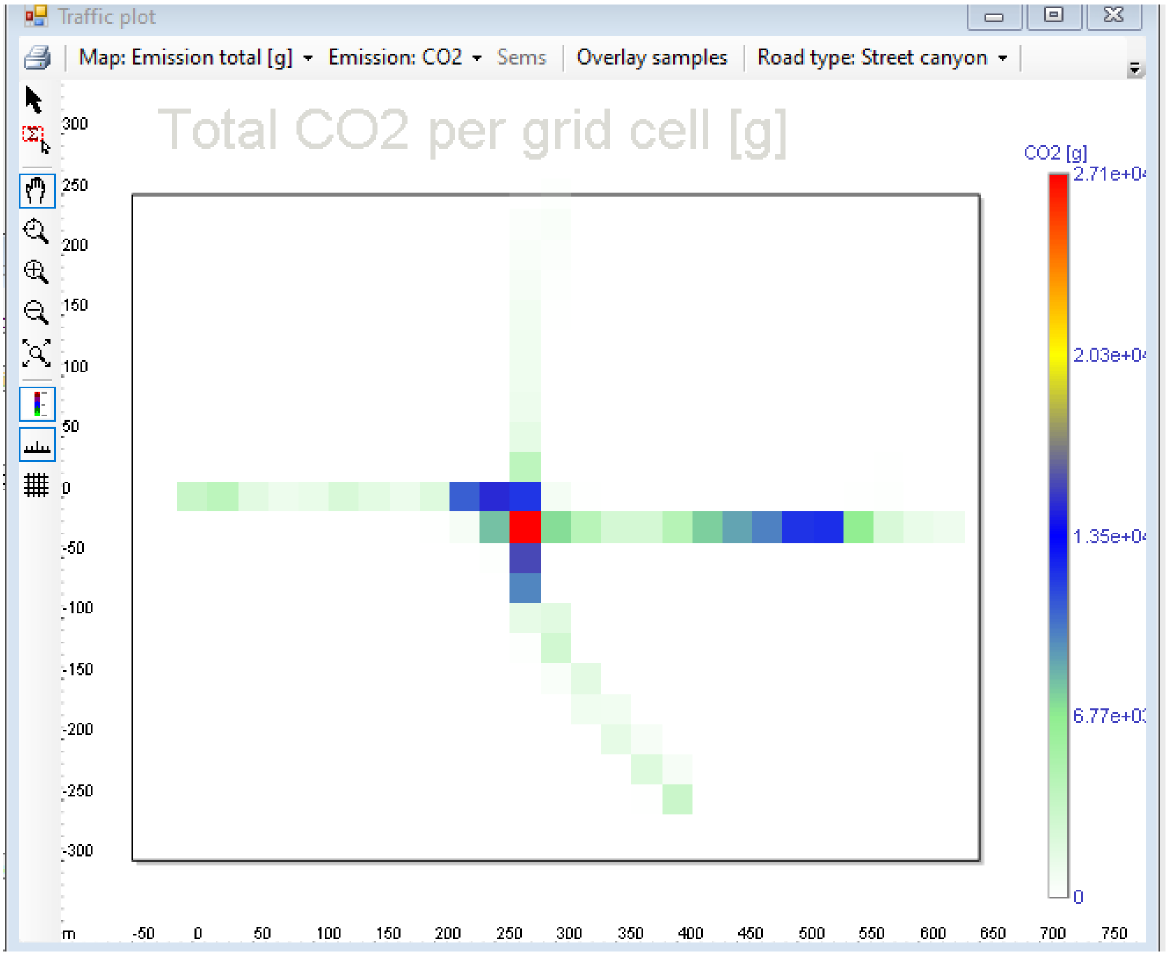
Even though both PHEM-Light and EnViver have a common HBEFA base for emission factors and the same traffic parameters, each model has different dynamics for estimations.

In SUMO, PHEMlight is available as a commercial add-on. The implementation itself is included in the usual version, but the major information is stored in the characteristic curves‘ and vehicle attribute files. It’s crucial to note that only two emission classes are included in SUMO’s open source release: an Euro-4 passenger car with a gasoline engine and a passenger car with the same emission class, but running on Diesel. The remaining emission classes have to be purchased from the Technical University of Graz (TU-Graz - TUG).

Therefore, the emissions considered for this thesis are derived from SUMO PHEM-Light’s implementation regarding vehicle types associated with equation 3, where factors are calculated by extracting the data from HBEFA and fitting them to a continuous function that was obtained by simplifying the function of the power the vehicle engine must produce to overcome the driving resistance force and move.

VERSIT+ is a model that considers a greater number of emission-source parameters e.g. Hot and Cold Running emission factors, air conditioning use impact and deterioration of vehicles. This formulation is based on linear regression, having a vehicle class’ acceleration and HBEFA baseline emission factor for iterations. This linear regression step is crucial for ensuring VERSIT+ stability, as well as facilitating its outputs through graphic representations (figure 11, 12, 13);

Figure 11 - Enviver emission map for CO2 in baseline scenario



Map: Emission total [g]

Emission: CO2

Road type: Street canyon

Source: Author (2023)

Figure 12 - Enviver emission map - NOx in baseline scenario

Map: Emission total [g]

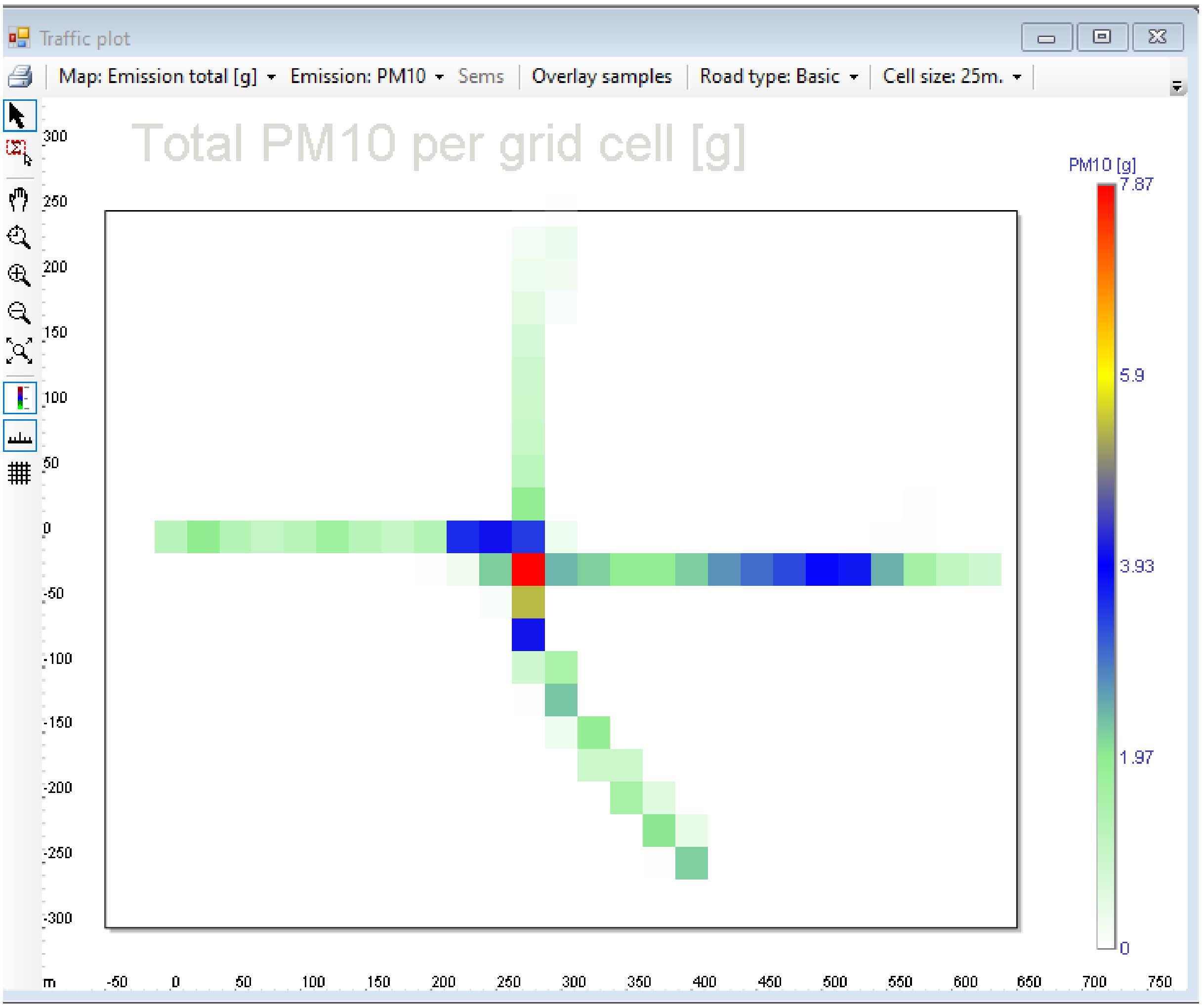
Emission: NOx

Road type: Basic

Cell size: 25m.

Source: Author (2023)

Figure 13 - Enviver emission map - PM10 in baseline scenario


Map: Emission total [g]
Emission: PM10
Sems
Overlay samples
Road type: Basic
Cell size: 25m.

Source: Author (2023)

4.6 Traffic flow and air pollutant emissions assessment

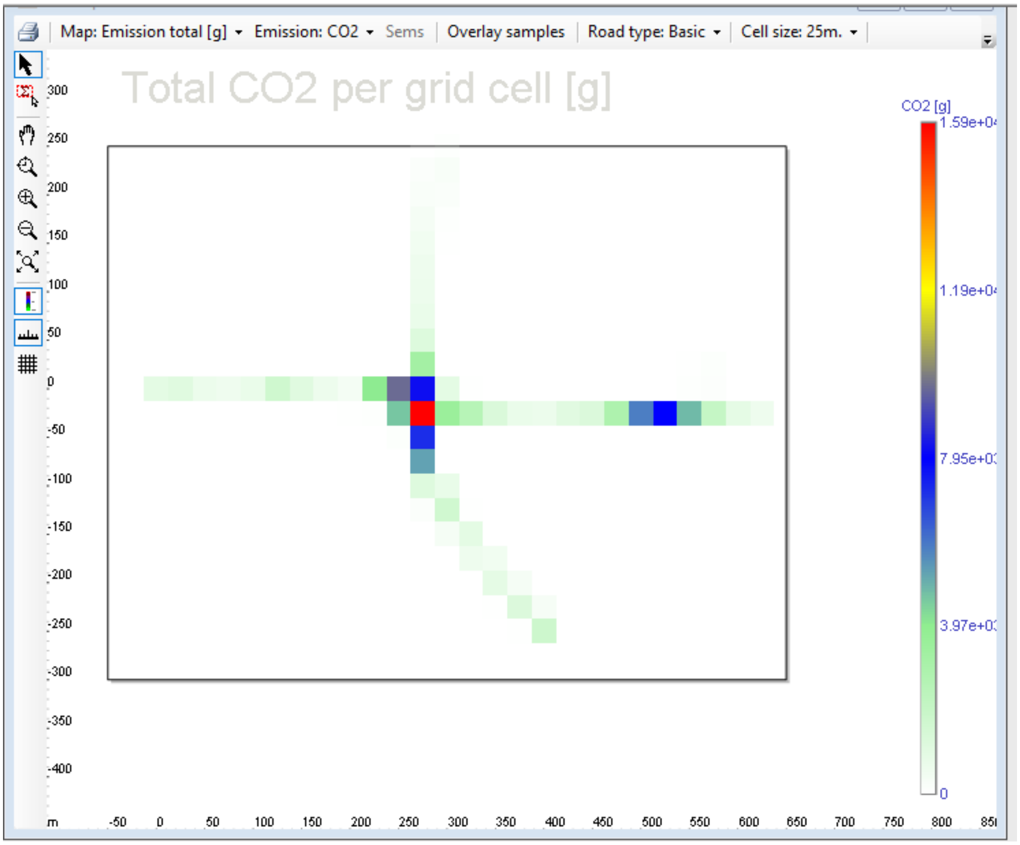
Mode switching from individual to collective transport has been fairly explored in the last few years as a possible solution for optimizing traffic conditions such as travel times, fuel and energy consumption. Beyond economic and infrastructure-related solutions, emissions have a huge consequence in human health and air quality, especially for CO, CO2, NOx and PM emissions.

Following mode switch volumes proposed for traffic-related metrics, this thesis also explored the impact on emissions per vehicle and pollutant. As mentioned in section 3.5, all passenger cars were configured to be gasoline-fueled; buses and

LDV as diesel-fueled. Fuel-type information for vehicles is important for understanding its performance and emission compounds.

Diesel fueled vehicle types operate in Diesel Motor engines, which are usually more efficient than gasoline fueled types (Otto Cycle). As a consequence of improved efficiency in terms of combustion, meaning it is closer to the complete process, diesel-powered vehicles release greater volumes of CO2. This correlation can be verified in figures 14 and 15, representing 100% and 50% scenarios, where the bus fleet is significantly increased, resulting in greater CO2 emissions for respective routes and lanes.

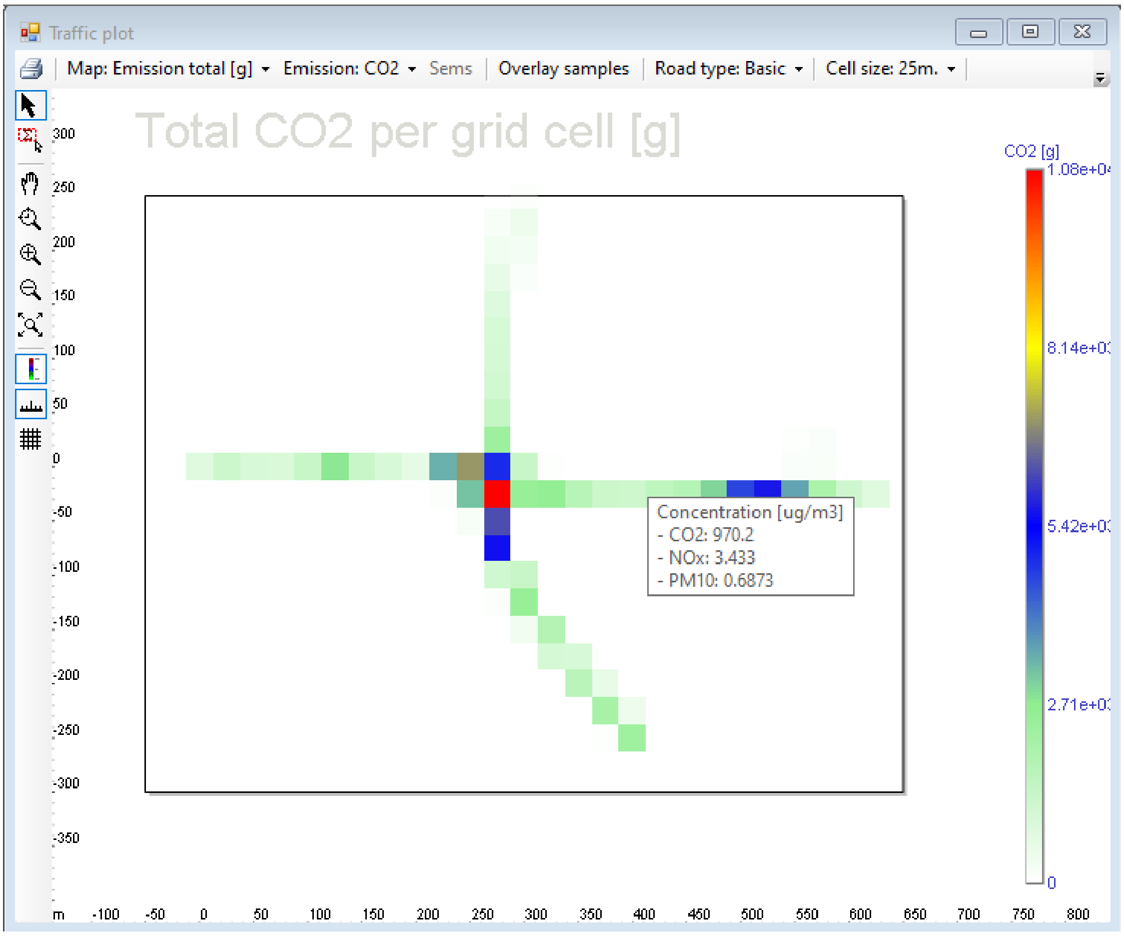
Figure 14 - Enviver emission map for CO2 in volumes as 100%



Map: Emission total [g] | Emission: CO2 | Sems | Overlay samples | Road type: Basic | Cell size: 25m.

Source: Author (2023)

Figure 15 - Enviver emission map for CO2 in volumes as 50%



Map: Emission total [g]

Emission: CO2

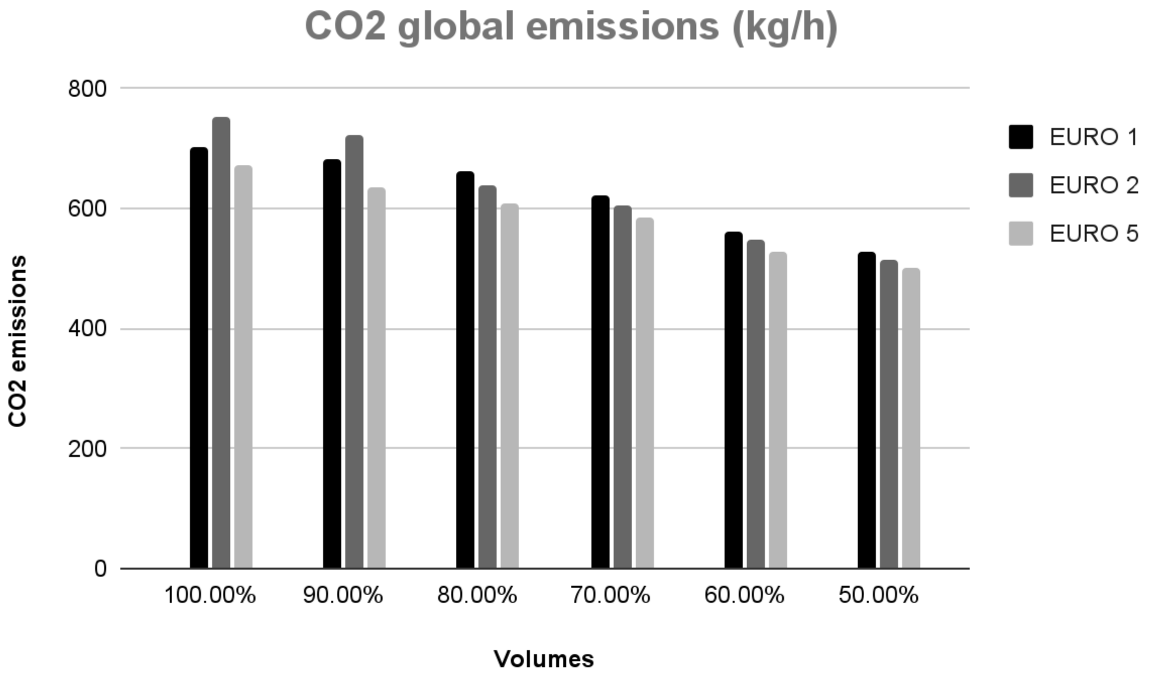
Road type: Basic

Cell size: 25m.

Concentration [ug/m3]
- CO2: 970.2
- NOx: 3.433
- PM10: 0.6873

For CO2 representation in SUMO, figure 16 summarizes the emission outputs for mode switch and EURO improvement scenarios.

Figure 16 - CO2 summarized emissions from SUMO output files

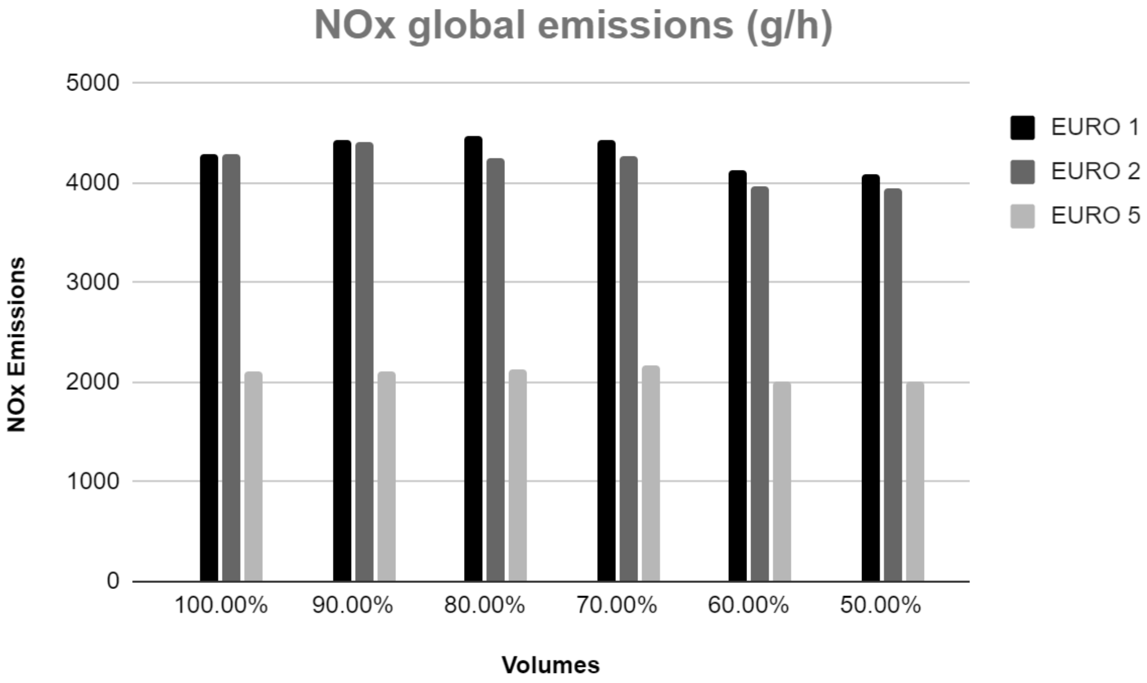


Source: Author (2023)

Global CO2 emissions, especially between EURO 1 and EURO 2, return higher rates for higher traffic volumes. This increase between generations can be explained through European Union Directive No 443/2009. This directive set a mandatory average fleet CO2 emissions target for new cars, after a voluntary commitment made in 1998 and 1999 by the automotive industry, who had failed to reduce emissions by 2007, where current standards were EURO 2. Following directive 443/2009, vehicles manufactured under EURO 5 (2008) returned lower CO2 rates compared to both EURO 1 and EURO 2 norms.

For NOx analysis, data in figure 17 shows how the compound’s concentration occurs through EURO 1, 2 and 5 generations. According to EURO 1 and 2 historical emission standards, NOx wasn’t regulated until EURO 3 introduction in 2001, which can be an explanation on why reductions or increases are not linear. Enviver maps for NOx can be verified in ANNEX B.

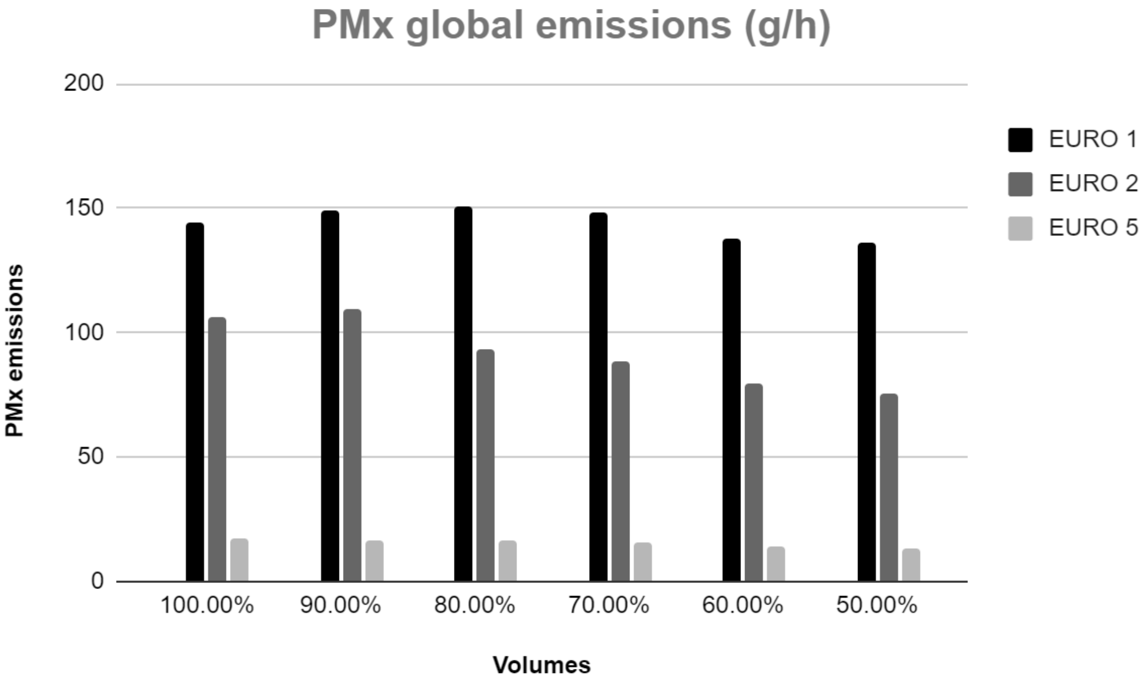
Figure 17 - NOx summarized emissions from SUMO output files



Source: Author (2023)

For PMx analysis, since EURO 1 introduction in 1993, EEA has had strict standards for this emission compound. The same pattern follows in EURO 2 and 5 based emissions, whose standards got even stricter (Figure 18). EnViver maps for PMx can be verified in ANNEX B.

Figure 18 - PMx summarized emissions from SUMO output files



Source: Author (2023)

5 CONCLUSIONS

The main objective of this thesis was to demonstrate, through the use of virtually identical microsimulation models built in two different packages, how traffic flow interactions and vehicle emissions are affected by mode switch policies and different EURO standards, as well as understanding why similar models return different outputs, based on traffic flow estimations and dynamic emission features.

As exposed in the introduction, urban expansion causes many impacts for the society, generating costs for its users both in terms of time and health. It also exposes how challenging it is to create urban policies for improving traffic flow dynamics once the private vehicle fleet keeps growing, especially in the Brazilian reality, where safety and access are also part of the concern. This chapter also indicates the application of simulation models as an instrument for exploring scenarios in such kinds of planning.

Through an extensive literature review, it became possible to conclude that simulation models, especially in microscopic approach, are crucial tools for understanding urban dynamics in the highest level of detail, including behavior-related models and its impacts on traffic flow’s performance measures as acceleration, deceleration and speed. It is fundamental to mention that microsimulation models require an extensive set of data and inputs for its codification, and absence of data or not enough information regarding the chosen area of study can be a limitation for scenarios’ construction and evaluation.

While exploring potentialities of working with microsimulation models, it also became possible to understand the capabilities of integrating traffic modeling with dynamic emission modeling, resulting in operational measures of air pollution impacts derived from traffic activity in the defined study area. The pollutants derived from vehicles’ incomplete fuel combustion, through chemical reactions with air, are responsible for environmental and health related issues.

The comparison of two simulation packages, SUMO and VISSIM, was performed through a methodology that started by choosing a study area with enough available data for its codification. This section also highlighted the importance of running multiple simulation runs, as well as having a robust calibration process, in order to reduce errors and deliver a model as similar as possible to the observed reality. This methodology's main contribution lies in the proposal of a mode switch policy aimed at reducing the use of private vehicles and increasing the public transport offer in terms of global capacity. This policy, combined with different generations of EURO standards, proves that increasing public transport offer and having a vehicle fleet with more advanced technologies and tighter restrictions for emissions, can be a positive intervention for the chosen study area.

Finally, the data analysis and discussion chapter features the study area and the set of inputs used for coding the microsimulation models: routes, traffic lights standards and traffic counting. As mentioned in sections 2 and 3, in order to become a complete model, a study area must have enough data available for its codification. Besides having enough data, the study area chosen for this study is an important connection from the Joinville central area to the rest of the city, which implicates in the presence of traffic volumes around 2100 vehicles per hour in the morning peak.

Modeling traffic scenarios, especially in two different simulators, requires that its calculation methods and results are understood. More importantly than operating these tools, is interpreting its results, and then formulating comparisons and hypotheses on why such results are found. The comparison between SUMO, an open source simulator, with VISSIM, a state-of-the-art, licensed simulator, required extensive research on how each tool was conceived, both in terms of network construction, native models and methods of calculation for its outputs.

This research employed statistical analysis to uncover crucial insights and fact-based conclusions regarding SUMO and VISSIM. The findings highlighted the potential benefits of mode switch and fleet renewal, particularly through the improvement of EURO standards. These measures were identified as feasible solutions for mitigating some of the consequences of traffic activity in a selected study area - emissions and road space. Furthermore, the use of microsimulation scenarios proved to be a low-cost and time-efficient approach for evaluating possible interventions and proposing improvements related to traffic management and pollutant emissions.

This thesis contributes to urban planning and transportation by highlighting there are more sustainable mobility strategies. The results underscore the importance of adopting measures that encourage mode switch for promoting public transportation, cycling infrastructure, and walking paths. Additionally, the research emphasizes the need for fleet renewal, as upgrading vehicles to meet higher EURO standards can significantly reduce pollutant emissions, as shown in chapter 4 for CO2, PM and NOX, resulting in improved air quality and overall urban livability.

By analyzing the specific intersection in the central area of Joinville, SC, this study provides valuable insights that can be applied to similar urban settings facing comparable challenges. The findings serve as a basis for policymakers, city planners, and transportation authorities to develop evidence-based interventions and policies that prioritize sustainable urban mobility, reduce pollution levels, alleviate congestion, and enhance the overall well-being of urban residents.

5.1 future research suggestions

For future studies, the author suggests approaches under traffic flow and emissions assessment, exemplified below:

- Implementation of new scenarios following the newest regulations in the European fleet. For the period 2020-2024, Regulation (EU) 2019/631 confirms the EU fleet-wide CO2 emission targets set under Regulations (EC) No 443/2009 and (EU) No 510/2011 (Cars: 95 g CO2/km, Vans: 147 g CO2/km);
- Verification of vehicle emissions through use of different emission models and sets of factors, in order to verify emissions from motorcycles and different technological generations of buses.
- Analysis of non-exhaust emissions, derived from braking activity and PMx resuspension;
- Analysis of the residues generated by tire+surface interaction;
- Application of the developed methodology in a different study section.

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ANNEX A - Vehicle emissions

Table AA - SUMO emissions derived from mode switch and EURO improvements

PHEM-Light, HBEFA V3.1 derived emissions				
Traffic Volumes	EURO generation	CO2 (kg/h)	NOX (g/h)	PM (g/h)
100%	EURO 1	702.13	4,287.85	144.54
	EURO 2	722.10	4,292.33	106.30
	EURO 5	672.09	2,115.00	17.47
90%	EURO 1	682.71	4,438.05	149.24
	EURO 2	753.98	4,411.94	109.63
	EURO 5	635.91	2,105.43	16.69
80%	EURO 1	661.65	4,480.33	150.71
	EURO 2	639.77	4,249.41	93.31
	EURO 5	607.89	2,131.52	16.17
70%	EURO 1	621.72	4,435.39	148.28
	EURO 2	605.75	4,267.64	88.10
	EURO 5	585.13	2,161.00	15.74
60%	EURO 1	562.24	4,136.44	138.14
	EURO 2	547.96	3,971.11	79.85
	EURO 5	526.69	2,010.66	14.17
50%	EURO 1	529.69	4,091.47	136.22
	EURO 2	516.08	3,951.75	75.32
	EURO 5	499.87	2,011.31	13.60

Source: Author (2023)

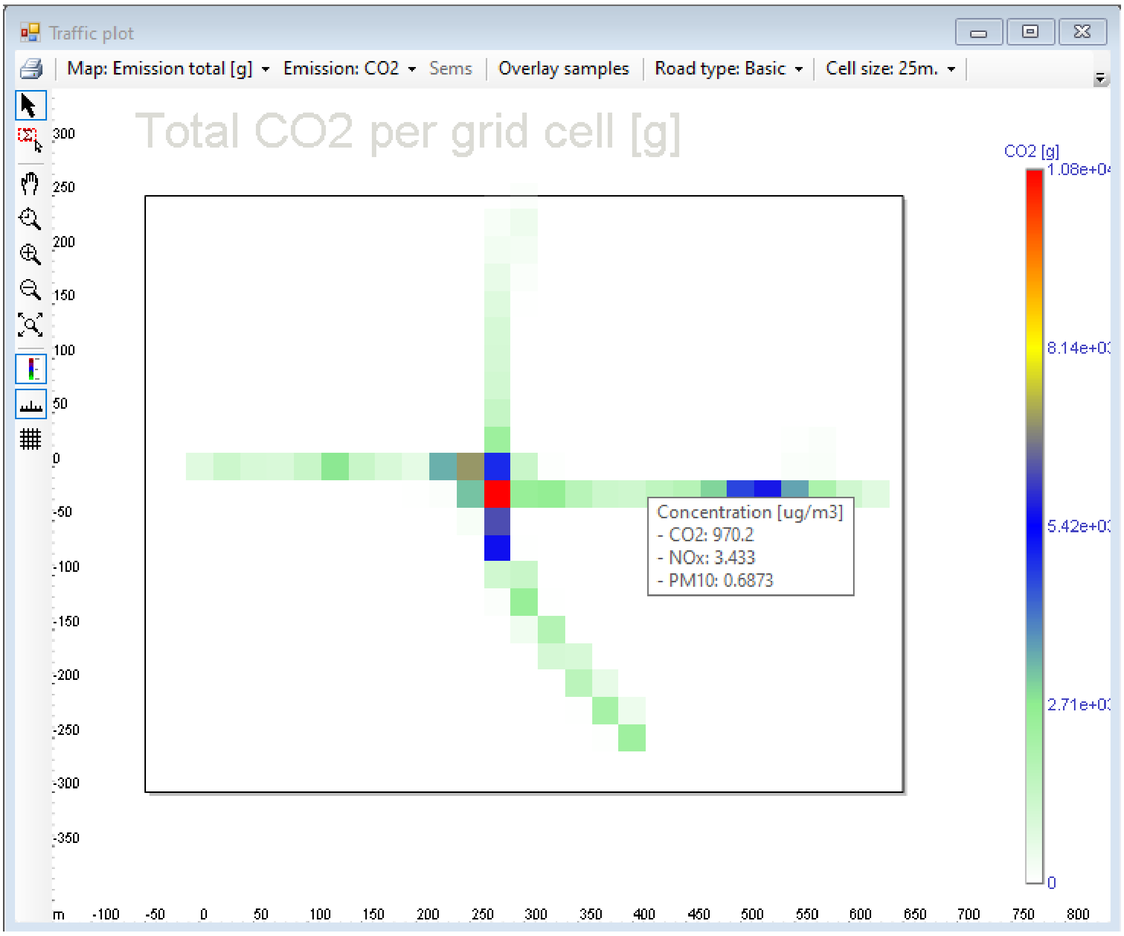
Table AB - VISSIM emissions derived from mode switch and EURO improvements

EnViver derived emissions				
Traffic Volumes	EURO generation	CO2 (kg/h)	NOX (g/h)	PM (g/h)
100%	EURO 1	243,03	1.096,99	162,24
	EURO 2	279,34	1.004,67	115,51
	EURO 5	243,91	741,20	37,45
90%	EURO 1	244,28	1.076,75	169,20
	EURO 2	279,34	993,26	116,63
	EURO 5	245,05	743,71	38,11
80%	EURO 1	225,00	994,82	156,40
	EURO 2	255,83	905,58	107,41
	EURO 5	224,78	683,31	35,24
70%	EURO 1	202,70	886,33	140,98
	EURO 2	228,93	804,03	96,84
	EURO 5	201,35	613,52	31,95
60%	EURO 1	187,10	828,69	131,05
	EURO 2	210,64	741,09	89,11
	EURO 5	184,69	565,16	29,38
50%	EURO 1	162,98	707,49	114,14
	EURO 2	181,55	630,10	77,91
	EURO 5	159,85	490,62	25,94

Source: Author (2023)

ANNEX B - Emission plots

Figure 19 - Enviver emission map for CO2, EURO 1, volumes in 50%



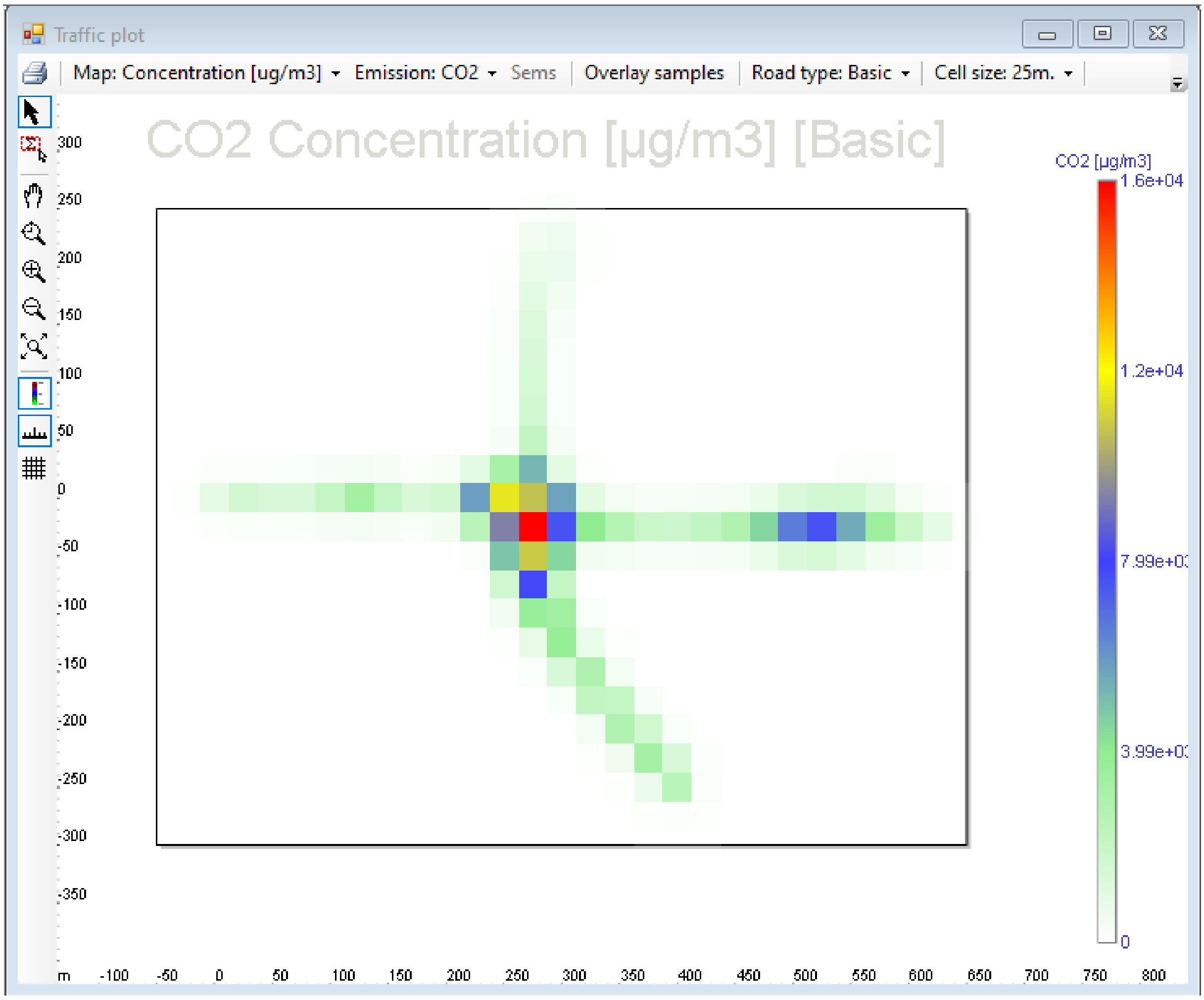
Traffic plot

Map: Emission total [g] | Emission: CO2 | Sems | Overlay samples | Road type: Basic | Cell size: 25m.

Concentration [ug/m3]
- CO2: 970.2
- NOx: 3.433
- PM10: 0.6873

Source: Author (2023)

Figure 20 - Enviver concentration map for CO2, EURO 1, volumes in 50%

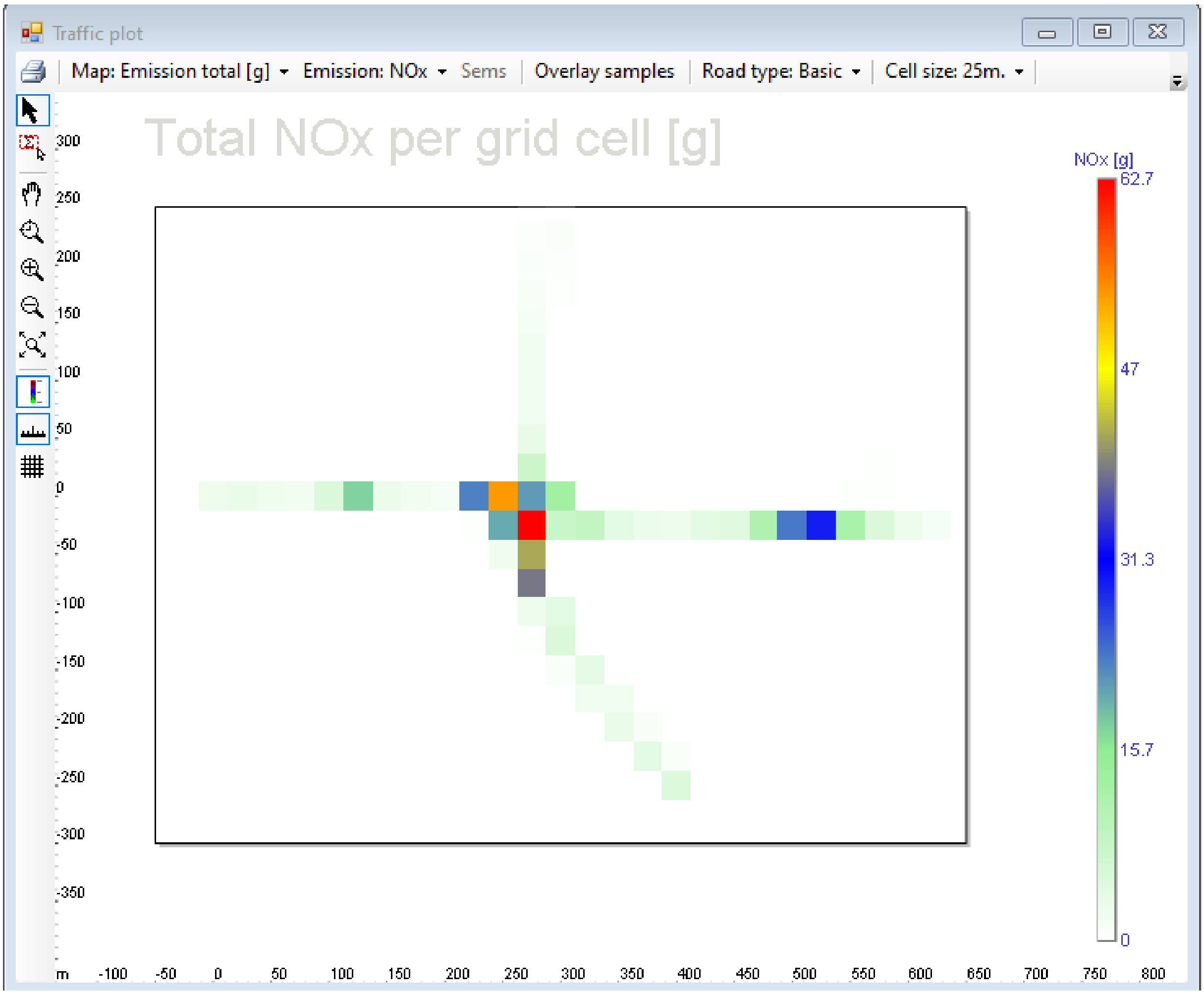


Traffic plot

Map: Concentration [ug/m3] | Emission: CO2 | Sems | Overlay samples | Road type: Basic | Cell size: 25m.

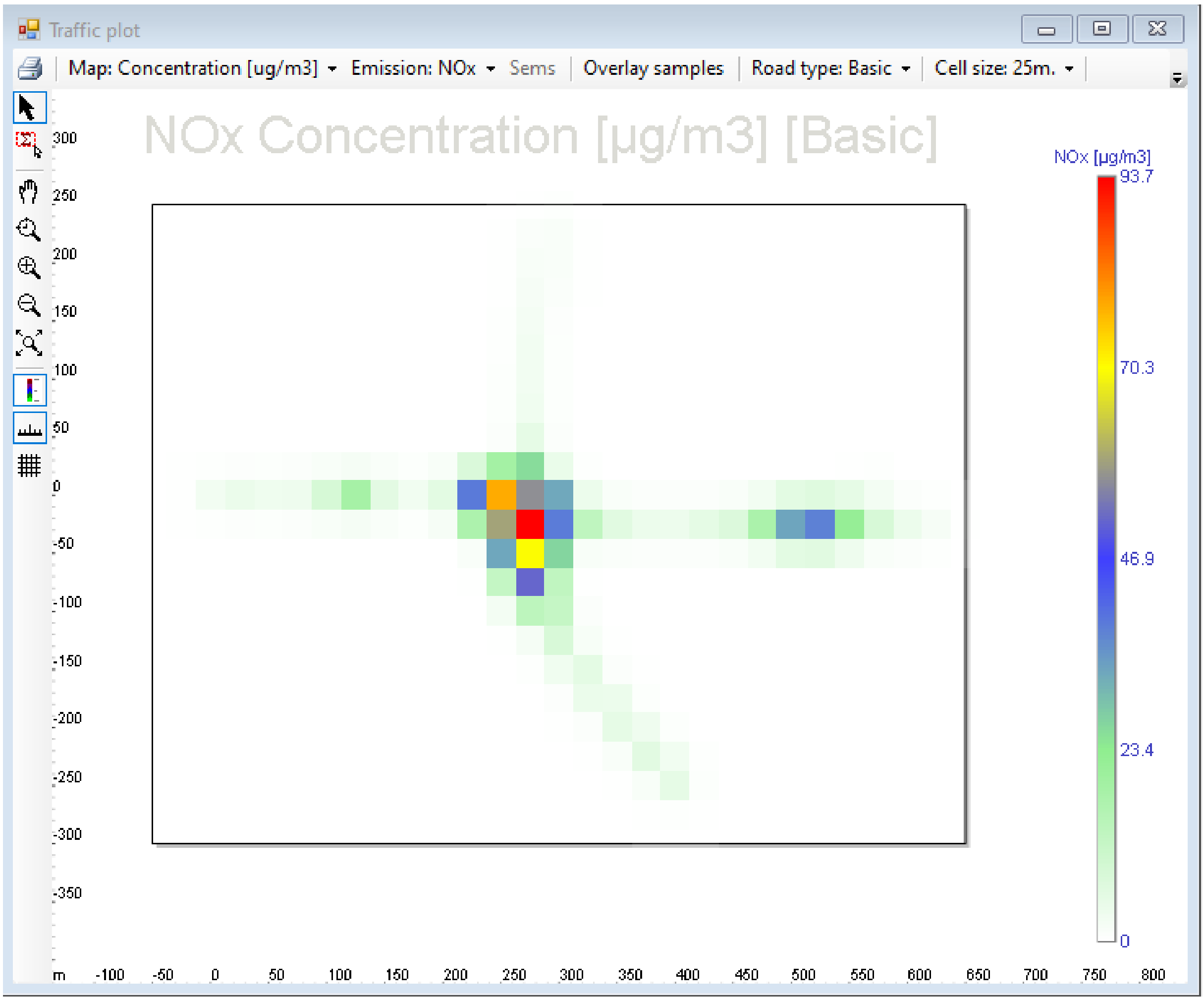
Source: Author (2023)

Figure 21 - Enviver emission map for NOx, EURO 1, volumes in 50%



Source: Author (2023)

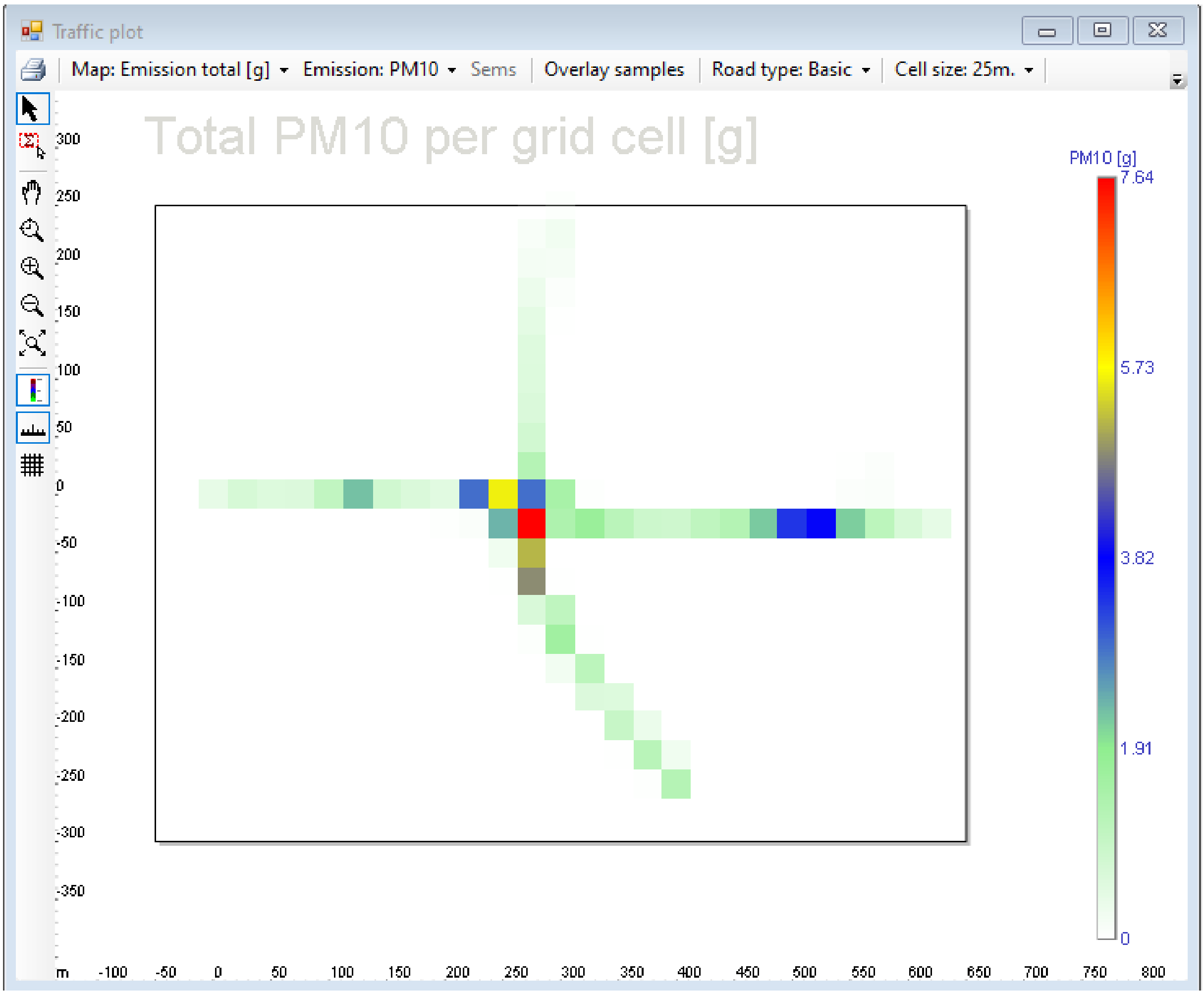
Figure 22 - Enviver concentration map for NOx, EURO 1, volumes in 50%



Map: Concentration [ug/m3]
Emission: NOx
Road type: Basic
Cell size: 25m.

Source: Author (2023)

Figure 23 - Enviver emission map for PM10, EURO 1, volumes in 50%



Map: Emission total [g]

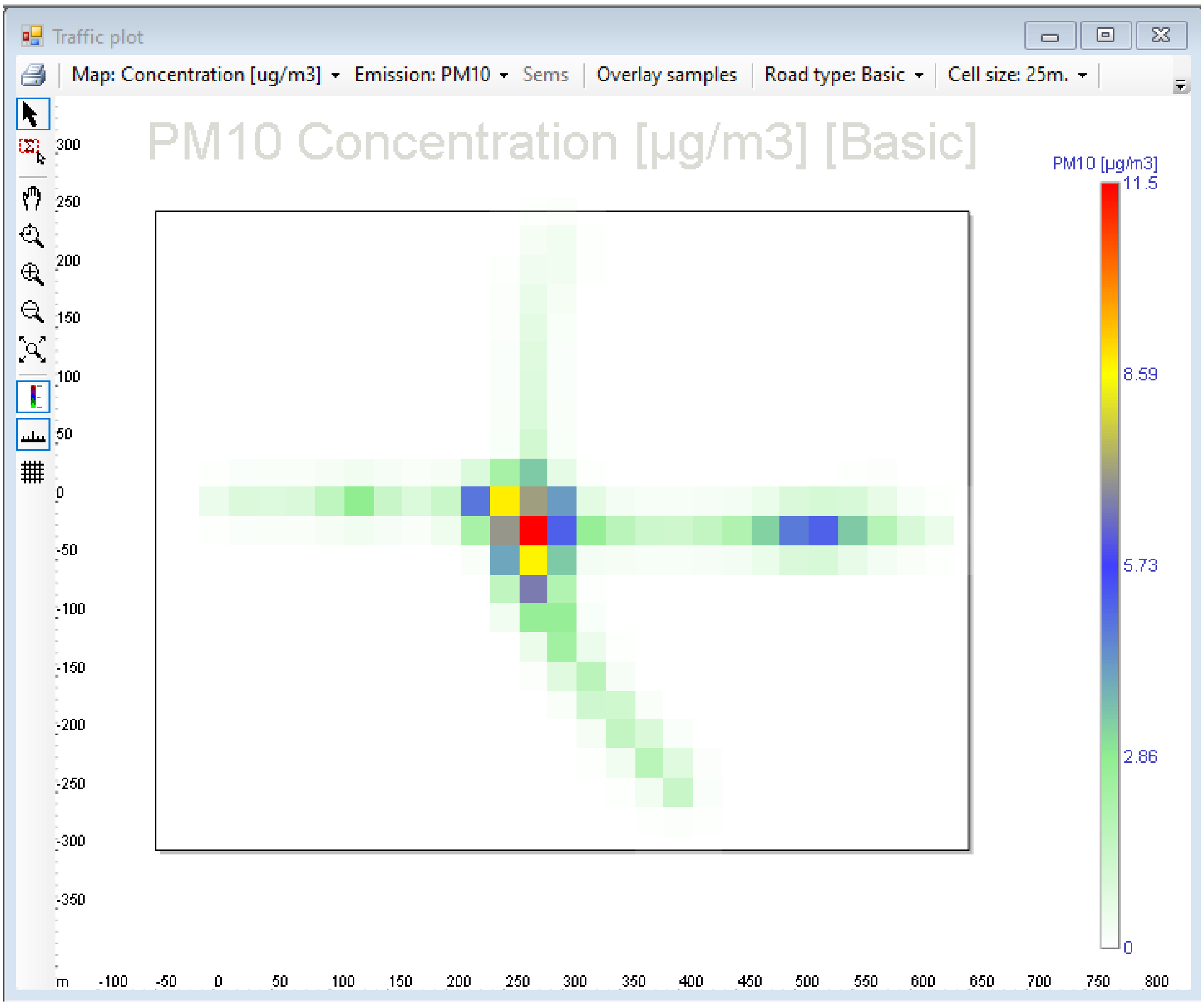
Emission: PM10

Road type: Basic

Cell size: 25m.

Source: Author (2023)

Figure 24 - Enviver concentration map for PM10, EURO 1, volumes in 50%



Map: Concentration [ug/m3]

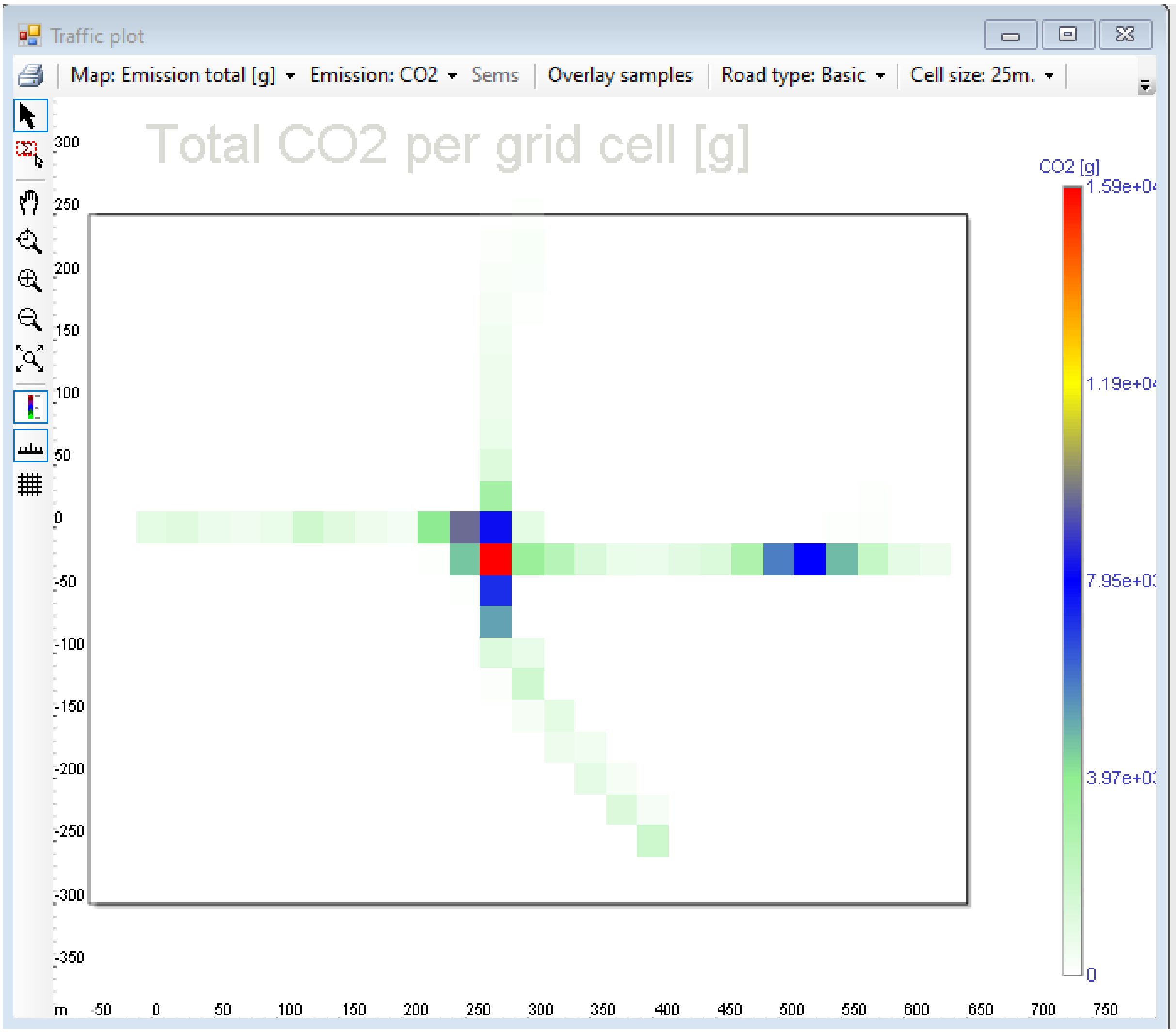
Emission: PM10

Road type: Basic

Cell size: 25m.

Source: Author (2023)

Figure 25 - Enviver emission map for CO2, EURO 2, volumes in 50%

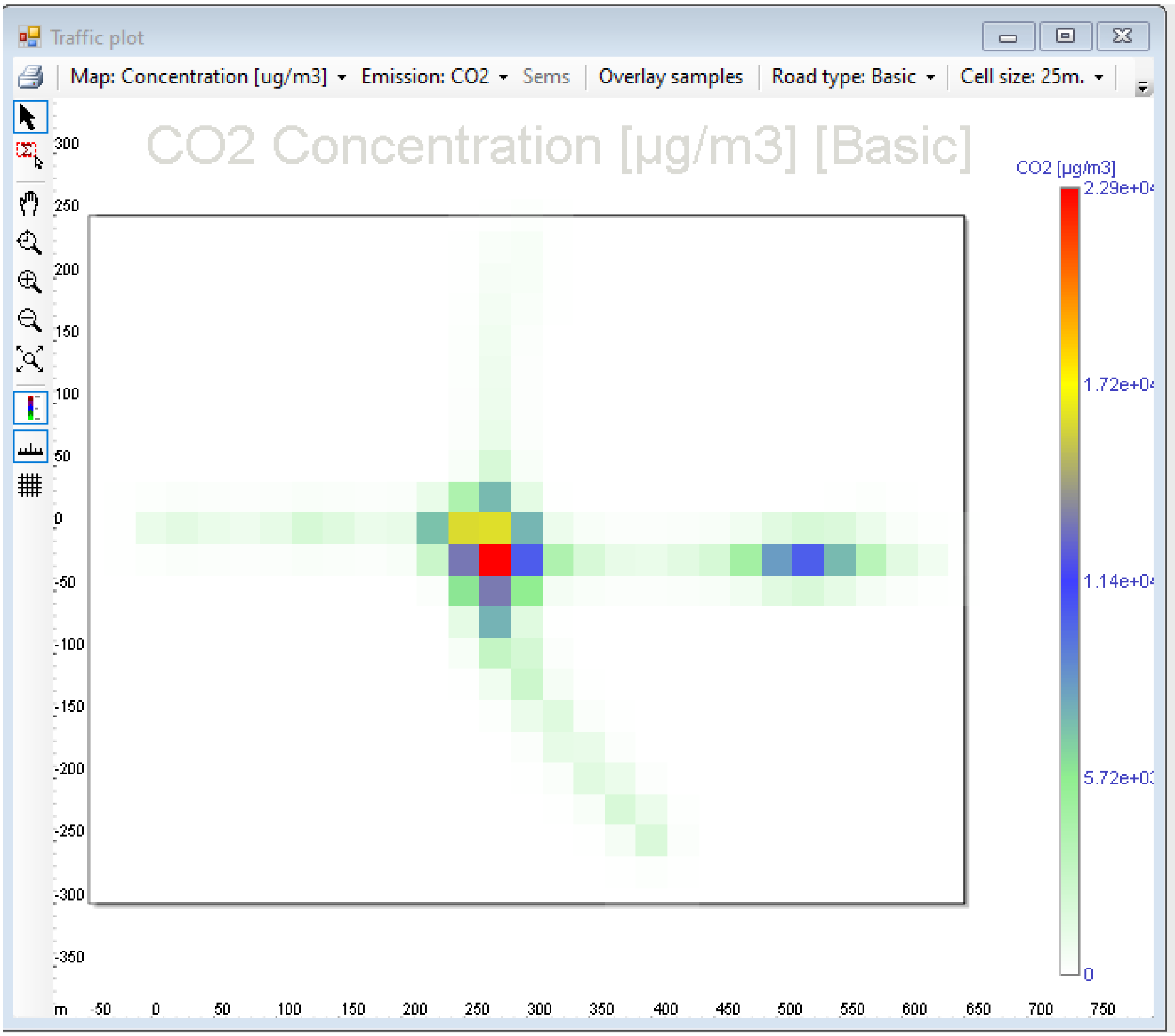


Traffic plot

Map: Emission total [g] | Emission: CO2 | Sems | Overlay samples | Road type: Basic | Cell size: 25m.

Source: Author (2023)

Figure 26 - Enviver concentration map for CO2, EURO 2, volumes in 50%



Map: Concentration [ug/m3]

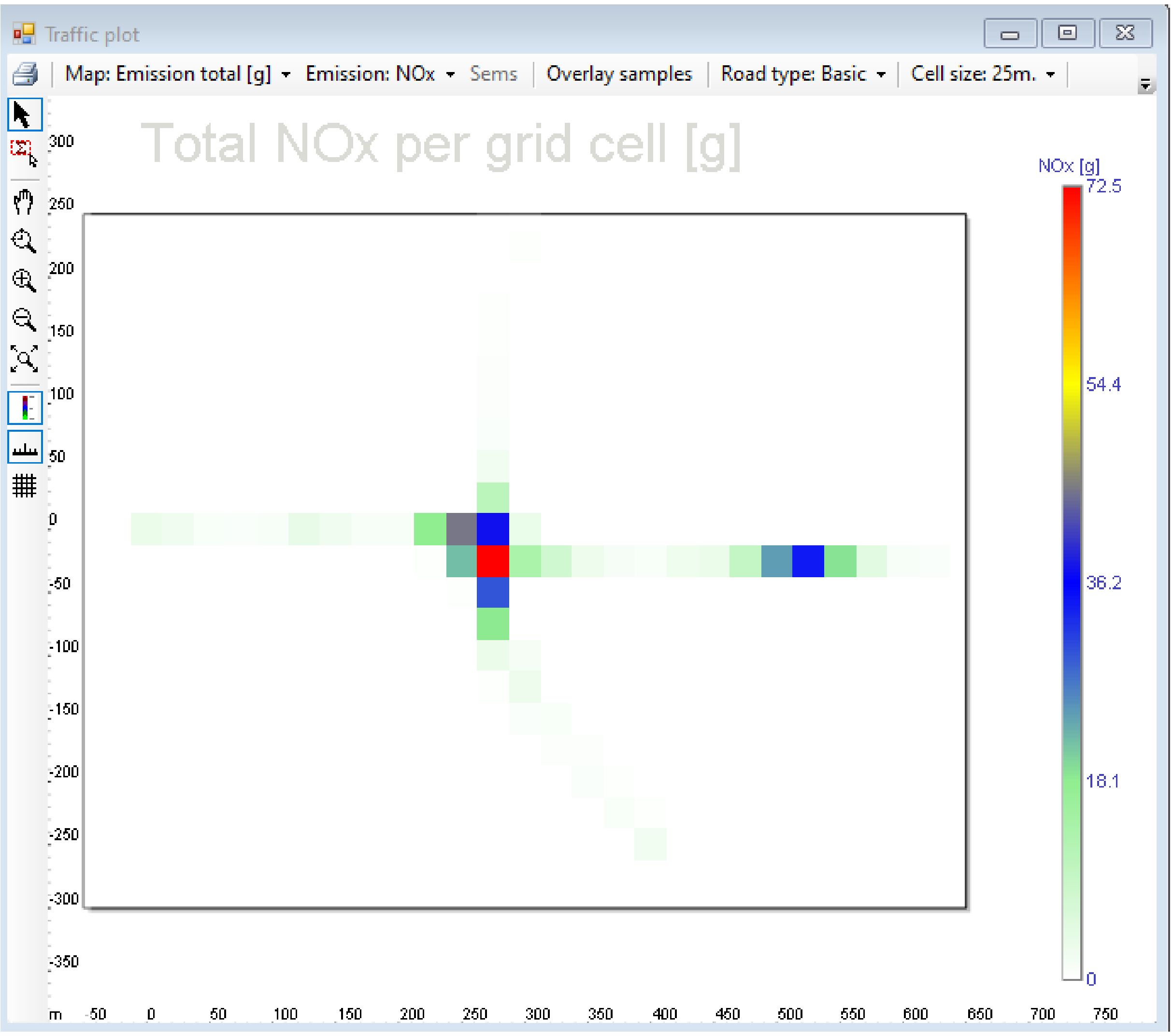
Emission: CO2

Road type: Basic

Cell size: 25m.

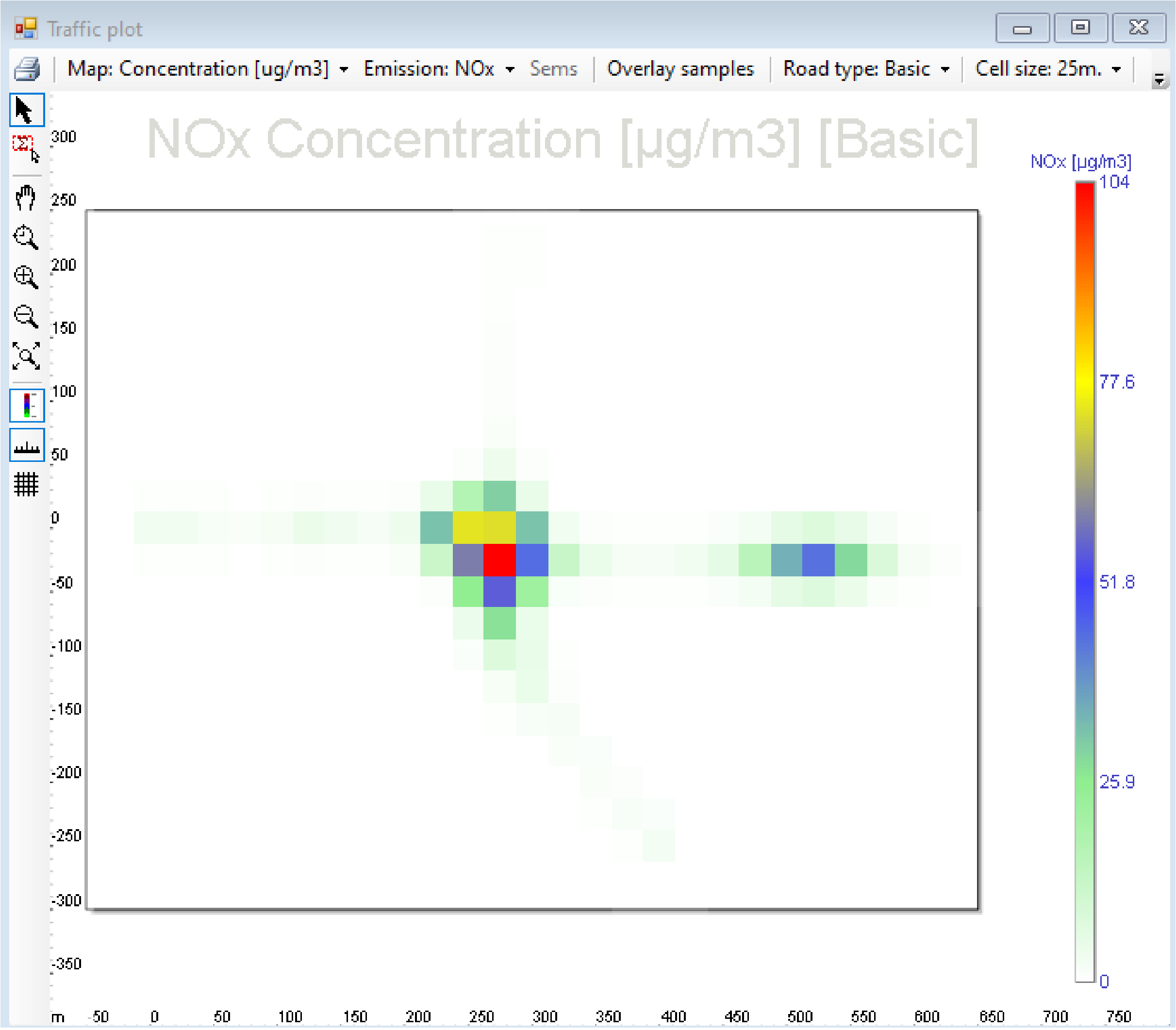
Source: Author (2023)

Figure 27 - Enviver emission map for NOx, EURO 2, volumes in 50%



Source: Author (2023)

Figure 28 - Enviver concentration map for NOx, EURO 2, volumes in 50%



Traffic plot

Map: Concentration [ug/m3]

Emission: NOx

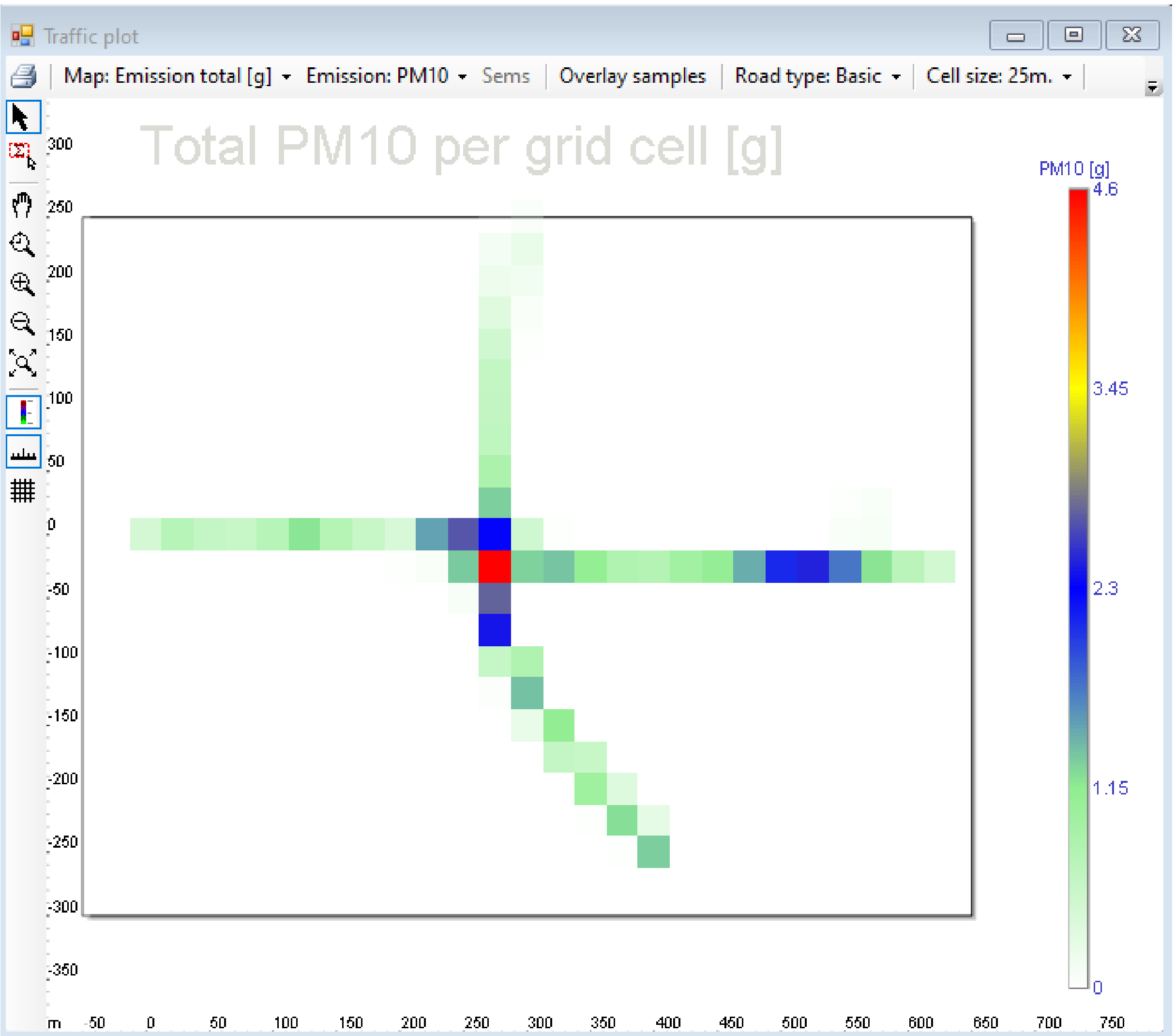
Overlay samples

Road type: Basic

Cell size: 25m.

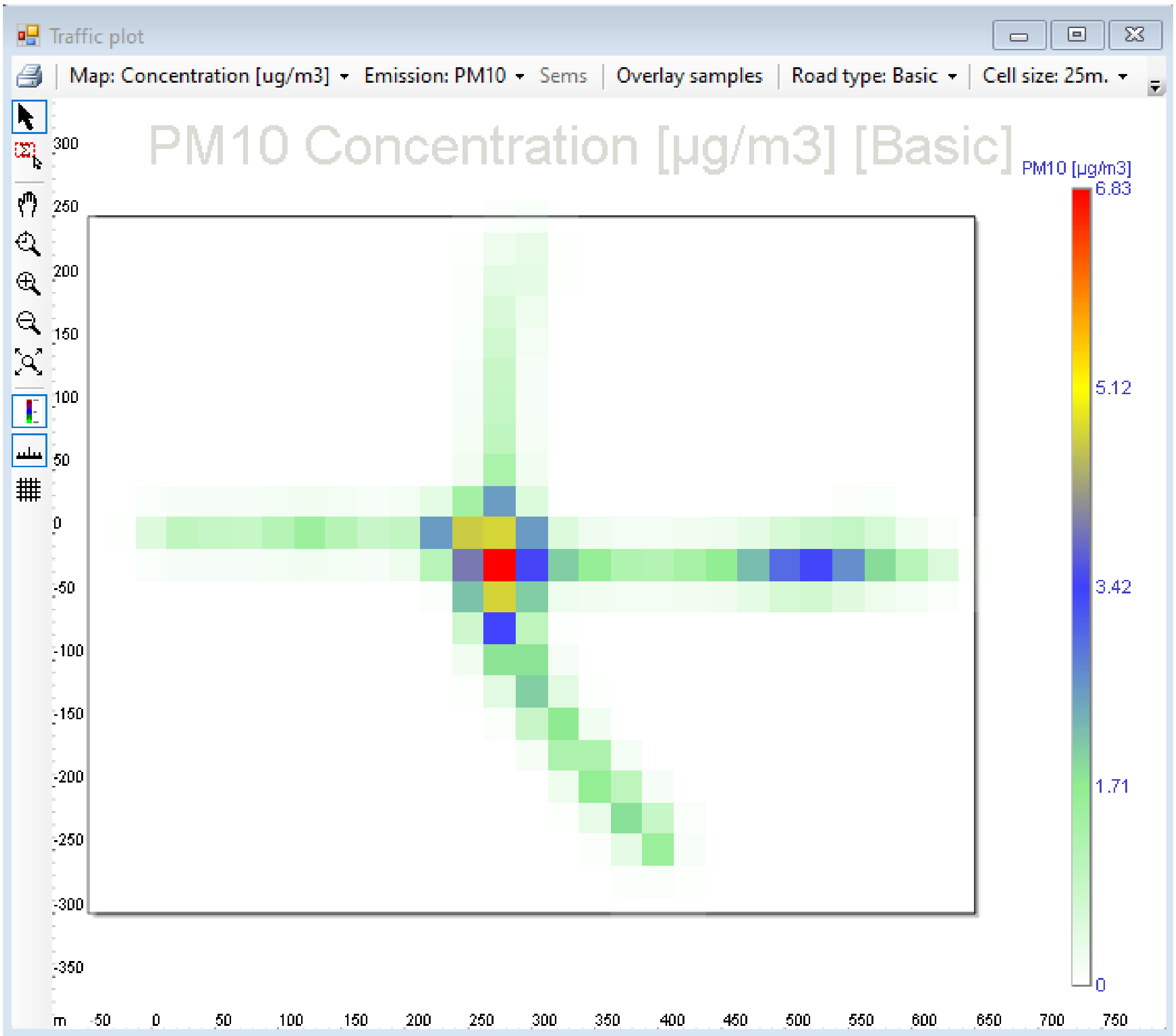
Source: Author (2023)

Figure 29 - Enviver emission map for PM10, EURO 2, volumes in 50%



Source: Author (2023)

Figure 30 - Enviver concentration map for PM10, EURO 2, volumes in 50%



Map: Concentration [ug/m3]

Emission: PM10

Road type: Basic

Cell size: 25m.

Source: Author (2023)