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TRABAJO FIN DE MASTER

DESIGN OF ALTERNATIVE ROUTING METHODS FOCUSED ON POLLUTION EXPOSURE AND THEIR EVALUATION THROUGH AGENT-BASED SIMULATION

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TRABAJO DE FIN DE MASTER

Título:	DISEÑO DE MÉTODOS DE ENRUTAMIENTO ALTERNATIVOS CENTRADOS EN LA EXPOSICIÓN A LA POLUCIÓN Y SU EVALUACIÓN MEDIANTE SIMULACIÓN BASADA EN AGENTES
Título (inglés):	DESIGN OF ALTERNATIVE ROUTING METHODS FOCUSED ON POLLUTION EXPOSURE AND THEIR EVALUATION THROUGH AGENT-BASED SIMULATION
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Resumen

La contaminación relacionada con el transporte en las ciudades es un problema creciente por su efecto en la salud de los ciudadanos y los pasajeros. En general, la exposición repetida a una contaminación atmosférica elevada se asocia a una reducción de la esperanza de vida y a una mortalidad prematura. Esto es especialmente peligroso en la ciudad de Madrid (España) porque, actualmente, es la ciudad con mayor concentración de NO_2 de Europa. Una forma de prevenir esa exposición a altas concentraciones de contaminación es evitar las zonas más contaminadas de la ciudad cuando se viaja por ella. Sin embargo, habitualmente, en un trayecto se suele optimizar el tiempo (en función de la distancia, velocidad y tráfico), o el coste (combustible, peajes), estando estas políticas incluidas en los algoritmos clásicos de enrutamiento. Es por eso que en este trabajo se ha analizado un método de encaminamiento alternativo que minimice el nivel de contaminación expuesto.

Para ello, se ha diseñado una simulación basada en agentes utilizando la herramienta de simulación SUMO y se ha implantado un algoritmo de encaminamiento que minimiza la exposición a polución de los pasajeros. De este modo, los agentes de la simulación priorizarán las rutas menos contaminadas sobre las más contaminadas. Para evaluar este tipo de políticas, se han llevado a cabo simulaciones de diferentes escenarios en la ciudad de Madrid variando las propias políticas de enrutamiento con respecto al NO_2. Al mismo tiempo, se ha llevado a cabo un análisis del efecto medioambiental (nivel macro) y del efecto sobre los ciudadanos (nivel micro) que dicho enrutamiento provoca.

Los resultados muestran que el enrutamiento basado en exposición a polución provoca una distribución de polución más homogénea en toda la ciudad, haciendo que no se superen ciertos umbrales de polución en las principales calles. A su vez, cuanto mayor es el porcentaje de vehículos que siguen este enrutamiento, la polución recibida de todos los vehículos de la red disminuye, incluidos los que siguen un enrutamiento estándar. El coste de este enrutamiento se ve reflejado en el aumento de la distancia y el tiempo de los viajes, siendo de un 7% y un 13% de media en los experimentos realizados, respectivamente.

Palabras clave: Enrutamiento alternativo, Exposición a polución, SImulacion basada en agentes, SUMO.

Abstract

Transport-related pollution in cities is a growing problem because of its effect on the health of citizens and passengers. In general, repeated exposure to high air pollution is associated with reduced life expectancy and premature mortality. This is particularly dangerous in the city of Madrid (Spain) because it is currently the city with the highest concentration of NO_2 in Europe. One way to prevent such exposure to high concentrations of pollution is to avoid the most polluted areas of the city when travelling through it. However, usually, a journey is optimised in terms of time (depending on distance, speed and traffic), or cost (fuel, tolls), being these policies included in classical routing algorithms. For this reason, in this work we have analysed an alternative routing method that minimises the level of pollution exposed.

For this purpose, an agent-based simulation has been designed using the SUMO simulation tool and a routing algorithm that minimises the pollution exposure of passengers has been implemented. In this way, the agents in the simulation will prioritise less polluted routes over more polluted ones. In order to evaluate this type of policies, simulations of different scenarios have been carried out in the city of Madrid, varying the routing policies themselves with respect to the NO_2. At the same time, an analysis of the environmental effect (macro level) and the effect on citizens (micro level) that such routing causes has been carried out.

The results show that routing based on pollution exposure leads to a more homogeneous distribution of pollution throughout the city, so that certain pollution thresholds are not exceeded in the main streets. In turn, the higher the percentage of vehicles which follow this routing, the less pollution is received from all vehicles in the network, including those following standard routing. The cost of this routing is reflected in increased travel distance and travel time, averaging 7% and 13% in the experiments, respectively.

Keywords: Alternative routing, Pollution exposure, Agent-based simulation, SUMO.

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Contents

List of Figures

CHAPTER 1

Introduction

This chapter will introduce the main points of this project. In this way, first of all we will talk about the context surrounding the different parts that will be discussed in the project. At the same time, a series of objectives in order to carry out this project will be presented. Finally, the concluding structure of this document will be introduced with an overview of each chapter.

1.1 Context

In recent years, some serious environmental challenges have arisen due to the great boom in technology and industrialisation, and among them, the deterioration of air quality. This can lead to serious health problems for people, causing diseases such as lung cancer, chronic bronchitis, heart disease, severe attacks among asthmatics or, in some cases, even death [18]. Thus, one of the major contributors to this deterioration of air quality is traffic in cities. Vehicles produce different damaging pollutant particles that can affect drivers and other city dwellers. As a consequence, governments are in need to establish different measures in order to face it because, as it is said in this article [3], air pollution control has been proved to be effective and have a positive impact on people health. Therefore, there is an urgent and global need to reduce exposure to polluted air in some way.

There are several pollutants produced by traffic which are harmful to health. Among them, NO_2 is considered to be one of the most dangerous. This particle is mostly produced by traffic - in fact it is estimated that up to 80% is produced by vehicles[1] - and as a consequence, concentrations of this particle are mostly recorded near the roadways. One city that stands out from the rest for the amount of NO_2 it produces is Madrid, Spain. According to this study [7], Madrid is the city in Europe with more deaths caused by exposure to NO_2 than any other European city . This makes NO_2 especially critical for the inhabitants of this city and demands engineering proposals to solve it.

The truth is that it is not an easy task to eliminate exposure to pollution and the health risks it entails; however, it is possible to try to minimise it. When moving around a city, applications that minimise time or distance are widely used. That is, they use routing algorithms that attempt to minimise these two parameters in order to find the fastest route or the shortest one. However, one way to reduce exposure to NO_2 could be avoiding the areas with the highest concentrations instead of taking these shortest or fastest paths, so by using less polluted traffic routes, exposure to this pollutant could be reduced in drivers. In this way, a new alternative routing emerges that prioritises routes with less accumulated NO_2 than the rest, i.e. a routing based on exposure to NO_2.

On the other hand, technological advances have enabled the development of new systems and applications. Among them, we would like to highlight the applications that allow agent-based simulations with respect to traffic. These kinds of simulations simulate the operations and iterations of multiple agents individually in an attempt to understand the behaviour of a whole system and what drives its outcomes. This allows traffic simulations to be carried out by modelling the behaviour of the different agents in the network (vehicles, people, bicycles...) and studying the final results of the simulation. One of the technologies which

[1] https://www.comunidad.madrid/servicios/salud/calidad-aire-salud

stands out in this kind of simulations is an open source tool called SUMO.

1.2 Project goals

In this context, we will present the objectives for this project.

- **Design of a traffic agent-based simulation in Madrid:** Through SUMO, we will create an agent-based simulation in the city of Madrid. Thus, we will have a collection of agents, in our case vehicles, whose behaviour will be influenced by rules in the system and by the evolution of the system itself. Thus, each agent will be routed at each moment according to rules that change during the simulation and are determined by the state of the pollution in the network. This pollution, as it is produced by the agents themselves, influences the behaviour of the rest of the system, which causes the system to change and therefore influences the rest of the agents in the network. In order to carry out these simulations, SUMO will be used. In turn, the iterative and real-time process between the simulation and the modelling of the behaviour of the network and the agents will be possible thanks to the TraCI tool and its API.

- **Design of an algorithm that minimises exposure to NO_2:** In order to be able to model the state of the network and penalise the most polluted routes, a cost function algorithm dependent on time and accumulated pollution will be needed. This cost function will be applied to each edge of the network in real time and varies throughout the simulation. Thus, the routing behaviour of each agent in the network will be influenced by the values of this cost function.

- **Design of different simulation scenarios:** In order to further study routing based on pollution exposure, several scenarios will be created by varying the amount of traffic, the percentage of vehicles with such routing and the interpolation window in terms of the time the pollution remains in the city.

- **Analysis and evaluation of the effect of pollution exposure routing on the city of Madrid:** Thus, this evaluation will be done at a micro level and at a macro level. Data will be obtained on the duration, pollution, noise, time, traffic... that routing due to exposure to pollution produces.

1.3 Structure of this document

This project is structured as follows:

- ***Chapter 1:*** It is the introduction of the project. A description of the context where the project is developed, the main goals, and the structure of the document are presented.
- ***Chapter 2:*** An analysis of the state of the art surrounding this project which include alternative routing algorithms and similar projects.
- ***Chapter 3:*** Description of the available technologies which will be used in this project.
- ***Chapter 4:*** It describes the architecture and the methodology followed to carry out the agent-based simulations.
- ***Chapter 5:*** It provides the development of the agent-based simulation.
- ***Chapter 6:*** It details the different scenarios that have been run and analyzes the results obtained.
- ***Chapter 7:*** It discusses the conclusions, the achieved goals and future work.
- ***Appendix A:*** It shows some graphs of interest regarding the simulation results and their analysis.
- ***Appendix B:*** It discusses the social, economic, environmental and ethical impact of this project.
- ***Appendix C:*** It details the economic budget for the realization of this project.

CHAPTER 2

State of Art

In this chapter, we will show the state of the art concerning the alternative routing algorithms and their use in agent-based simulations. Thus, firstly an introduction to alternative routing will be made, focusing our attention pollution exposure-based routing. Later, several articles which has implemented similar projects will be analysed. Finally, a conclusion will be made.

2.1 Alternative routing

Routing is the function of selecting a path among all possible paths in a network where there are connections between different nodes. Usually, the objective when routing is to find the best possible route, but to do so, it is necessary to define what is meant by best route and consequently what is the metric to be used in order to measure it.

Currently, there are several types of routing with respect to transport, two of which stand out: distance-based routing and time-based routing, both of which tend to be the fastest. However, there are also other types of routing that offer different advantages depending on the metric to be minimised. Among these alternative routing methods, fuel consumption routing also stands out. Thus, thanks to this type of routing, it is possible to find those routes with the lowest fuel consumption. There are also other algorithms that try to minimise the average speed, the price of the trip, and so on.

On the other hand, there is also pollution-based routing. This tries to find the roads along which vehicles will pollute the environment the least, thus being a type of 'green' routing. Related to this type of routing we have pollution exposure routing. This type of routing attempts to minimise the exposure of vehicle passengers and it is this type of alternative routing that we will focus on.

2.1.1 Routing based on pollution exposure

As mentioned in the previous section, this type of routing seeks to minimise the pollution exposure of vehicle travelers, that is, routes with lower pollution concentrations are prioritised over routes with higher pollution concentrations. In the following paragraphs we will explain the reasons and usefulness of this type of routing, the chosen pollution metric and how it can be calculated.

2.1.1.1 Health problems

Exposure to pollution can lead to chronic respiratory diseases; in fact air pollution has been a major public health problem for several years. The diseases that exposure can cause include lung cancer, chronic bronchitis, heart disease, severe attacks among asthmatics and, in some cases, even death [18].

As a consequence, exposure to pollution is associated in the long term with premature mortality and reduced life expectancy [18].The people most affected by pollution exposure are people with previous respiratory problems, pregnant women, the elderly - especially men [21] - and children. Thus, prolonged exposure to pollution can lead to adverse health problems for many people. This exposure can occur in multiple locations: workplaces, residences, leisure facilities, and of course, road journeys, hence the need for alternative routing to minimise exposure.

2.1.1.2 Pollutants

We will see in the next secion of this Chapter that different projects have relied on different pollutants for the calculation of pollution exposure routing. This is because, depending on the objectives and characteristics of each project, some metrics were of more interest than others. In this section we will explain the different pollutants in the atmosphere, how they affect it and on which of them we will base the routing knowing that the city chosen for the simulations is Madrid.

The main pollutants are:

- **Ozone (O_3):** Ozone is a colourless gas which, depending on the layer of the atmosphere in which it is found, can be beneficial or harmful to health, and thus the following distinction can be made [12].

  - **Stratospheric ozone:** this is not harmful to health, it is located in the stratosphere (between 12 to 50 km above the earth's surface), and protects us from the sun's harmful ultraviolet rays.
  - **Tropospheric ozone:** this type of ozone is dangerous to health as it is located in the troposphere (part of the atmosphere where human life develops). This type of ozone is formed as a result of chemical reactions, in the presence of sunlight, from pollutants emitted by cars, thermal power plants, refineries, various industrial processes, etc. The higher the sunlight and temperature, the more ozone is formed.

  Among the main consequences that ozone can cause are irritation of the eyes and respiratory tract with coughing, greater difficulty in breathing normally, greater susceptibility to respiratory infections, asthma attacks, emphysema or chronic bronchitis... [17].

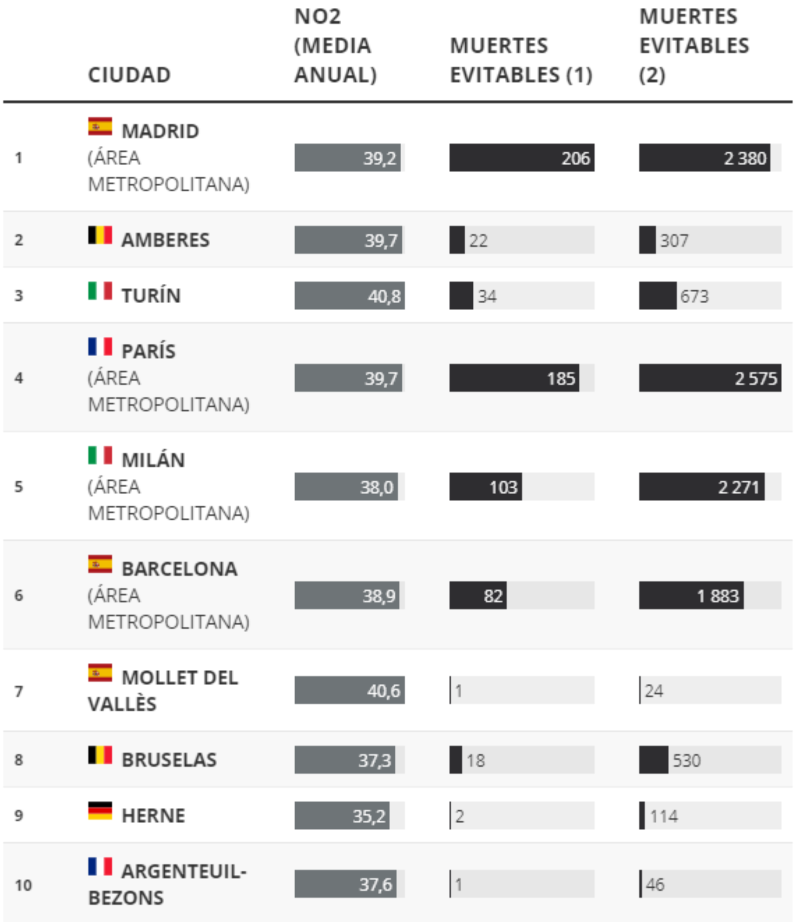
- **Nitrogen dioxide (NO_2):** is an air pollutant that is mainly produced by the combustion of motor vehicles (up to 80%), with diesel vehicles being a particular contributor[1]. The rest may well be generated by gas, oil or coal combustion, thermal power stations, industrial activities, heating, incinerators, etc.

  Symptoms associated with continuous exposure to NO_2 include itchy eyes, nose and throat, as well as irritation of the bronchial tubes with coughing, phlegm and difficulty

[1] https://www.comunidad.madrid/servicios/salud/calidad-aire-salud

breathing.

We have considered important to highlight the importance of NO_2 in the city of Madrid. This is because Madrid is the European city with more deaths caused by nitrogen dioxide than any other city in Europe [7] as can be seen in Fig. 2.1.



	CIUDAD	NO2 (MEDIA ANUAL)	MUERTES EVITABLES (1)	MUERTES EVITABLES (2)
1	MADRID (ÁREA METROPOLITANA)	39,2	206	2 380
2	AMBERES	39,7	22	307
3	TURÍN	40,8	34	673
4	PARÍS (ÁREA METROPOLITANA)	39,7	185	2 575
5	MILÁN (ÁREA METROPOLITANA)	38,0	103	2 271
6	BARCELONA (ÁREA METROPOLITANA)	38,9	82	1 883
7	MOLLET DEL VALLÈS	40,6	1	24
8	BRUSELAS	37,3	18	530
9	HERNE	35,2	2	114
10	ARGENTEUIL-BEZONS	37,6	1	46

Figure 2.1: Ranking of European cities with the highest number of deaths associated with air pollution by nitrogen dioxide (*https://isglobalranking.org/es/ranking/*): (1) Avoidable deaths according to WHO criteria. (2) Preventable deaths according to the lowest levels.

This study also shows that if the WHO standard were met in Madrid, until 206 deaths would be avoided; and if the best in this case (Tromso, Norway), was met, these deaths would be reduced by approximately 2,400 per year.

- **Particulate matter:** This is a mixture of particles and droplets in the air, consisting of a variety of components from both natural sources (sandstorms, volcanic eruptions, forest fires, etc.) and human activity (traffic, especially diesel vehicles, incinerators, coal-fired heating, etc). Based on size, particulate matter is often divided into two main groups:

- **$PM_{2,5}$:** They are smaller than 2.5 microns, hence their name. These come mainly from human activity and can penetrate deep into the lungs and enter the bloodstream, making them particularly harmful.

- **PM_{10}:** On the other hand, these are usually smaller than 10 microns and come mainly from natural activity. Because they are larger, the respiratory system is able to retain higher portions of the particle, making them less harmful to health than $PM_{2.5}$. However, they are not harmless. This particle is especially abundant in Madrid when dust arrives from the Sahara desert pushed by southerly winds[2].

Among the possible diseases that exposure to this particle can cause are: premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing[3].

- **Sulfur dioxide (SO_2):** This particle is a colorless, reactive air pollutant with a strong odor whose emissions mainly come from fossil fuel combustion and natural volcanic activity. As in previous cases, these particles in high concentrations can pose serious health hazards, including: inflammation and irritation of the respiratory system, coughing, throat irritation, and breathing difficulties, lung function, worsen asthma attacks, and worsen existing heart disease in sensitive groups[4].

- **Carbon dioxide (CO_2):** This particle is an acidic colorless gas which is produced by all aerobic organisms when they metabolize organic compounds in order to produce energy. At the same time, it can be produced by combustion of organic materials and fossil fuels which has made it the most significant greenhouse gas in Earth's atmosphere. However, its direct health consequences are somewhat less than the previous gases. Nevertheless, it can still cause effects such as inflammation, reductions in higher-level cognitive abilities, bone demineralization, kidney calcification, oxidative stress and endothelial dysfunction as it is indicated in this article [6].

[2] https://www.comunidad.madrid/servicios/salud/calidad-aire-salud
[3] https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm
[4] https://www.nps.gov/subjects/air/humanhealth-sulfur.htm

2.2 CAR: The Clean Air Routing Algorithm for Path Navigation With Minimal $PM_{2.5}$ Exposure on the Move

The authors of this paper [10] present the Clean Air Routing (CAR) algorithm which consists of creating optimal routes for the health of travelers between an origin and a destination. So one way a lower personal exposure to pollution is achieved. To do this, they use $PM_{2.5}$ particles as a measure of pollution. In this way, they use the open source data of these particles in the city of Taiwan, which they integrate with the road network of the same city thanks to the use of OpenStreetMaps[5]. They also use Graphhoper[6], which is an OSM-based routing library. With regards to the interpolation, they perform it both spatially and temporally using IDW and Kringing algorithms, obtaining better results with the former.

In turn, they perform $PM_{2.5}$ predictions, since to accurately recommend a route with the lowest total $PM_{2.5}$ exposure, it is first necessary to know how $PM_{2.5}$ varies during travel time. To do this, they employ a Neural Network Autoregression (NNAR) and an Autoregressive Integrated Moving Average (ARIMA) model, which let them achieve a 79% of accuracy. Thus, the basis of the concentration values for interpolation would already be obtained.

Once the $PM_{2.5}$ value is obtained at each link at each time, a weight function is introduced to evaluate the amount of communication in the link itself.

It is assumed that the travel time between two nodes is directly proportional to the distance, and that in addition, the inhaled particles are proportional to the exposure time. Therefore, they multiply the particle concentration and the length of the road segment to obtain the cost function. Depending on the time, the calculated weight will replace the existing one and the updated data will be used to calculate the shortest path.

Thus, the routing algorithm uses these weights to establish the optimal route in terms of pollution.

With regards to the experiments carried out, a multitude of different scenarios encompassing different types of travel, such as driving, cycling or walking, have been performed. The results obtained show that on average the exposure to pollution of travelers can be reduced by 17.1%, increasing on average the distance by 2.4%.

[5] https://www.openstreetmap.org/
[6] https://www.graphhopper.com/

2.3 Promoting Pollution-Free Routes in Smart Cities Using Air Quality Sensor Networks

The authors of this article [16] use air quality sensors in the city of Madrid to know the level of pollution in real time. They obtain NO_2, O_3, PM_{10} and $PM_{2.5}$, and develop a new indicator called MLAQI (Madrid Local Air Quality Index). In this way, its main pollutant is NO_2, and the auxiliary pollutants are O_3, PM_{10} and $PM_{2.5}$. With the MLAQI, the index at a given station must be calculated with the main pollutant and at least one of the secondary pollutants. Also, they establish different categories according to the ranges, depending on whether they are good, acceptable, poor or very poor as shown in Fig. 2.2.

Index Range	Index Category	Color	Core Pollutant	Auxiliary Pollutant		
			NO_2	O_3	PM10	PM2.5
0–50	Good	Green	0–100	0–90	0–50	0–30
51–100	Acceptable	Yellow	101–200	91–180	51–90	31–55
101–150	Poor	Orange	201–300	181–240	91–150	56–90
>150	Very Poor	Red	>300	>240	>150	>90

Figure 2.2: Madrid Local Air Quality Index definition [16].

Once the value for each sensor has been established, the authors have developed a spatial interpolation using the IDW algorithm. And by using ArcGIS Server[7] and the *GaLayerToContour* tool they generate a polygonal feature class categorized by the MLAQI. Once the polygons are generated, they are published as a layer to make the data available online.

At the same time, they elaborate alternative routes that avoid the most polluted areas of the city, for which they establish entry barriers to the areas of the city, and this can be used both for people who walk and for people who walk. When there is a highly polluted area, this acts as a barrier in the routing service, thus excluding from the analysis all the streets that cross and calculates a pollution-free route.

2.4 Computing least air pollution exposure routes

On the other hand, in this publication [18], they have used data from the U.S. Environmental Protection Agency (EPA) air pollutant monitoring stations to map the streets using the IDW and Kriging algorithms. Better results were obtained, in this case, with the second

[7] https://www.arcgis.com/

one. The pollution data collected are O_3, $PM_{2.5}$, PM_{10}, CO, SO_2, NO_x, which are used to calculate the air quality index (AQI).

To add the weight to the different road links, they use a systematic sampling that is based on a fixed time, rather than a fixed distance as they argue that the amount of pollution inhaled is higher for longer exposure minutes and not necessarily the longer the segment distance, the more time in the lane.

Finally, thanks to the use of NAVTEQ[8], they conducted the experiments in two random areas of the city of Pittburgh. Using 60 pairs of randomly selected origin and destination locations, they calculated the routes with the lowest exposure to pollution (APE). The results are shown in Fig. 2.3 and Fig. 2.4 where distance and weights between least APE routes and shorter routes are compared.

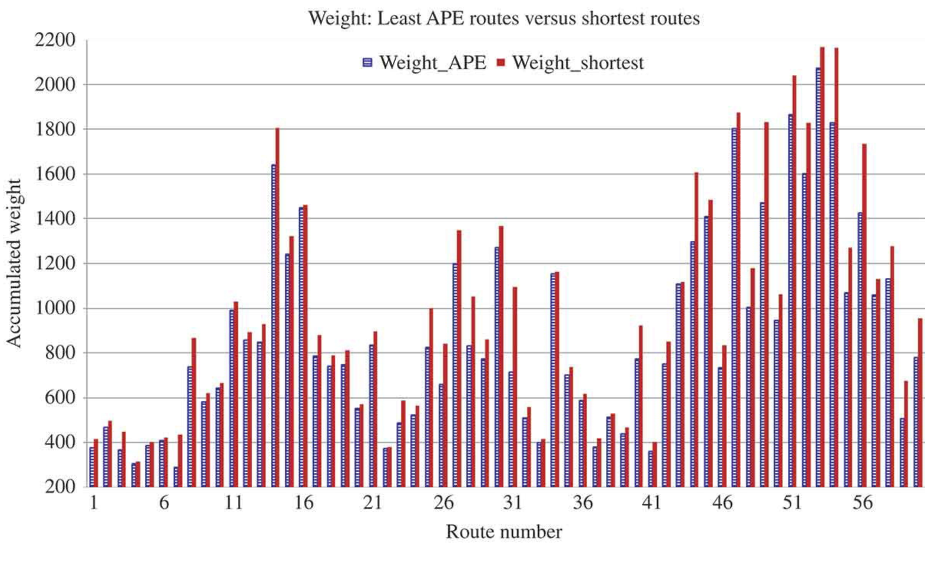


Figure 2.3: Accumulated weight (AQI-Sec) for least APE routes and shortest routes to compare the differences in APE weight for all computed routes [18].

[8]https://www.here.com/navteq

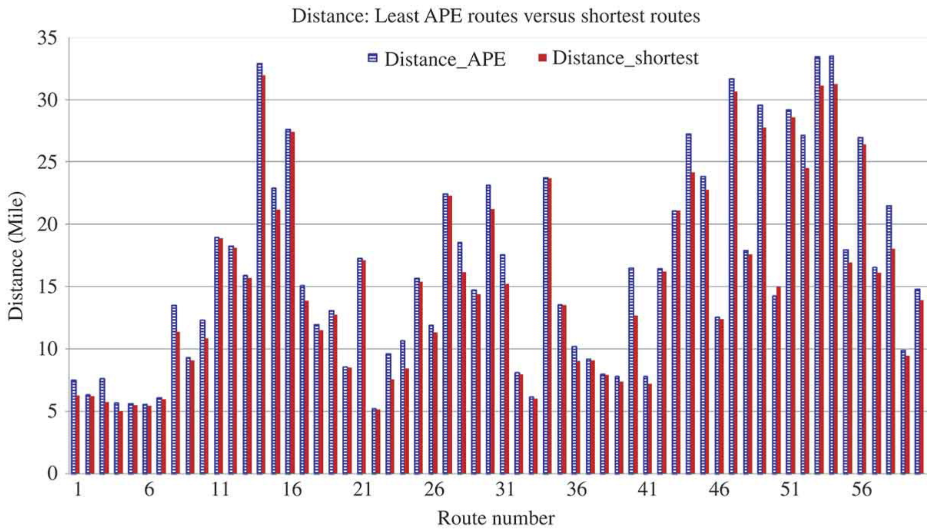


Figure 2.4: Route distance for least APE routes and shortest routes to compare the differences in route distance for all computed routes [18].

The results show that the average difference in weight is about 106.63 units less in least APE routes for an average 0.90 miles more route distance; however, the travel time is 3.06 min less compared to shortest routes. Nevertheless, they do not compare the shortest routes in duration with those of APE, so this value should not be taken into consideration.

2.5 Dynamic route planning framework for minimal air pollution exposure in urban road transportation systems

The authors of this article [20] propose a dynamic route planning algorithm for an urban scenario in order to distribute the traffic density in real time to other low dense traffic junctions. Thus, this framework tries to minimize the number of congested traffic junctions by distributing the real time traffic using diversion suggestions. In this way, it reduces air pollution at traffic junctions. In order to do so, the cost function based approach is proposed with pollution levels, junction connectivity and road type as the key parameters at the same time as taking into consideration the possible shortest distance metric. Thus, pollution data is not collected in this paper but traffic data. Finally they use QGIS (Quantum geographical information system)[9] which is a cross-platform that allows them to create, visualize, query and analyze geospatial data.

[9] https://qgis.org/

2.6 Health-optimal routing in urban areas

In this paper [4], the authors combine high-resolution pollution maps of the city of Zurich with road network data to analyze the extent to which the pollution exposure of inhabitants is affected when instead of moving from an origin to a destination by the shortest route, they move by a healthier route. The map of the city is obtained through OpenStreetMap meanwhile high-resolution pollution maps of ultrafine particles are collected from mobile sensor nodes from this other article [5].

As in several previous studies, they introduce a cost function for edges as a function of distance and pollution exposure. With regards to the evaluation of the algorithm used, the authors show that there is a 7.1% reduction in pollution exposure at the cost of increasing the distance to the optimal path by 6.4%.

Finally, they implement the algorithm as stand-alone application for iOS and Android devices.

2.7 Simulation of Population-Based Commuter Exposure to NO_2 Using Different Air Pollution Models

The authors of this paper [15] have created a simulation of commuter routes and the pollution they produce in the city of Basel. They evaluate three air pollution models with different spatial resolution for estimating commute exposures to nitrogen dioxide (NO_2): high resolution dispersion model, lower resolution model and land use regression model. With respect to the cost function, NO_2 concentration of a leg is calculated from the sum of the extracted NO_2 grid concentrations weighted by the length of the leg within the grid

Exposure to pollution was evaluated for motorized transport, bicycle and walking. The Fig. 2.5 shows the distribution of the concentration, the exposure and the dose received as a function of transport.

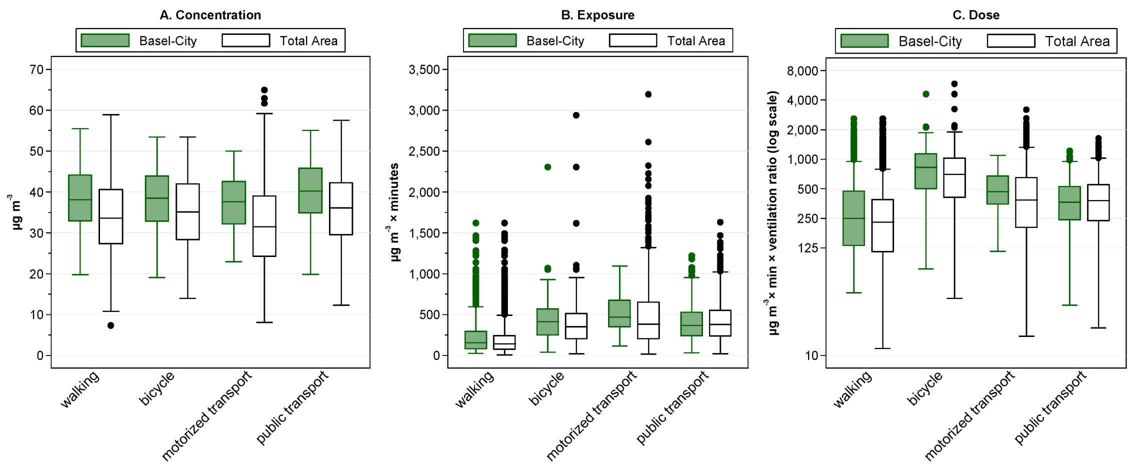


Figure 2.5: Box plots of in-traffic NO_2 concentration (A); exposure (B); and dose (C) by travel mode and study area using the PolluMap model. Estimates are based on commute legs: boxes represent 25th to 75th percentile, central line the median, bars outside the box represent the most extreme values within 1.5 × the inter quartile range of the nearer quartile, and circles are outliers [15].

2.8 Assessing personal exposure to traffic-related air pollution using individual travel-activity diary data and an on-road source air dispersion model

The authors of this study [14] show a method for reconstructing individuals' movement trajectories from travel-activity diaries and, at the same time, they assess exposure by integrating the trajectories with $PM_{2.5}$ concentrations which are derived from on-road source air dispersion modeling. Among traffic-related air pollutants, $PM_{2.5}$ is known to be the most detrimental to human health [2] and the reason they use it.

They estimate hourly traffic-related $PM_{2.5}$ concentrations using the Research LINE-source dispersion model [19] and MOVES[10]. R-LINE is a line-type source dispersion model designed to capture the fine-scale spatiotemporal variability of traffic-related air pollution concentrations. On the other hand, MOVES (motor vehicle emission simulator)is a modeling tool that estimates emissions from all on-road mobile sources. They use This study uses MOVES2010b software to estimate total $PM_{2.5}$ emissions in the 20-county Atlanta metropolitan area in Georgia.

Thanks to the use of the Google Maps Directions API and ravel-activity diary dataset

[10]https://www.epa.gov/moves

collected by the ARC in 2011[11], they create minute-by-minute track points on the travel routes which will be used to estimate air pollution exposure every minute along the individual's movement trajectory. It is important to remark that each individual's total daily exposure is calculated by averaging the concentrations based on the time the person spent at each location.

Between the final results they obtain, one we want to take into consideration is that exposure during transport accounts for 7.8% of the total daily exposure, although the time fraction of the day spent in transit is relatively small (4.5%).

2.9 Vehicle road navigation to minimize pollutant exposure

In this paper [9], a new vehicle routing methodology is introduced with the objective to minimize pollutant exposure to localized populations along roadways. To do so, a modeling suite has been developed for the evaluation of environmental Intelligent Transportation System (ITS) applications from a traffic emissions exposure point of view. In Fig. 2.6, it is shown the modeling methodology diagram.

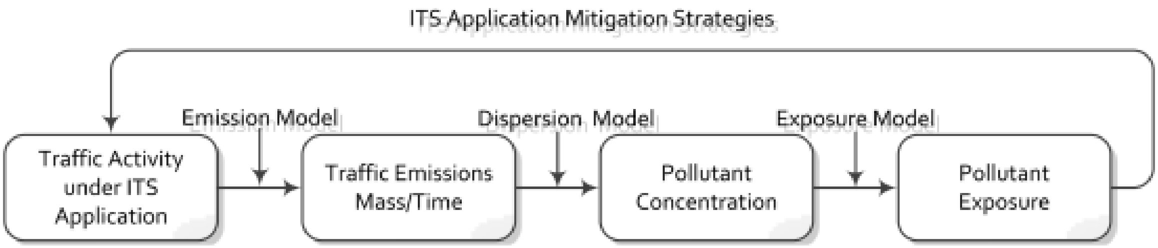


Figure 2.6: Overall traffic pollutant exposure modeling methodology flow diagram [9].

For the traffic emission modeling, CMEM (Comprehensive Modal Emission Model) [1] is used for the emission factor component. For the dispersion modelling, they employ CALINE4[12] which is a steady-state Gaussian dispersion model designed to determine air pollution concentrations at receptor locations downwind of highways located in relatively uncomplicated terrain. In relation to the routing algorithm, they model the exposure as a routing cost taking into account the combined cost for each link, the weight factor driving and the driving time for each link derived from link length and speed limit. Finally, routes can be generated and visualized with ArcMap[13].

In relation to the evaluation, they have developed three different scenarios results with PM_{10} as the target pollutant chosen and 5–14 year-old children as the target population.

[11] www.nrel.gov/tsdc
[12] https://trid.trb.org/view/215944
[13] https://desktop.arcgis.com/es/arcmap/

The results show that the intake fraction of particulate matter for children on school days can be reduced approximately 80%-90% on a typical school day while only adding 50 seconds to a nine-minute route and 10% of distance.

2.10 Influence of walking route choice on primary school children's exposure to air pollution — A proof of concept study using simulation

Closely related to the previous study, the authors of this article [11], developed a walking network whose routes can be calculated either based on the shortest duration or based on the lowest cumulative NO_2 or PM_{10} exposure. In this way, an analysis of the costs and benefits of faster routes versus lower pollution exposure for walking routes to primary schools is carried out and . The geographic setting for this research is the Greater Manchester area in the North West of England. With ArcGIS Network Analyst and Walkit[14] online service which provides 'low pollution' routes, the authors are able to find the fastest walking route and the routes with the lowest cumulative NO_2 and PM_{10} exposure using 100,000 hypothetical school routes.

The evaluation indicated that for 50% of routes a 1% increase in travel time was associated with a 1.5% decrease in NO_2 and PM_{10} exposure. It should be noted that this data is for walking routes, not vehicle routes. Fig. 2.7 shows the comparison between time-minimising routing versus those that minimise exposure to NO_2 and PM_{10}. With those results, the authors suggest that for a large proportion of alternative low exposure routes the benefit of lowered exposure is greater than the cost associated with walking for a longer time.

	Fastest route	Low NO_2 route	Low PM_{10} route
Time (s)	1144 (784, 1434)	1152 (789, 1446)	1144 (785, 1435)
NO_2 exposure (μg/m^3)	32.9 (31.6, 34.6)	32.5 (31.1, 34.1)	32.9 (31.6, 34.6)
PM_{10} exposure (μg/m^3)	20.9 (20.6, 21.2)	20.8 (20.6, 21.1)	20.8 (20.6, 21.1)

Figure 2.7: Median (IQR) travel time and exposure [11].

[14]www.walkit.com

2.11 Conclusions

With respect to alternative routing based on exposure to pollution, we find the idea of trying to minimise NO_2 particulate matter in the city of Madrid particularly interesting. As NO_2 is a particle mainly emitted by vehicles and is especially abundant in Madrid, engineering solutions are needed to solve this problem.

Among the articles that have addressed issues similar to the idea of this project, there are two recurring particles that researchers are concerned about and have been used for routing based on pollution exposure, namely NO_2 and $PM_{2.5}$.

Most projects that have designed alternative routing have employed temporal and/or spatial interpolation techniques for pollution emissions. In this way, more realistic scenarios are acquired. For this purpose, IDW or Kringing algorithms have been used.

Regarding the source of the road network on which to deploy the alternative routing, mainly OpenStreetMap and ArcGIS have been used, although other technologies such as NAVTEQ or QGIS have also been used.

With regard to the pollution exposure-based routing algorithm itself, most projects have used cost functions based on distance or time and the amount of pollution in the edge at any given time. In this way, they have created a network of weights calculated through the cost function on which to base their routing. The algorithms most commonly used to find the best route within this weight map have been Dijkstra and A+.

Finally, the routing tools that have allowed the deployment of these articles vary greatly, with ArcGis being the most used, followed by SUMO, OSRM, NAVTEQ...

CHAPTER 3

Enabling Technologies

This chapter provides an overview of the main technologies that have made this project possible. These are divided into three main blocks: OpenStreetMap, SUMO and all its applications and, finally, Jupyter.

3.1 OpenStreetMap

OpenStreetMap [13] is an open source project which develops and distributes free geographic data for the world. In that way, the authors provide a free and editable map of the whole world that is being updated in a daily basis. Being built and maintained by volunteers, the geospatial information is gathered from car trips to casual jogs, photos, GPS traces, and hand-taken notes. At the same time, OpenStreetMap uses a topological data structure where the primitive data or basic elements are:

- **Nodes:** single points in space defined by their latitudes, longitudes and node ids.
- **Ways:** they usually are linear features on the ground (i.e. a road, wall, or river).
- **Relations:** groups of elements.
- **Tags:** they consist of two items, a key and a value describing specific features of map elements.

Finally, OpenStreetMap offers a real-time stream of instructions representing how to add, change or delete cartographically projected geometries and associated metadata. Fig. 3.1 shows an example of the graphical user interface of OpenStreetMap.

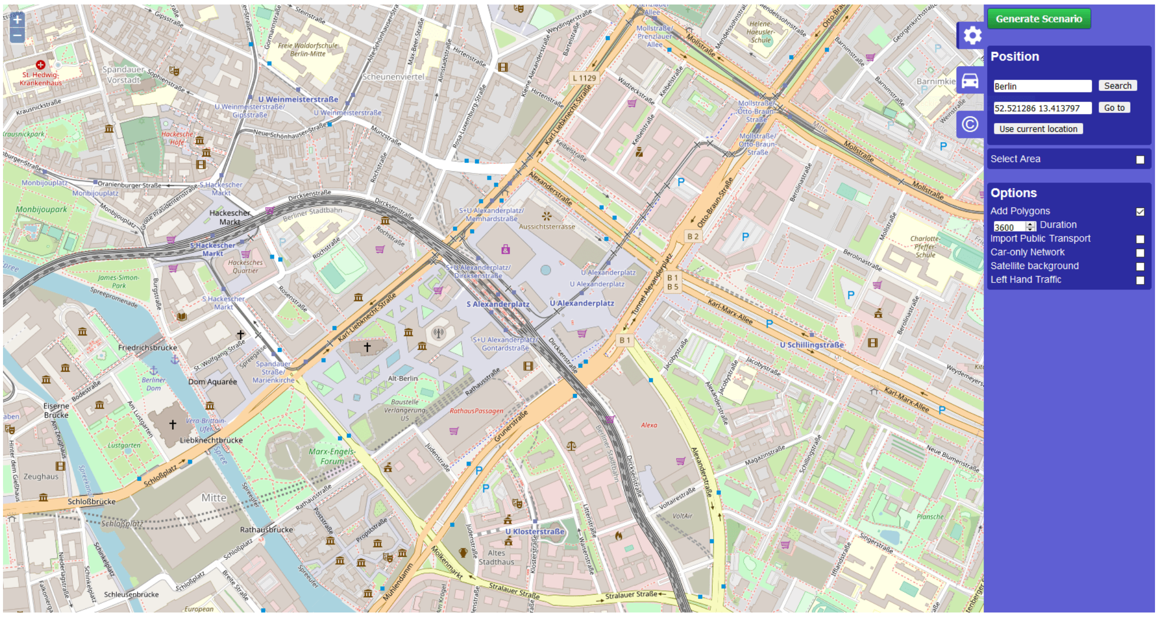


Figure 3.1: Example of the graphical user interface of OpenStreetMap. (*sumo.dlr.de/docs/Tutorials/OSMWebWizard.html*).

3.2 SUMO

Simulation of Urban MObility (SUMO) [8] is the main tool of this thesis. It is an open source, highly portable, microscopic and continuous traffic simulation package designed to handle large networks. It allows for intermodal simulation and comes with a large set of tools for scenario creation. This tool has been mainly developed by employees of the Institute of Transportation Systems [1] at the German Aerospace Center [2].

The most interesting features SUMO has for this project are:

- The inclusion of many different and external applications which add extra functionalities. Some of them will be explained further below.

- With regards with the simulation itself, SUMO is capable of simulate space-continuous and time-discrete vehicle movements including different vehicle types. Also it let the change of multi-lane streets, right-of-way rules and traffic lights. With regards to the volume of data it can manage networks with several 10.000 edges (streets) and with a fast execution speed (up to 100.000 vehicle updates/s on a 1GHz machine). It can produce network-wide, edge-based, vehicle-based, and detector-based outputs. Finally a fast OpenGl graphical user interface is provided as we explain in 3.2.1, and interoperability with other application at run-time can be carried out as shown in 3.2.6.

- Microscopic routes and different dynamic routing algorithms such as routing by effort, distance or time can be implemented in SUMO.

- All files used in SUMO are within a XML-derivate which.

As mentioned above, SUMO includes several applications and tools in the main package. In Table 3.1, the most relevant ones are shown. Throughout this section we will detail some of these.

[1] https://www.dlr.de/ts

[2] https://www.dlr.de/DE/Home/home_node.html

Application/Tool	**Description**
Sumo	The microscopic simulation with no visualization
Sumo-gui (3.2.1)	The graphical user interface
Netconvert (3.2.2)	Network importer and generator from different formats
Netedit (3.2.3)	A graphical network editor.
Netgenerate	Abstract networks generator
Duarouter	Computes the fastest routes through the network
Jtrrouter	Computes routes using junction turning percentages
Dfrouter	Computes routes from induction loop measurements
RandomTrips (3.2.4)	Generates a set of random trips for a given network
TraCI (3.2.6)	It allows to retrieve values of simulated objects and to manipulate their behavior ”on-line”

Table 3.1: Main SUMO applications and tools

3.2.1 Sumo-gui

Sumo-gui application[3] is the same application as sumo but adding a graphical user interface. Thus, it allows the visualisation of the vehicles, pedestrians and elements in general on the map during the simulation. At the same time, it allows some customisation in the visualisation itself, being able to change sizes, colours, shapes, of all the elements of the simulation. This tool will allow us, as we will see later, to visually discern between the different types of vehicles and the accumulated emissions of the streets.

On the other hand, it also presents a window where the possible warnings and errors of the map and the simulation are shown. This will be especially important for the teleports that occur in the simulation. In Fig. 3.2, an example of the graphical interface is shown.

[3]https://sumo.dlr.de/docs/sumo-gui.html

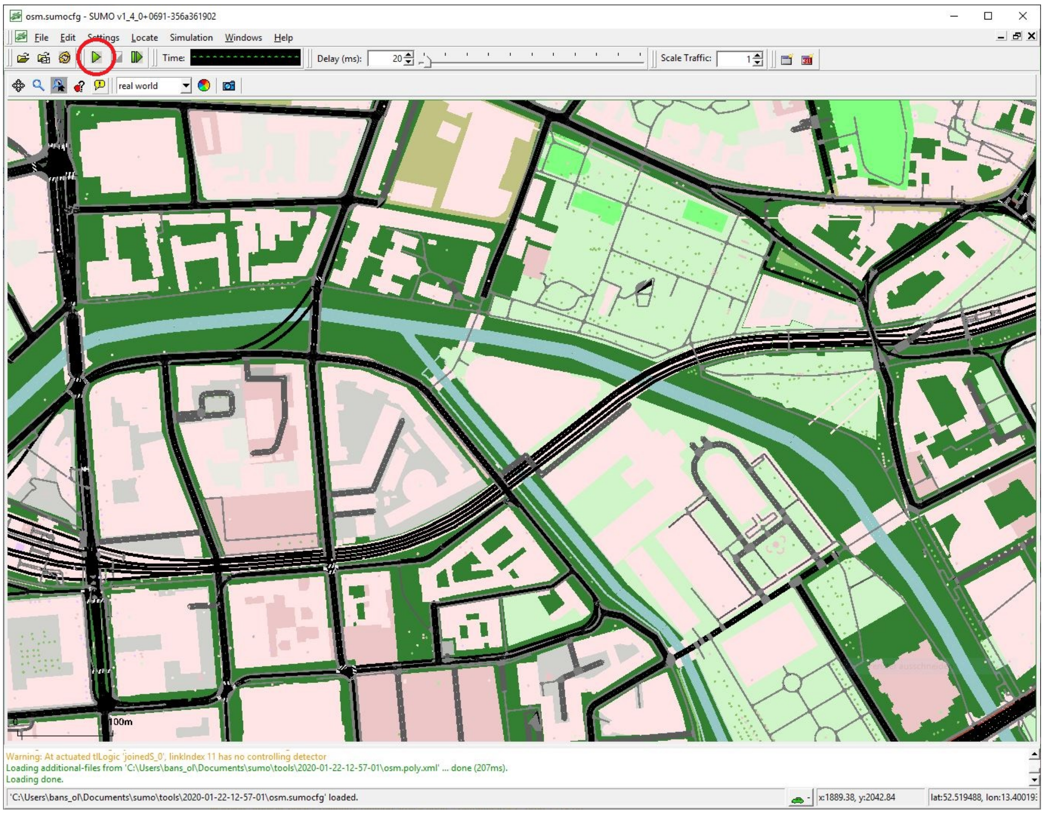


Figure 3.2: Example of simulation with Sumo-gui (*https://sumo.dlr.de/docs/Tutorials/OSMWebWizard.html*).

3.2.2 Netconvert

As we mentioned before, SUMO uses only XML files as both input and output. That is why an application that transforms real maps from other sources into XML format is needed. This application is called Netconvert[4]. Thus, Netconvert is able to transform the map obtained from OpenStreetMap [13] with OSM format into XML. However, this change of format introduces some errors in the map, as the conversion is not perfect. This causes certain points of the map to present errors such as wrong crossings, wrongly placed traffic lights, dead-end streets... so it is necessary to use another tool to edit and solve these errors which is called Netedit.

It should be mentioned that this application also allows conversion from other formats such as VISUM, MATSim or shapefiles.

[4]https://sumo.dlr.de/docs/netconvert.html

3.2.3 Netedit

Netedit[5] is a graphical network editor which can be used to create or modify networks. At the same time, it can be used to debug different network attributes. This application is built on top of Netconvert, so anything that Netconvert can do, Netedit can do it as well. On the other hand, the user interface closely follows that of sumo-gui as it is shown in Fig. 3.3.

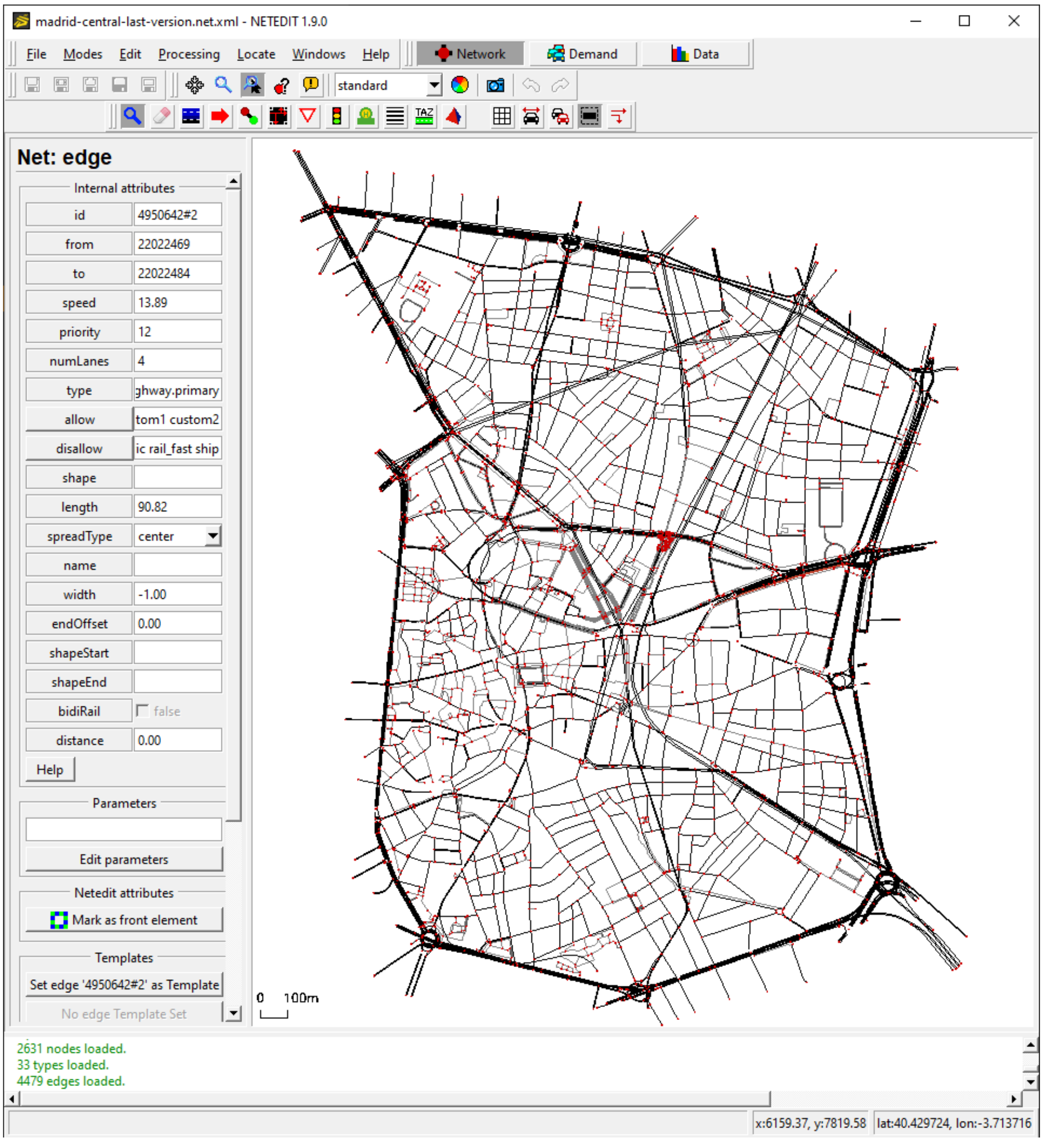


Figure 3.3: Example of Netedit application.

[5]https://sumo.dlr.de/docs/Netedit/index.html

3.2.4 RandomTrips

RandomTrips[6] is a tool provided by SUMO that is capable of generating a set of random trips for a given network. Thus, given a map, it chooses, either uniformly at random or with a modified distribution, origins and destinations of different routes. Among the parameters to modify the distribution, it is important to highlight the option of the minimum distance that trips should have and that these trips should be possible within the network. Thus, RandomTrips will keep sampling until enough trips with sufficient distance are found.

3.2.5 Plot Net Dump

Plot Net Dump[7] tool can be used to shows a network with PYTHON. Thus, the network visualization can be personalised changing the edges' colors and width depending on defined edge attributes; for example, edgelane traffics, edgelane emissions, or edgelane noise. This is especially useful for visualising the network result at the end of a simulation.

3.2.6 TraCI

TraCI (Traffic Control Interface)[8] is another SUMO's application which gives access to a running traffic simulation. Thus, it allows to retrieve values of simulated objects and to manipulate their behavior at run-time. The connection with SUMO is based on a TCP architecture with SUMO acting as a server and is achieved thants to the TraCI API. On the other hand, TraCI's main programming language is PYTHON.

One thing to be aware of with this tool is the performance of the simulation when it is being used because it slows down the simulation speed depending on many factors:

- Number of TraCI function calls per simulation step. SUMO uses a time step of one second per default.
- Types of TraCI functions being called (some being more expensive than others)
- Computation within the TraCI script
- Client language

The functions offered by TraCI can be divided into two main groups, those that access simulation data and those that change simulation data. The first group includes real-time value retrieval on routes, vehicles, traffic lights, pedestrians, lanes... From the second group, it is worth highlighting the routing change functions by effort, as we will see later on.

[6] https://sumo.dlr.de/docs/Tools/Trip.html

[7] https://sumo.dlr.de/docs/Tools/Visualization.html#plot_net_dumppy

[8] https://sumo.dlr.de/docs/TraCI.html

3.3 Jupyter Notebook

Project Jupyter is a non-profit and open source project which support interactive data science and scientific computing across dozens of programming languages. For this project, the product which has been used is Jupyter Notebook which is a web-based interactive computational environment for the use of the PYTHON programming language. A Jupyter Notebook document is a JSON document with ".ipynb" extension. which contains ordered lists of input and output cells. Those cells, in turn, may contain code, text, images, plots, videos...

CHAPTER 4

Methodology and Architecture

This section will explain both the architecture and the methodology followed to carry out the agent-based simulations. Later chapters will go into detail on agent-based simulations and the results obtained from them.

4.1 Introduction

In first place, the methodology and the general architecture will be shown in order to have, throughout the chapter, a clear idea of the structure and the procedures carried out in this project. Later we will go into detail with each of the modules of the methodology.

4.1.1 Methodology

On the first hand, this section will detail the methodology to carry out this project. Thus, a scheme of this methodology and the internal processes of each part can be seen in the Fig. 4.1.

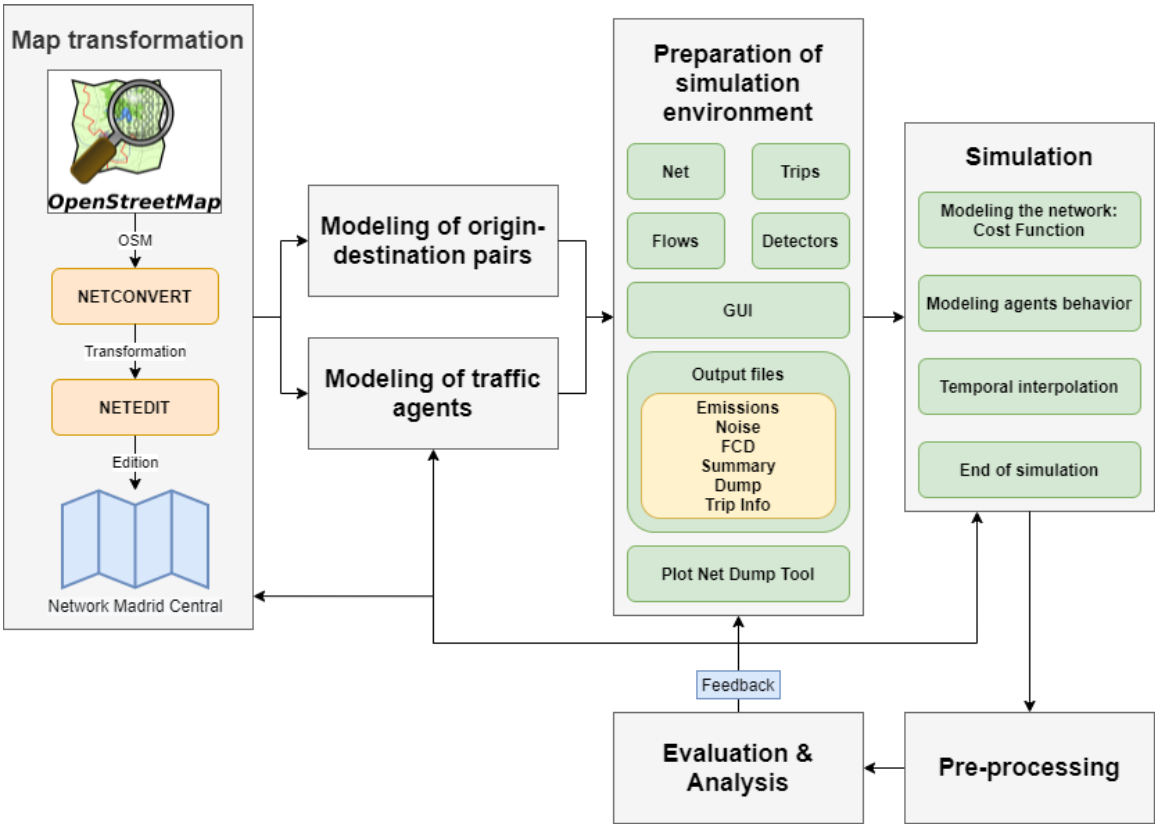


Figure 4.1: Schema of the methodology followed in this project.

In the first place, we have the process of transformation of the map. Here we have faced one of the first challenges, and that is that in order to use a map of Madrid in SUMO through OSM, a conversion has to be done through Netconvert, which causes many failures in the map. These bugs in the map are very abundant and we have to deal with them one by one by editing them by hand. Finally, we got a version of Madrid Central very close to reality and with almost no bugs.

Secondly, once a realistic map has been obtained, the different origin-destination pairs must be modelled, which will later be assigned to the traffic agents in the simulation. On the other hand, it is also necessary to model the traffic agents, where the characteristics that these agents will have and that will affect their subsequent behaviour in the simulation will be assigned.

Subsequently, it is necessary to prepare the simulation. This includes setting up the different agents (flows and trips) for the simulation, as well as the creation and placement of the detectors in the network, which will be used to obtain real-time data from the simulation itself. At the same time, the graphical user interface has been customised and the different data outputs produced by the simulation have been formatted for later use in the evaluation. Finally, we have also created our own tools to facilitate the visualisation of the output data in the evaluation.

Once the environment is ready for simulation, the simulation can be run. This simulation process is the most complicated process in the system and where we have encountered the most problems. These include problems in managing real-time communication between TraCI and SUMO, in managing the data processing during the simulation, in making decisions based on the data obtained, and in modelling the behaviour of the agents according to the data itself. Thus, this module includes the real-time updating of the network based on the data obtained from the simulation, the routing of the traffic agents and the creation of a temporal interpolation in terms of pollution.

Subsequently, the output data from the simulations must be pre-processed. Thus, by means of different processing techniques, we obtain data ready for evaluation and analysis.

Finally, an evaluation of the results and an analysis of the different simulations have been carried out. Thus, we have evaluated the different scenarios by measuring pollution data and its distribution, travel characteristics, exposure to pollution, distribution of agents... According to the conclusions obtained from these analyses, the rest of the network blocks have been modelled following the feedback, in order to improve them, fix errors, add blocks, change parameters... in short, to achieve simulations that cover everything necessary for the final evaluation and analysis to be conclusive.

4.1.2 General architecture

As for the architecture of the system, it is composed of several modules, as shown in Figure 4.2.

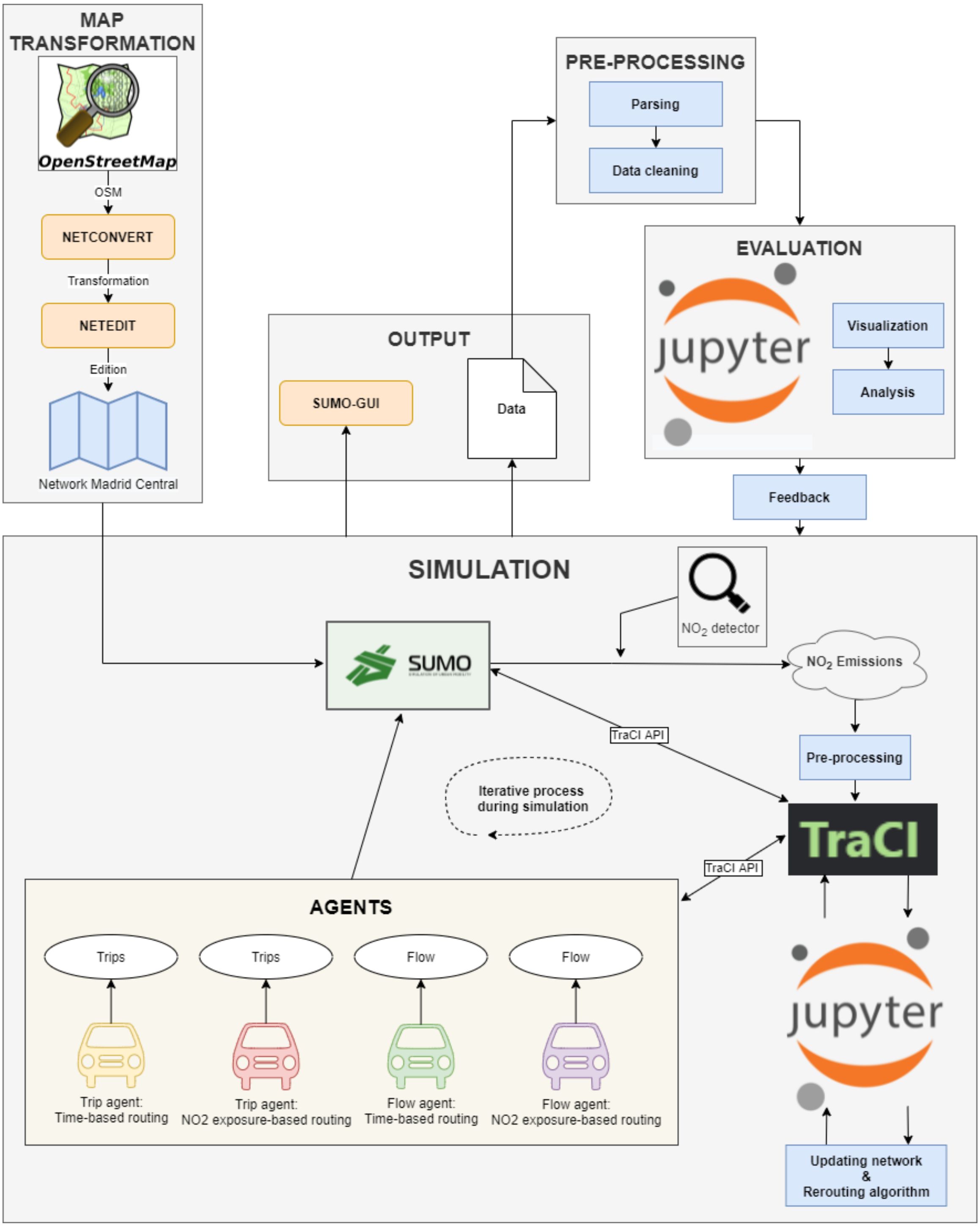


Figure 4.2: General Architecture of the agent-based simulation.

On the one hand, we have the **map transformation module**. As we have seen above, a very elaborate process has been carried out in order to obtain a realistic and faultless map that can be used in the simulation and that its results are correct for the evaluation. For that, we have used Netconvert tools to obtain the map from OpenStreetMap, and Netedit to edit it by hand and get the map that finally gives no bugs, which are very abundant and are in need to be solved one by one. As a result we have the map of Madrid Central which will be introduced to SUMO as input for the simulation.

Secondly, we have **traffic agents**, which are four types of agents depending on whether they are trips or flows and whether the routing is based on pollution exposure or time. These, too, will be introduced as inputs in the simulation and their behavior is modeled by the rest of the entire network. That is, the agents will be routed depending on how the network is at each moment.

The NO_2 detector will get real-time NO_2 emissions from the entire map. Once data is been pre-processed, we will use the TraCI API to communicate with SUMO and we will use Jupyter Notebook for the development environment to manage and use that data. With this NO_2 data, we will finally **model the network** and the **behavior of the agents**. This process will be iteratively repeated in the simulation until there are no vehicles left in the network.

On the other hand, in the **output module** we can visualize the simulation in real time using the Sumo-gui tool. At the same time, once the simulation is finished, several output files will be produced that can be used in the evaluation module.

Finally, the data obtained from the simulation must be **pre-processed** and cleaned in order to be used for the **evaluation** in Jupyter. In this way the visualization and the analysis can already be carried out. The results in this module produce a feedback, and as we have seen in the methodology section, this feedback will let us make decisions which will affect future simulations.

4.2 Methodology

Now, we will look in more detail at each of the modules that have been explained in the introduction of the methodology.

4.2.1 Map transformation

In this part we will explain the process of obtaining a map for the simulation. On the one hand, SUMO offers some already created maps of the cities of Bologna, Dublin, Monaco or Cologne among others. These maps vary in their characteristics, both in size and in the elements introduced. However, these maps are not completely up to date and have bugs that cause teleports in the simulations. On the other hand, an initial objective of the project was to carry out simulations in a Spanish city, and Madrid, as we have seen in Section 2.1.1.2, is the city with more deaths caused by nitrogen dioxide than any other city in Europe. For these reasons, we have decided to carry out the entire project on a new map of the city of Madrid.

OpenStreetMap maps and SUMO Netconvert application have been used for this purpose. Initially, the map of the entire city of Madrid was obtained. However, as mentioned above, the Netconvert tool is not able to perfectly transform the OSM file into XML (SUMO requires the maps to be XML). This resulted in a multitude of wrong crossings, wrongly placed traffic lights, streets that did not resemble those of the city, problems at intersections... so that when the different simulations were carried out, traffic jams and continuous teleports were produced, disabling the results obtained for the simulations. At the same time, with such a large city, the simulation process required a lot of computing power.

As a solution to these problems, instead of using the entire city of Madrid, the ring of the area known as Madrid Central was used. The location and dimensions of this area can be seen in Fig. 4.3 and Fig. 4.4,respectively.

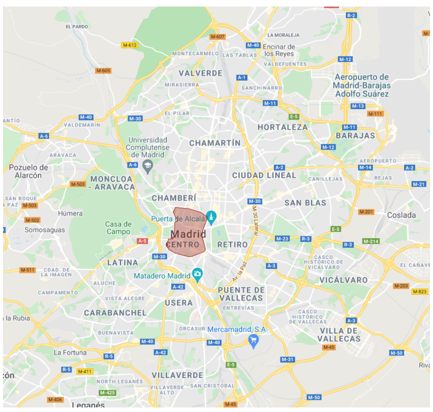


Figure 4.3: Location of the Madrid Central area in the city of Madrid.

Figure 4.4: Dimensions and shape of the Madrid Central area. https://www.madrid.es

In this way, the XML file of Madrid Central has finally been obtained thanks to Netconvert. However, this part, even so, was also flawed. So, using Netedit, we have been editing each of these faults, until we have a map in which all the elements were well placed and working correctly. An example of this editing process in Netedit can be seen in Fig. 4.5.

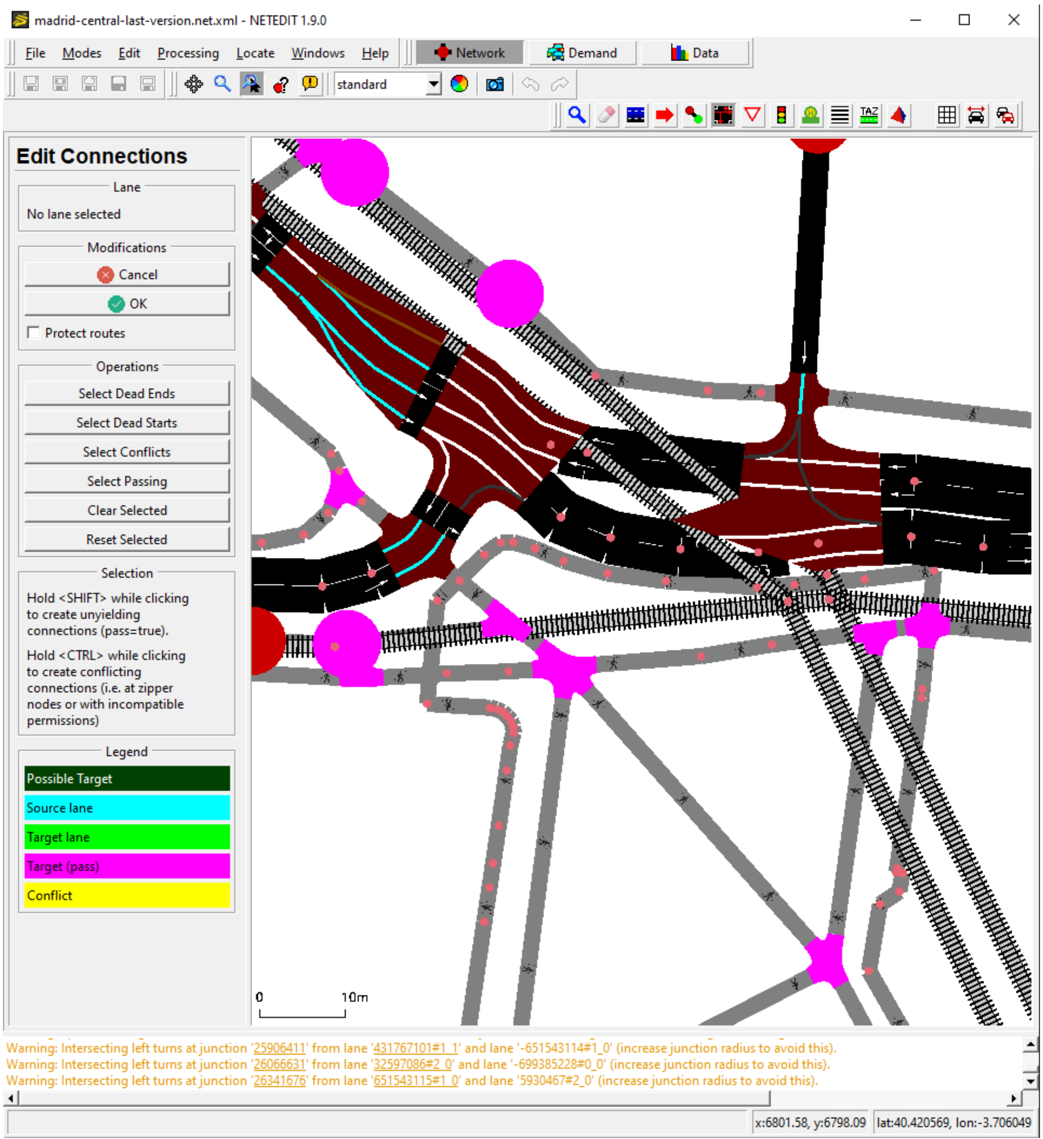


Figure 4.5: Correction in Netedit of junction between edges with ids 45757391#0 and 239499976.

4.2.2 Modeling of origin-destination pairs

In this section we will detail the process for the creation of different random origin - destination pairs within the map already created for the vehicles that will travel during the simulation. To do this, the *RandomTrips* tool explained above is used. It is important to clarify that these random trips created are only formed by an origin and a destination and therefore do not include the lanes along which the vehicles will be routed.

In this way, a file of random origin-destination pairs that meet certain requirements will be created. The requirements that these origin-destination pairs must meet are as follows:

- The direct distance between the two must be at least 100 metres.
- That there are routes connecting both points. That is to say, it could be the case that the origin is a lane with a cut-off road, or with an exit road from the simulation, which would make it impossible for a vehicle to reach the destination. To achieve this, RandomTrips offers a check option called 'validate'.

Once this file with the origin - destination pairs has been created, vehicle trip files will be created and assigned to these pairs. These trip files will also contain the time of entry into the simulation (time when the vehicle starts its route), as well as the type of vehicle it is. Of course, this will vary depending on the different scenarios.

4.2.3 Modeling of traffic agents

This section will explain the process of modeling the traffic agents - vehicles - for the simulations. Thus, two types of vehicles will be available, differentiated only by the name of the vehicle type and the color. This division is made because the default vehicles will follow a standard routing, i.e. they will be re-routed minimizing the route time.

On the other hand, the second type of vehicle will be the one that follows the pollution exposure routing. This will allow a comparison between the behaviour of both vehicles in the different simulations. As for the colour distinction, yellow has been chosen for vehicles with default routing and red for vehicles with pollution exposure routing. This will be especially useful to visualize the behaviour of the vehicles in the SUMO graphical tool.

The explanation of these vehicles' own behavior is explained in Section 5.4.

As for the rest vehicles' values, the following ones have been selected:

- **Acceleration:** The acceleration ability value is 2.6 m/s^2.
- **Deceleration:** The deceleration ability value is 4.5 m/s^2.
- **Length:** The vehicle's netto-length is 5 meters.
- **Width:** The vehicle's width is 1.8 meters.
- **Maximum Speed:** The vehicle's maximum velocity is 200 km/h.
- **Minimum Gap:** the minimum empty space after the leader vehicle is 2.5 meters.
- **Sigma:** The driver imperfection (0 denotes perfect driving) by car-following Krauß-model

4.2.4 Preparation of simulation environment

This section will detail all the elements necessary for the execution of the simulations. In this way, for each different scenario, certain parameters of the elements will be changed but the scheme will remain the same.

4.2.4.1 Net

Under the name **.net.xml*, this file represents the network itself over which the simulation will run, it describes the traffic-related part of a map, the roads and intersections where vehicles run across. For this project, as explained in Section 4.2.1, a map of Madrid Central has been obtained thanks to the use of OSM, Netedit and Netconvert. In this way, the following elements appear in the resulting map:

- **Edges:** are junctions between two nodes (points referenced by coordinates). They are treated as straight road (street) lines ending at an intersection.

- **Lanes:** These are the lanes that make up an edge. An edge can be composed of one or more lanes.

- **Traffic lights:** These are the traffic lights that regulate traffic at some of the intersections. They show the phases they have and the duration of each phase.

- **Junctions:** it represents the area where different streams cross, including the right-of-way rules vehicles have to follow when crossing the intersection[1].

- **Connections:** They describe which outgoing lanes can be reached from an incoming lane, so they act as connectors between the entry lanes to an intersection and the exit lanes.

In Fig. 4.6 we can see the final network for our simulations.

[1]https://sumo.dlr.de/docs/Networks/SUMO_Road_Networks.html#junctions_and_right-of-way

Figure 4.6: Final Madrid Central Network

4.2.4.2 Trips

For each simulation, a trip XML file shall be created from the random routes file created in the Section 4.2.2. This file shall contain the origin-destination pairs for each vehicle that will participate in the simulation. At the same time, it will take into account the distinction of the type of vehicle it is, because depending on that, the future type of routing to be followed changes, as explained in Section 4.2.3. Finally, the time in the simulation at which the trip will start must also appear for each trip. This file will change depending on the scenario, as there may be scenarios with a higher number of vehicles than others or a higher number of vehicles with alternative routing...

4.2.4.3 Flows

For future comparisons of the different scenarios, a flow has been created in the simulations. These flows are batches of vehicles repeated every so often, departing from the same origin to the same destination. In turn, they coincide in the rest of the parameters. In this way, the same vehicle will repeat origin and destination every so often, but not necessarily the same route.

For our simulations, two flows have been created. One that will follow the standard routing, minimizing the time and departing every 300 seconds from point A to point B. This will be used to evaluate the route of the vehicle. On the other hand, a flow will also be created that leaves at the same time as the previous one and also from A to B but following the alternative routing due to exposure to pollution. This will be used to evaluate the behaviour of both flows during the simulation.

Fig. 4.7 shows where points A and B of both flows are located. Both points have been chosen because there are many routes connecting them and they are far enough apart for the routing to be decisive.

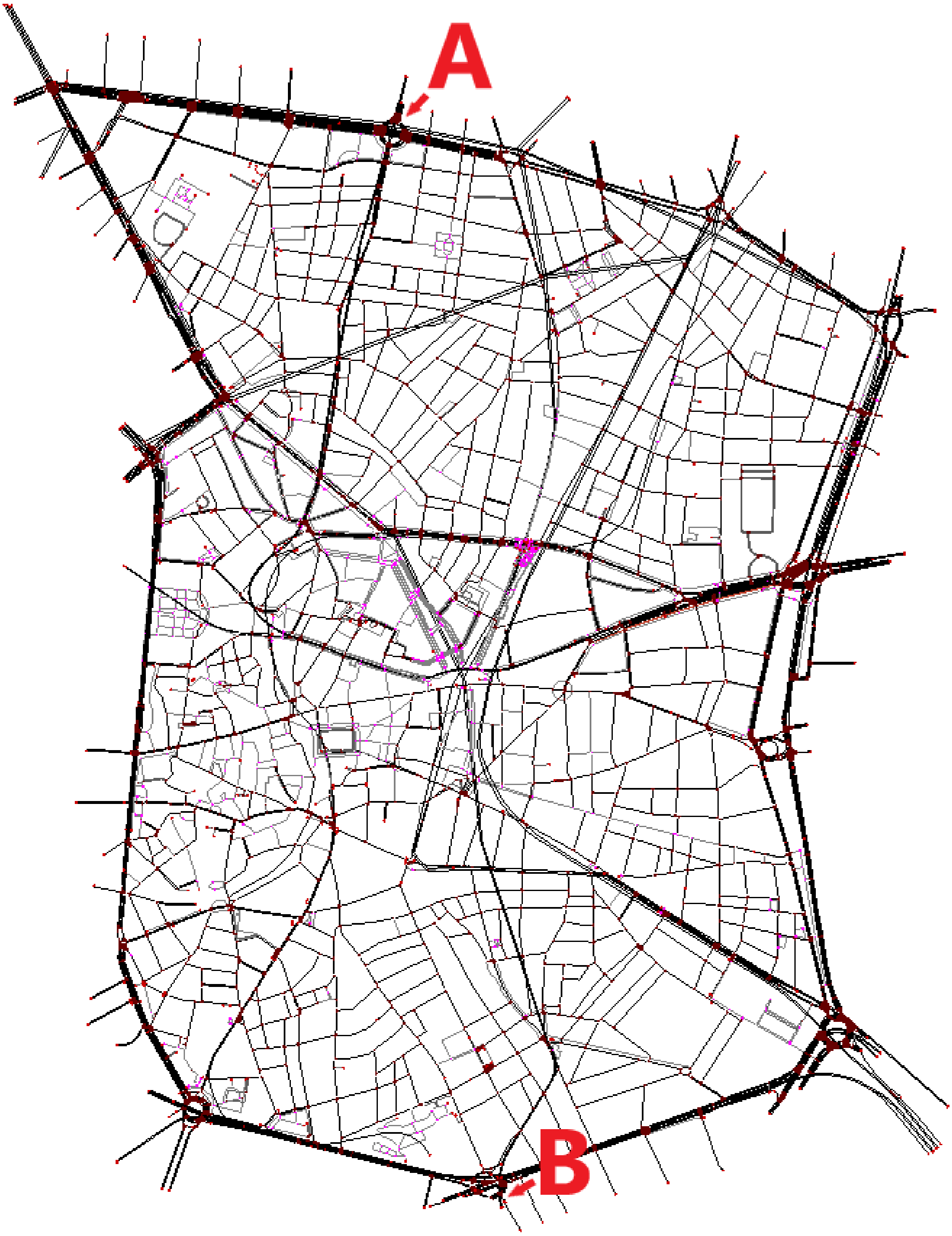


Figure 4.7: Location of A (origin) and B (destination) points in Madrid Central Network for flows.

4.2.4.4 Detectors

These types of files are not necessary for the simulation as such; however, they are very useful for extracting information from the simulation. Detectors are artificial devices for the recognition and/or recording of the states of different elements during the simulation. This will allow us to obtain certain information during and after the simulation itself. For the simulations we are going to deploy we have used three different detectors:

- **10s emission detector:** This detector has the mission of detecting every 10 seconds the emissions produced by vehicles in all the links of the network. In this way, we will have, in a file created during the simulation, the emissions every 10 seconds of all the edges, with special emphasis on the NO_2 value. This data will be used in real time to recalculate the weight of the network links and therefore influence the routing of the network, the format of this output file and the calculation of the weights can be found in Sections 4.2.4.7 and Section 5.3, respectively.

- **300s emission detector:** On the other hand, this detector of the same type as the previous one detects and stores in a file the emissions every 300 seconds on all edges during the entire simulation. This is because this data is going to be used for further evaluation only, so it is not necessary to handle the data every 10 seconds. This type of detector, in turn, has an active *excludeEmpty* parameter that if set, edges which were not used by a vehicle during this period will also be written in the document. This is really useful for the evaluation but unnecessary for the calculation of the weights as in the previous case. Like the previous detector, the format of the output file can be seen in Section 4.2.4.6.

- **300s noise detector:** Very similar to the previous case, this detector records the atmospheric noise produced by vehicles at all edges every 300 seconds throughout the simulation. In this way, we will have another file that collects the atmospheric noise and that we will use as an evaluation. The format of this output file can be seen in Section 4.2.4.7.

4.2.4.5 Graphical User Interface (GUI)

SUMO allows the creation of a *gui.xml* file to customize the display in the sumo-gui tool. Thus, we have produced a customized file to discern between the different types of vehicles and the state of the edges' weights during the simulation. This allows ,in a visual way, to understand the behaviour of the simulation and to discover routing errors, failures, teleports, badly placed edges, edges with excessively high weights, etc. Therefore, with respect to the vehicles, they are shown with the *raster images* option and depending on the type of routing they acquire a different colour, as shown in Fig. 4.12.

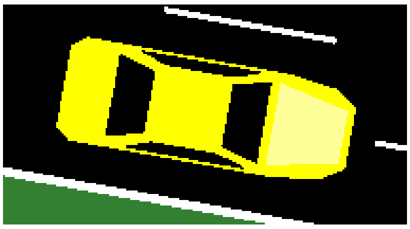


Figure 4.8: Time-based routing vehicles.

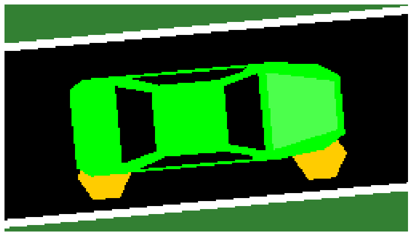


Figure 4.9: Time-based routing flows.

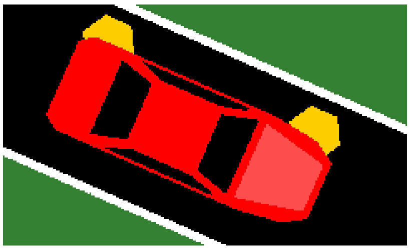


Figure 4.10: PE-based routing vehicles.

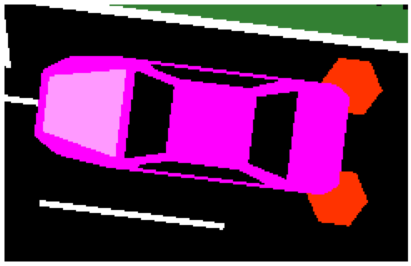


Figure 4.11: PE-based routing flows.

Figure 4.12: Visualization of the vehicles and flows in sumo-gui.

On the other hand, the visualization of the edges has also been changed in order to know how the contamination is in them during the simulation. To do this, the colour code shown in Fig. 4.13 has been followed according to the weight of the link, so that as the weight of the edges changes in real time, their colour changes.

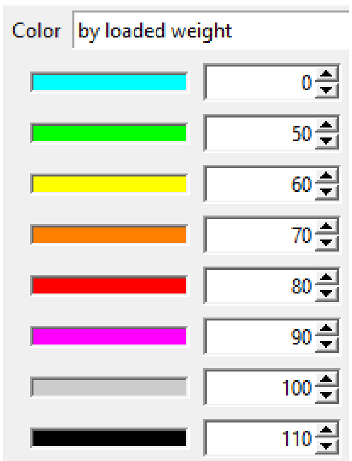


Figure 4.13: Colour code of edge weights.

Finally, an example of the appearance of part of the map during the simulation with the colours according to the weights on the edges can be seen in Fig. 4.14.

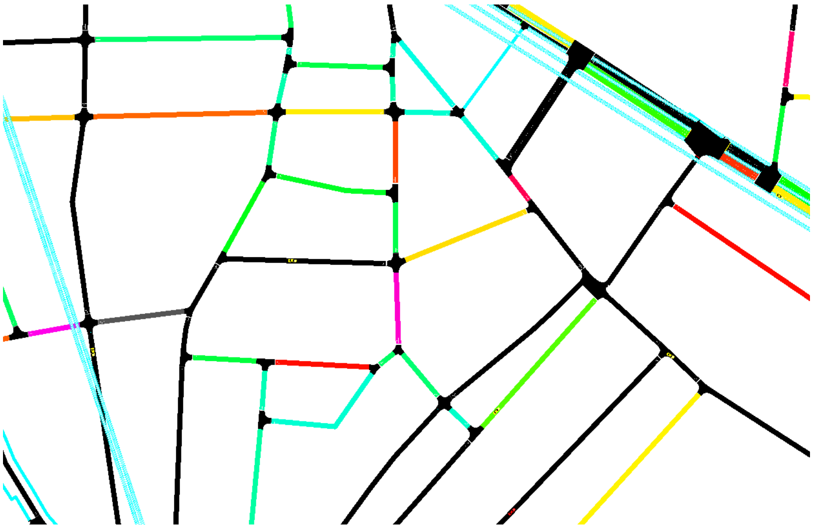


Figure 4.14: Example of colour coding applied to the weights of the links of Madrid Central during simulation.

4.2.4.6 Output file: Emissions

As explained in Section 4.2.4.4, we have three different detectors, two of which produce emission output files. In this section, the output file format[2] will be explained so that the evaluation can then be carried out. As usual in SUMO, the file is an XML file, which contains for each edge, the set of emissions between a *begin* time and an *end* time. All output values can be seen in Table 4.1. For the evaluation we will pay special attention to the NOx_abs and NOx_normed values for each edge.

Name	**Unit**	**Description**
begin	seconds	The first time step the values were collected in
end	seconds	The last time step + DELTA_T in which the reported values were collected
edge@id	(edge) id	The name of the reported edge
sampledSeconds	seconds	Number seconds vehicles were measured on the edge.
traveltime	seconds	Time needed to pass the edge (estimation)

[2]https://sumo.dlr.de/docs/Simulation/Output/Lane-_or_Edge-based_Emissions_Measures.html

CO_abs	mg	The complete amount of CO emitted by the vehicles on this edge during the aggregation period
CO2_abs	mg	The complete amount of CO2 emitted by the vehicles on this edge during the aggregation period
HC_abs	mg	The complete amount of HC emitted by the vehicles on this edge during the aggregation period
PMx_abs	mg	The complete amount of PMx emitted by the vehicles on this edge during the aggregation period
NOx_abs	mg	The complete amount of NOx emitted by the vehicles on this edge during the aggregation period
fuel_abs	ml	The complete amount of fuel the vehicles on this edge during the aggregation period have consumed
electricity_abs	Wh	The complete amount of electricity the vehicles on this edge during the aggregation period have consumed
CO_normed	g/km/h	CO emissions during this interval normed by time and edge length
CO2_normed	g/km/h	CO2 emissions during this interval normed by time and edge length
HC_normed	g/km/h	HC emissions during this interval normed by time and edge length
PMx_normed	g/km/h	PMx emissions during this interval normed by time and edge length

NOx_normed	g/km/h	NOx emissions during this interval normed by time and edge length
fuel_normed	l/km/h	fuel consumption during this interval normed by time and edge length
electricity_normed	W/km	electricity consumption during this interval normed by time and edge length
CO_perVeh	mg	Assumed CO emissions a vehicle would produce when passing the edge
CO2_perVeh	mg	Assumed CO2 emissions a vehicle would produce when passing the edge
HC_perVeh	mg	Assumed HC emissions a vehicle would produce when passing the edge
PMx_perVeh	mg	Assumed PMx emissions a vehicle would produce when passing the edge
NOx_perVeh	mg	Assumed NOx emissions a vehicle would produce when passing the edge
fuel_perVeh	ml	Assumed fuel consumption a vehicle would need when passing the edge
electricity_perVeh	Wh	Assumed electricity consumption a vehicle would need when passing the edge

Table 4.1: Emissions output file format

4.2.4.7 Output file: Noise

The atmospheric noise detector will also be evaluated during the simulations. The format[3] of this XML document produced by SUMO is as shown in Table 4.2. As in the previous case, the set of noise between a time *begin* and an *end* time is shown for each edge.

Name	Unit	Description
begin	seconds	The first time step the values were collected in
end	seconds	The last time step + DELTA_T in which the reported values were collected
edge@id	(edge) id	The name of the reported edge
lane@id	(lane) id	The name of the reported lane
sampledSeconds	seconds	Number seconds vehicles were measured on the edge
noise	dBA	The average noise generated by the vehicles on the edge during the interval

Table 4.2: Noise output file format

4.2.4.8 Output file: FCD

In addition, SUMO allows the creation of XML files which collect information from the simulation. Among them, the FCD (Floating Car Data)[4] file contains the location and speed along with other information for each vehicle in the network at each step of the simulation. In this way, it behaves as a kind of very precise high-frequency GPS device for each vehicle. Thus, for each step, we will have information such as speed, angle, coordinates, slope, or the edge on which the vehicle is located... In order to get this file, it is enough with activating the option *'–fcd-output.geo'* when launching the simulation.

[3]https://sumo.dlr.de/docs/Simulation/Output/Lane-_or_Edge-based_Noise_Measures.html
[4]https://sumo.dlr.de/docs/Simulation/Output/FCDOutput.html

4.2.4.9 Output file: Summary

On the other hand, an output called *summary*[5] can also be produced through SUMO by activating the *'–summary'* option when launching the simulation. This XML file contains the simulation-wide number of vehicles that are loaded, inserted, running, waiting to be inserted, halting, teleporting, have reached their destination and how long they needed to finish the route. Therefore, for each step, we can know the number of vehicles in the simulation and what they are doing.

4.2.4.10 Output file: Dump

The XML output file dump[6] contains detailed information for each edge, each vehicle and each simulation step. This file has a huge amount of simulation data, which makes it a bit heavy to handle for long simulations, hence we have usually used the FCD output file more than this one. Still, it comes in handy if you want to acquire more detail at some point in the simulation, e.g. when teleport errors occur. To enable this option just add the *'–ndump'* command when the simulation is launched.

4.2.4.11 Output file: Trips Info

This output file[7] is very important because it provides information about the timing of all vehicles in the simulation in a unified form. This makes it very convenient to use for the evaluation. The information is generated when each vehicle arrives at its destination and is removed from the network. The data provided by this XML file are listed in Table 4.3.

Name	Unit	Description
id	id	The name of the vehicle that is described by this entry
depart	s	The real departure time (when vehicle was inserted)
departLane	id	The id of the lane the vehicle started its journey
departPos	m	The position on the lane the vehicle started its journey
departSpeed	m/s	The speed with which the vehicle started its journey
departDelay	s	The time the vehicle waited before it could start his journey

[5]https://sumo.dlr.de/docs/Simulation/Output/Summary.html
[6]https://sumo.dlr.de/docs/Simulation/Output/RawDump.html
[7]https://sumo.dlr.de/docs/Simulation/Output/TripInfo.html

arrival	s	The time the vehicle reached his destination at
arrivalLane	id	The lane's id the vehicle was on when reaching his destination
arrivalPos	m	The lane's position the vehicle was when reaching the destination
arrivalSpeed	m/s	The speed the vehicle had when reaching the destination
duration	s	The time the vehicle needed to accomplish the route
routeLength	m	The length of the vehicle's route
waitingTime	s	The time in which the vehicle speed was below or equal 0.1m/s
stopTime	s	The time in which the vehicle was taking a planned stop
timeLoss	s	The time lost due to driving below the ideal speed.
rerouteNo	#	The number the vehicle has been rerouted
vtype	ID	The type of the vehicle
speedFactor	float	The individual speed factor of the vehicle
vaporized	bool	Whether the vehicle was removed from the simulation before reaching its destination

Table 4.3: Trip info output file format

4.2.4.12 Development of a customized Plot Net Dump tool

On the other hand SUMO offers a tool called Plot Net Dump with which you can draw the network with Python changing the network edges' colours and width in dependence to defined edge attributes, as we have explained in Section 3.2.5. That is why this tool has been used to make certain evaluations on the map once the simulation is finished. However, instead of using the already defined tool, some code adjustments have been made to use this tool as a pollution comparison between two simulations. In this way, what our version of the tool does is to compare two final pollution scenarios and create an image in which the differences are visualized. An example of this customized tool comparing the NO_2 accumulated at the edges of the network in two different scenarios can be seen in Fig. 4.15.

The lanes shown in red are those with the highest NO_2 concentration in scenario 1, while the lanes shown in green are those with the highest NO_2 concentration in scenario 2.

Figure 4.15: Example of the comparison of two scenarios with the customised Plot Net Dump tool in Madrid Central.

4.2.4.13 Sumo file

Finally, it is necessary to create a .sumocfg file which acts as the central file of the simulation and in which all the files to be used during the simulation are indicated. Thus, on the one hand, the input files, such as detectors, flows, trips, custom gui, etc., are inserted. And on the other hand, the output files. Thus, the simulation will be launched every time the sumo command is executed with the .sumocfg file. To this call we must add certain options, such as the output files we want to produce that are not calculated by the detectors, or other options such as the minimum teleport time as we will see in Section 5.7, or the activation of the statistics of the trips to see them in real time... You can also modify the simulation behaviour by setting the *ignore-route-errors* parameter to "true".

CHAPTER 5

Agent-based simulation

This chapter will explain everything about the development of the agent-based simulation that has been carried out in this project. This includes the alternative routing cost function algorithm, the agent and network modelling, the time interpolation and the errors that have been handled.

5.1 Introduction

The simulations in this project are based on agent-based techniques, which model the evolution of a system through the individual behaviours of autonomous agents within the system. That is, the operations and iterations of multiple agents are simulated individually in an attempt to understand the behaviour of a whole system and what drives its outcomes. In this way, micro-scale agents' behaviour cause macro-scale state changes. These agent-based simulations can combine elements of game theory, computational sociology, emergence, multi-agent systems, complex systems, and evolutionary programming.

Thus, we will have a collection of agents, rules for the behaviour of these agents and the simulation environment itself. The agent, in our case each vehicle, has the purpose of reaching the destination point from an origin point and the way to do so is determined by the routing rules. In this way, each agent will be routed at each moment according to rules that are changeable during the simulation. These rules are determined by the state of pollution in the network at all times, so that areas with more pollution will be avoided by the agents to the detriment of those with less pollution. Pollution, being produced by the agents themselves, influences the behaviour of the rest of the system, which causes the system to change and therefore influences the rest of the agents in the network.

In our case and once the map has been obtained and the vehicles and the simulation environment have been set up, the simulations can be carried out. In order to do this, there are two key tools: Jupyter, for the Python development environment, and TraCI to interact with SUMO during the simulation itself which is possible thanks to the use of the TraCI API.

Each proposed scenario will have different values from the rest which can vary from the number of cars in the simulation to the number of cars with different types of alternative routing, or the chosen pollution accumulation window, or the hours of simulation, etc. That is why for each scenario custom files have to be created among which are: the two emission detectors, the atmospheric noise detector, creation of the custom trips, creation of the custom flows and finally the choice of the chosen pollution window, which will be explained in Section 5.5.

At this point, the simulation is ready to be launched. Now, we will explain the cost function where we have included the reasons why we have chosen Madrid and NO_2 as the city and the pollutant to simulate our scenarios. Later, we will also explain the continuous interaction that occurs during the simulation between TraCI and SUMO, and all the processes to be able to have the iterative simulation in which the behaviour of the agents and the map are modelled.

5.2 Cost function

Taking into account all the pollutant particles mentioned in Section 2.1.1.2, their characteristics, their health effects and their prevalence, we have considered that NO_2 stands out from the others particles. This is because NO_2 is especially important in the city of Madrid as it is the European city with more deaths caused by nitrogen dioxide than any other city in Europe, as previously mentioned in in Fig. 2.1. In addition, approximately 80% of its emission is produced by traffic as we have seen it in Section 2.1.1.2. Therefore, we have considered that one of the main objectives of this project should be to decrease the exposure to this metric with the alternative routing in the city of Madrid.

When routing on the basis of any metric, an edge weight cost function is generally used. In other words, a cost is applied to each edge in the network, and algorithms such as Dijkstra or A* are used to find the path with the lowest total weight between the source and destination. To do this, it is necessary to create a cost function, as we will explain in this section.

The chosen mathematical algorithm to calculate the shortest path once the total link weights have been calculated is Dijkstra, as it is well suited to routing in time-dependent networks and it performs well in the SUMO simulator, as we will see later. In summary, the idea of this algorithm consists of exploring all the shortest paths starting from the origin vertex (i.e. the origin of the trip) and leading to all the other vertices; when the shortest path from the origin vertex to the rest of the vertices that make up the network is obtained, the algorithm stops.

As mentioned in the previous paragraphs, the pollution exposure routing to be minimised will have NO_2 exposure as a metric. Therefore, in our cost function we will have to take into account the NO_2 exposure value in each edge and of course the estimated time to drive in that edge. It is assumed that the number of particles a person inhales in an edge is proportional to the time spent in that lane. Thus, each edge will have a cost function made by the product of time weight and NO_2 exposure weight. Thus the total cost function for a trip is:

$$CF(t) = \sum_{i=0}^{m} w_t i * w_{NO_2} i$$

where t is the trip, m is the number of traffic junctions in the trip of user interest, w_t is the time weight, and w_{NO2} is the weight assigned for exposure to pollution, in our case, NO_2.

Therefore, to find the optimal path, it is sufficient to find the function that minimises the value of the above function.

$$CF = \min_{\forall t \epsilon N} CF(t)$$

where CF(t) is the cost function of a path among all possible N paths between the chosen source and destination. Thus, the result function CF will be the minimum cost function of all possible routes. In the following Section, we will explain where and how we use this function to model the network.

5.3 Modeling the network

With respect to the simulation itself, every 10 steps (real life seconds) the edge weights are updated. This is achieved thanks to the information collected by the 10s emission detector explained in Section 4.2.4.4. In this way, the emission data of all the edges through which a vehicle has passed is accessed in real time and therefore the value has changed. The NO_2 values of each edge are collected and added to the cumulative NO_2 value that was previously present at each edge. Then the link weight itself is calculated as explained in Section 5.2. And finally, the weight value is updated in SUMO thanks to the function TraCI *traci.edge.setEffort* for all those edges that have seen their weight change during these 10 steps. Thanks to this process and the continuous interaction of SUMO and TraCI, the system is constantly updating the weight values of all the links in the network. This makes it possible to see in real time on the sumo-gui display the change in link weights.

5.4 Modeling agents behavior

On the other hand, we have to model the behavior of the agents, so the interaction between TraCI and SUMO is also necessary for the routing of these vehicles. We will have different scenarios and it is possible that all vehicles are routed by time-based routing, or all by pollution exposure-based routing, or a mixture of both, so a distinction has to be made between vehicles and their routing. The process consists in the fact that each time a vehicle is inserted into the simulation, it has to calculate the route connecting its origin and destination. This route is calculated by minimizing the time or minimizing the exposure to NO_2 depending on the type of vehicle. In this way, and thanks to the fact that the link weights are continuously updated, the pollution exposure routing is achieved through these weights. Thus, using the TraCI tool *traci.vehicle.rerouteEffort* it is possible to route those vehicles that we want to have the alternative routing.

Sometimes when a vehicle is inserted, it cannot be introduced into the network because its space is already occupied at that precise moment, so these vehicles remain in a state called pending. In these cases, when their status becomes inserted, the vehicle is re-routed.

Throughout this process and for all vehicles, both the route they would have followed and the route they finally take are calculated, as well as the accumulated weights of both routes. This is achieved thanks to the use of the *traci.edge.getEffort* and *traci.vehicle.getRoute* tools and will allow us to evaluate how the routing of the vehicles changes. Thus, by knowing the difference between the NO_2 weights of the initial routing they would have and the routing they finally take, we have a value that measures the change in pollution exposure that each vehicle suffers. An overview of this process can be seen in Fig. 5.1.

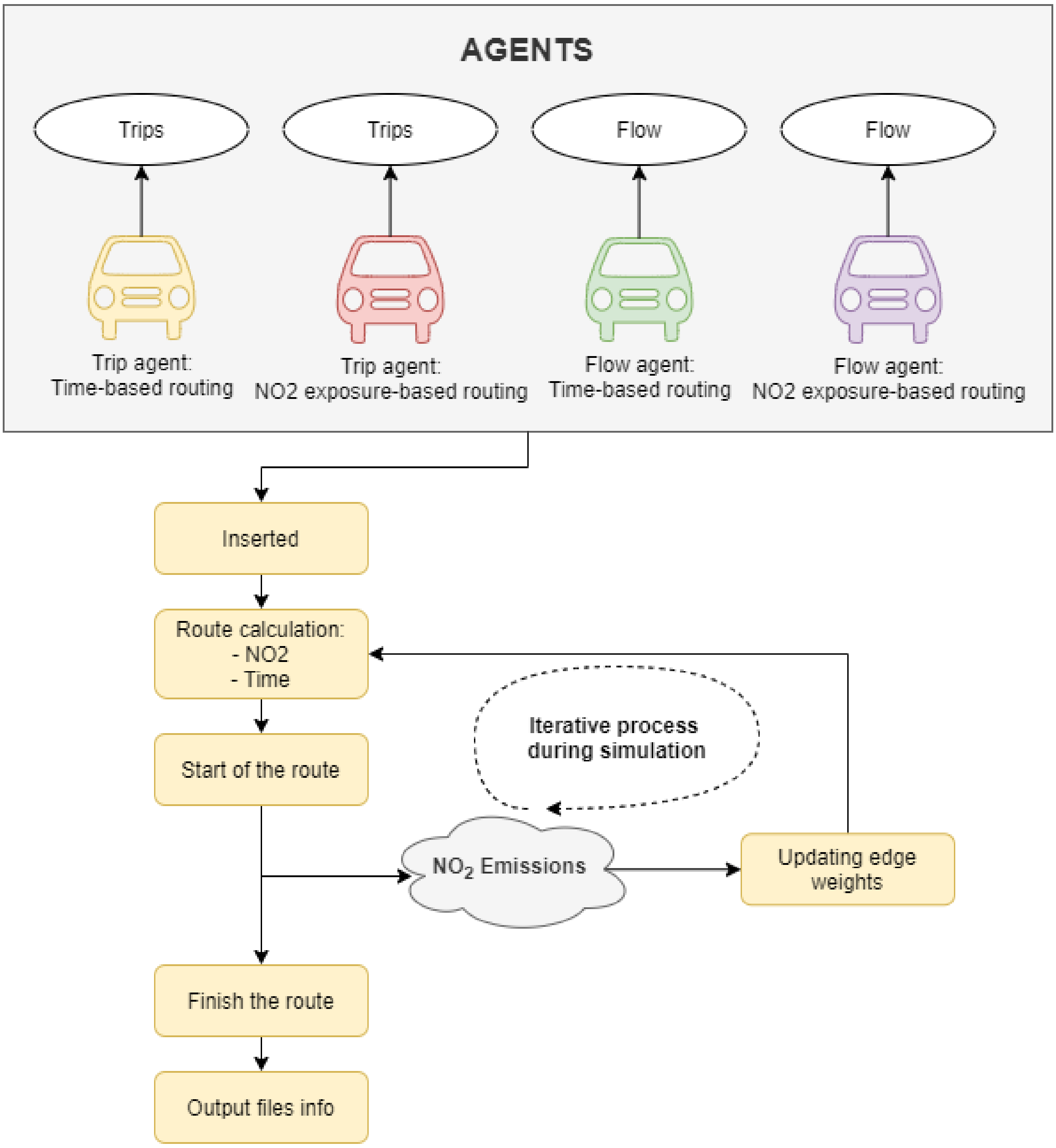


Figure 5.1: Scheme of agents behavior during simulation.

5.5 Temporal interpolation

As we have seen, the calculation of the weights is updated every 10 steps and cumulatively, however, it is necessary to have a temporary pollution dispersion model, as pollution is not permanent in real life. That is why the solution that has been implemented to solve this problem is the creation of pollution windows that only take into account the pollution for the time that the window has. This means that if, for example, we want our simulation to have a one-hour pollution window, only the pollution accumulated during the last hour will be taken into account in the weights. Thus, when calculating the weights of the links, not only the pollution on each link is obtained every 10s and added to the accumulated pollution, but also the pollution accumulated in t -1 steps must be removed, where t is the duration of the window. This is achieved simply by saving the pollution values that accumulate at each moment. It is important to note that only those edges that have either updated their weights or whose value was non-zero at t - 1 steps are updated, as this way, the simulation is much faster. With this pollution window model, a more realistic model is created. Fig. 5.2 provides an outline of this procedure.

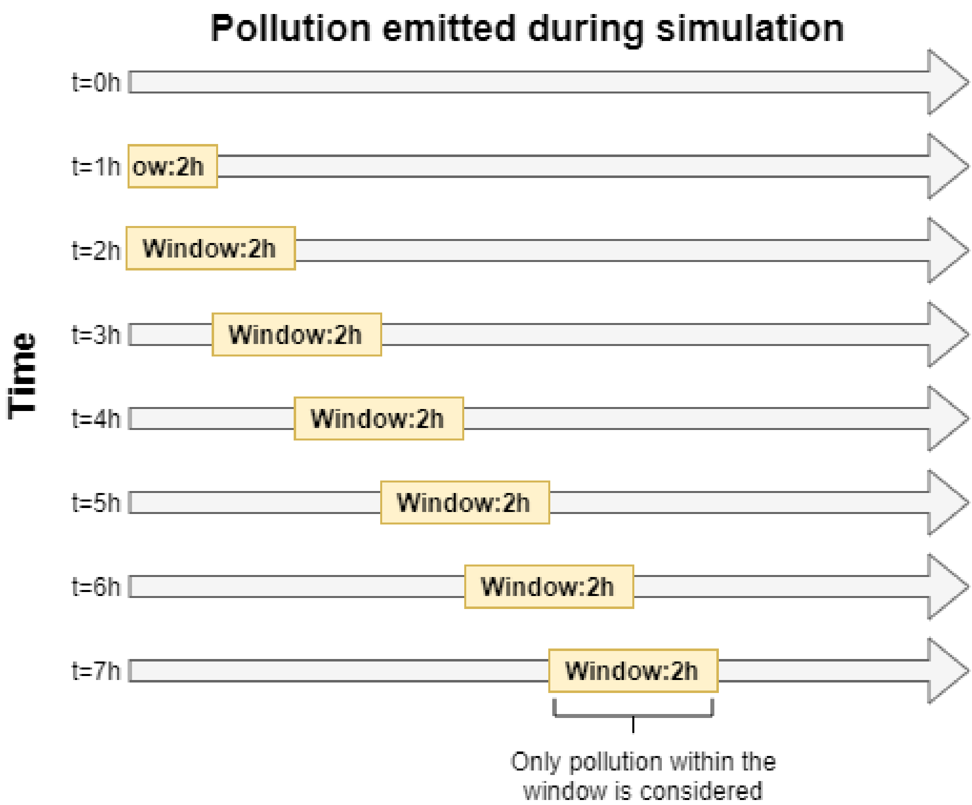


Figure 5.2: Behavior of temporal interpolation window of 2 hours for the agent-based simulation

5.6 End of simulation

Finally, the simulation ends when there are no more vehicles to be inserted and all vehicles has arrived to their destinations. When SUMO finalizes the simulation, all the output files we have seen in Section 4.2.4 above are finished and the evaluation of the data can start.

5.7 Error handling

SUMO is a tool under constant development with some recurring errors during simulations. These errors are mostly due to the network itself and to the wrong behaviour of certain vehicles.

One of the most frequently occurring errors was, as mentioned above, teleports. This can be due to two reasons: the vehicle stood too long in front of an intersection or the vehicle has collided with his leader.

The first case occurs because a vehicle waits too long at an intersection. This can be due to:

- **Wrong lane:** The vehicle is basically stuck on a edge which has no connection to the next edge on its route. This can be partially avoided with the option *'departLane="best"'* when inserting vehicles to ensure that they are placed on the correct edge for following their route.
- **Yield:** The vehicle is stuck on a low-priority road and did not find a gap in the prioritized traffic.
- **Jam:** The vehicle is stuck on a priority road and there is no space on the next edge.

Many of these errors are caused by errors in the network itself - thanks to the changes we made with Netedit, as we have explained in Section 3.2.3, these errors were reduced to practically zero - or due to random circumstances of cars getting stuck in front of each other. SUMO counts the number of steps in which the vehicle is at a speed of less than 0.1 m/s. These steps are accumulated in the waiting time variable, as explained in Section 4.2.4.11 . If the vehicle exceeds this speed again, the count is reset. By default, teleportation occurs when the waiting time count exceeds 300 steps, i.e. a vehicle is stationary and waiting for 300 seconds in real life. Teleportation occurs as a measure when a vehicle is stalled, as it is most likely that the vehicle has been grid-locked. In this way, with teleportation, the vehicle instantly travels to the next free edge of its route and the grid-lock is solved. If there is no room for teleporting, the vehicle suffers from a special teleporting-buffer and virtually crosses to another edge. Therefore, teleports are actually a protective measure against stalemates.

However, for evaluation purposes, if a vehicle is stationary on an edge for too long, the weight of the link becomes disproportionately high. This means that this edge will have too high a penalty for future vehicles, so many vehicles routed by pollution exposure routing will tend to avoid this edge until it is balanced with the rest. To minimize this effect, we have changed the teleport time setting from 300 seconds to 150 seconds with the –time-to-teleport option. In this way, what we do is to reduce by half the time that a vehicle in a stagnant state and thus, we minimize the effect that this has on the network.

Despite this solution, in the evaluation we can observe some cases of pollution peaks at certain edges due to the fact that one or more vehicles were stagnant for a moment in the simulation. These abnormally high pollution values have been discarded by data cleaning as they are not realistic.

As for the second cause of teleports - the vehicle has collided with his leader - it is something that does not occur as often as the other cases, so the effect they can have on the network is merely anecdotal.

CHAPTER 6

Simulation results and analysis

In this section, we will detail the different scenarios that have been run and we will analyze the results obtained.

6.1 Objectives

Knowing that one of our objectives is to analyze the effect of pollution exposure-based routing on the city and passengers, one of the parameters that we will have to analyse is the pollution exposure itself in the network. That is, we have to create a metric in order to measure how much the agents are being exposed and how it varies depending on if they are following the pollution exposure-based routing or not. Our hypothesis is that alternative routing will lower the pollution exposure of the vehicles that use it, but also lower those of others. Since, if secondary edges are used for routing, they are, in a way, distributing pollution throughout the city. So there is more homogeneous pollution when this routing is present.

On the other hand, it is also necessary to know the cost of this alternative routing. In other words, in principle, these vehicles will be less exposed to pollution, but this may mean that they will take routes that are too long, or too slow, etc. So we also need to measure all of this. We know for sure that the routes will be longer and slower, but we need to know by how much. Also, we need to measure what is the effect on the network of our alternative routing at the level of pollution emitted. That is, to see what effect our routing has on pollution levels. We hypothesise that by taking longer routes in principle - as shorter or faster routes are achieved with standard routing - the overall pollution of the system could go up, but we need to find out how much and by how much. We also need to see how this depends on the number of vehicles being routed for pollution exposure, as it is not the same for a single agent as it is for the whole network.

At the same time, we have also added a time interpolation. In the end, pollution is not permanent. We need to know how these windows affect our alternative routing. Since in principle, shorter windows make the agents more important in the weight function, while longer interpolation windows make the importance of the agents decrease.

We know that traffic varies a lot throughout the day, so it would also be interesting to see how routing varies with the number of total vehicles on the network. Our hypothesis is that it should behave in the same way, but with a higher number of vehicles, the pollution emitted will increase, so the cost function of the weights would have a higher value and therefore, the incidence of each agent in the network would be reduced.

6.2 Description of the scenarios

Once we know the objectives we have, we will carry out the evaluation of several scenarios, all of them on the Madrid Central map. Thus, these scenarios will be different from each other in their input parameters. Thus, a total of 36 different scenarios have been run in which the parameters have been varied, and are divided in two different experiments.

Knowing that one objective is to analyze the effect of pollution exposure routing, one of the parameters that we will change between the scenarios will be the percentage of vehicles in the network that decide to follow the pollution exposure based routing instead of the standard one.

On the other hand, we will also vary the chosen dispersion window, since the effect that a vehicle can have on the network when the window lasts one hour is not the same as when the window lasts 4 hours, or even when there is no window.

In turn, we will have scenarios that we will call base scenarios for each window. These scenarios are, for each window, the ones that do not have any routing agent based on pollution exposure, i.e., they are normal traffic simulations where all agents are routed based on time. Also, the term PE routing will be used in the figures to refer to the pollution exposure-based routing itself.

Finally, we have also tested scenarios with much denser traffic, in which pollution is higher, and therefore routing due to exposure to pollution will be conditioned.

In the first part, Experiment 1 in Section 6.3, we will focus on the variation of the percentage of vehicles in the network with routing based on pollution exposure. Thus, we will have six different scenarios with 0%, 20%, 40%, 60%, 80%, and 100% of them following this routing. This will help us to understand the effect of routing in the city with respect to the number of vehicles with the alternative routing. On the other hand, we will also vary the pollution window, that is, we will have five types of scenarios in which the windows will be 1 hour, 2 hours, 3 hours, 4 hours and no window. Thus, each simulation will last 10 hours in real life. Table 6.1 in the following Section shows all scenarios in this experiment 1.

On the other hand, we will later simulate six scenarios - also varying the percentage of vehicles with routing due to pollution exposure - with the 2-hour window in which there will be denser traffic - the total number of vehicles in the simulation is three times higher - and use it to compare with the respective lower traffic. This comparison can be seen in Experiment 2 in Section 6.4.

6.3 Experiment 1

In this section, we will present the results of the first experiment; the analysis is divided into four parts, in which what is being analyzed varies. Thus, the first part is focused on pollution data which includes a comparison between the different final emission maps of the simulation, the second part is focused on travel characteristics, the third part is focused on pollution exposure, and, finally, the fourth part details the conclusions of this Experiment 1.

As mentioned above, it consists of a total of 30 scenarios in which the percentage of vehicles routed through pollution exposure - 0%, 20%, 40%, 60%, 80%, and 100% - and window duration varies - 1 hour, 2 hours, 3 hours, 4 hours and no window. The duration of all simulations is 10 hours in real life. Table 6.1 shows all scenarios in this first experiment.

Scenario	**Window**	**Agents with PE Routing**	**Agents with time routing**
1	0h	0%	100%
2	0h	20%	80%
3	0h	40%	60%
4	0h	60%	40%
5	0h	80%	20%
6	0h	100%	0%
7	1h	0%	100%
8	1h	20%	80%
9	1h	40%	60%
10	1h	60%	40%
11	1h	80%	20%
12	1h	100%	0%
13	2h	0%	100%
14	2h	20%	80%
15	2h	40%	60%
16	2h	60%	40%
17	2h	80%	20%
18	2h	100%	0%
19	3h	0%	100%
20	3h	20%	80%
21	3h	40%	60%
22	3h	60%	40%

23	3h	80%	20%
24	3h	100%	0%
25	4h	0%	100%
26	4h	20%	80%
27	4h	40%	60%
28	4h	60%	40%
29	4h	80%	20%
30	4h	100%	0%

Table 6.1: Scenarios Experiment 1.

All these scenarios start from the same baseline scenario in which there is no cumulative pollution at all. However, only the scenario after 4 hours is taken into account in the analysis, so that the comparison is made on an equal footing, since the largest window is the 4-hour window.

As mentioned above, data cleaning is necessary due to certain outliers in the values that are due to teleports. These values have simply been replaced by the mean of the corresponding value.

One thing to keep in mind is that in all simulations there will be the same number of total vehicles and with the same origin - destination pairs. So, as the longest window is 4 hours, comparisons between the different simulations will be made from the fourth hour onwards in order to do it on a level playing field.

We will now present the results of each of the parts into which the analysis is divided: emitted pollution, characteristics of the trips, exposure to pollution and the conclusions.

6.3.1 Pollution emissions: NO_2

In this first part we will analyse the behaviour with respect to the pollution emitted in the thirty simulations. We have the cumulative NO_2 values for each edge every 300 seconds. There are two types of values, one normalised and the other absolute. The normalised is simply the absolute value divided by the length of the edge. Thus, all the values to be given are measured in total grams of NO_2.

6.3.1.1 Normalised mean of NO_2

The mean absolute NO_2 in the simulations has been calculated. These values can be seen in Fig. 6.1. As can be seen, within each window the behaviour is similar. The higher the percentage of vehicles in the system that follow the alternative pollution exposure procedure, the higher the average pollution in the system. This happens because in this routing they are taking routes that are neither the shortest nor the fastest, so their time and distance is at least equal to the normal routing and therefore they pollute more.

As for the evolution between the windows, a similar behaviour seems to be observed. However, at high percentages of alternative cars, the simulation, in general, with no window has the lowest average, followed by the one with the largest window of 4 hours, then 3 hours, 2 hours, and finally 1 hour. This is because the larger the window, the point at which the incidence of each agent in the system is reduced. That is to say, in high windows, the accumulated pollution is greater, so that what is produced by each agent has less incidence. This means that routing by exposure to pollution tends more towards standard routing. We can see that in the 1-hour window, the average pollution is much higher than in the rest of the windows.

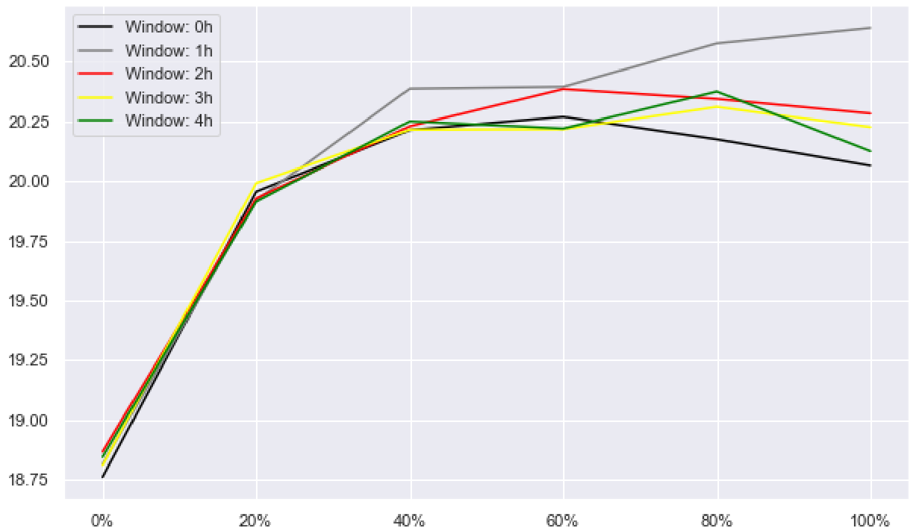


Figure 6.1: Comparison of the evolution of NO_2 normalised mean in the 30 scenarios.

6.3.1.2 Total sum of NO_2

Although it was already intuited in the previous point, Fig. 6.2 shows the total sum of NO_2 distribution at the end of the simulation in each of the simulations. In this way we can see a similar behaviour to the previous case, where up to 60% more cars with alternative routing based on pollution, the more pollution in the system. Subsequently, in the 60% and 80% simulations, the total sum decreases or increases minimally depending on the window. Anyway, this increment of NO_2 emissions is approximately 9%.

The reason for this is the same as in the previous case, as the trips with pollution routing are at least as short as those with 0% alternative routing, the pollution is expected to be higher.

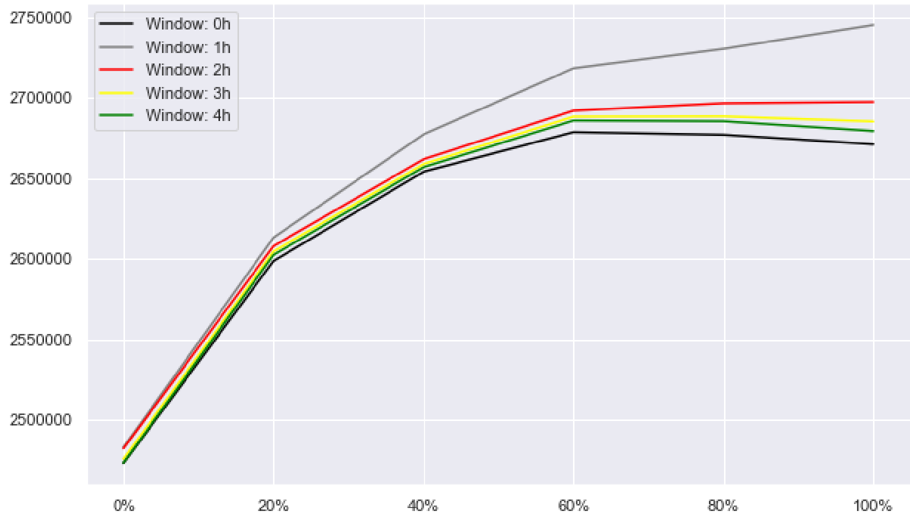


Figure 6.2: Comparison of the evolution of NO_2 total sum in the 30 scenarios.

6.3.1.3 NO_2 distribution at the end of the simulation

A histogram of the number of edges with the total sum of NO_2 for each edge at the end of the simulation can be seen in Fig. 6.3 for a single window. That is, for a single window, in this case for the 2-hour window, the number of edges that are in the same bin of total sum of NO_2 is shown for each of the simulations with different percentage of alternative routing.

This shows how the pollution is distributed at the end of the simulation. The most remarkable thing about this graph is that at zero percentage routing for pollution exposure, the number of edges with low values is much higher. While in the rest, comparatively, it is already lower. This is because standard routing tends to pass through the same streets, while vehicles with alternative routing tend to occupy streets that have not been passed through previously because they have less accumulated pollution. This is confirmed in the next graphs.

Only the graph belonging to the two-hour window is shown, as the rest of the graphs have the same behaviour. However, these graphs can be found in the Appendix A, specifically in Section A.1.1.

6.3.1.4 NO_2 emissions over time in different streets

In this section, a comparison of the evolution over time of NO_2 emissions in three specific streets will be made. This is because, as mentioned above, in scenarios where there is no routing due to exposure to pollution, vehicles tend to pass through main streets and avoid secondary streets. However, vehicles with alternative routing tend to go on these streets when they are lighter in weight and the pollution exposure compensates for the extra metres

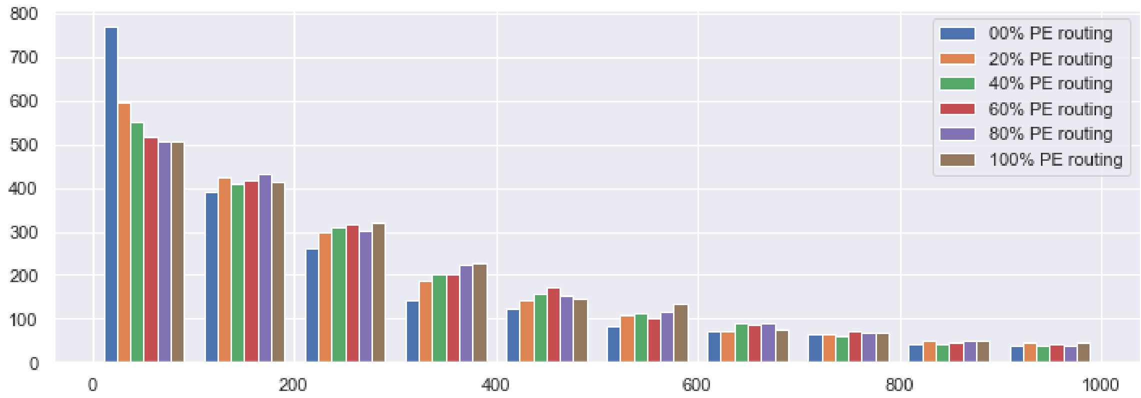


Figure 6.3: Comparison of the evolution of NO_2 distribution at the end of the simulation with 2-hour window.

they can travel. Thus, three types of streets will be studied and are represented in Fig. 6.4. These are: Calle del Barco (A), Calle de Gran Vía (B) and Paseo del Prado (C).

As in the previous case, the behaviour is quite similar between the different windows, so only the graphs with the 2-hour window will be shown. The rest can be consulted in the Appendix A and specifically in Section A.1.2.

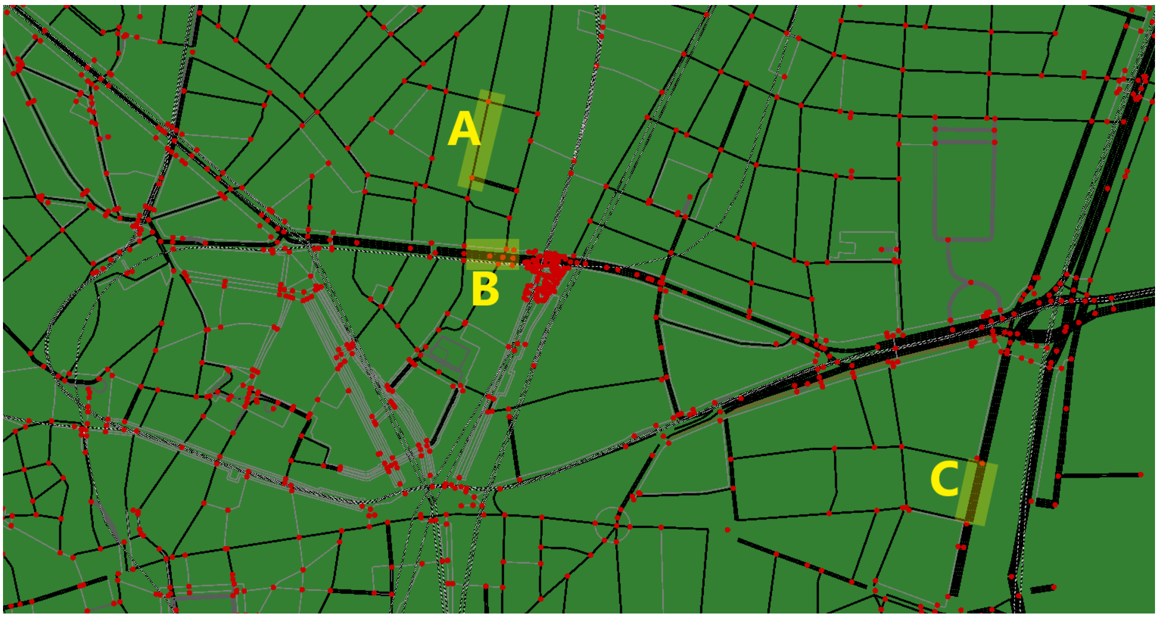


Figure 6.4: Location of the streets: Calle del Barco (A), Calle de Gran Vía (B) and Paseo del Prado (C).

- **Calle del Barco (A):** This is a secondary street, so a higher value is expected the higher the percentage of vehicles with routing due to pollution exposure. Fig. 6.5

shows the evolution over time of this street and indeed, it can be seen that the higher the percentage, the more pollution is emitted. However, it should be noted that this is partly due to the fact that there is a greater amount of pollution in the street. However, it should be noted that this is partly due to the fact that there is a higher sum of total pollution with this percentage. It is only partly due to this, because we already commented in Section 6.3.1.2 that the total NO_2 sum from 60% onwards tended to stabilise; however in this street this is not the case.

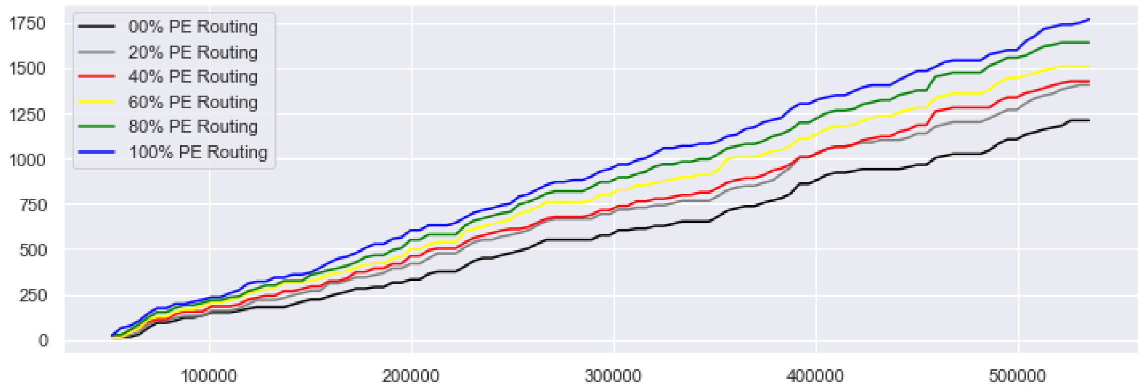


Figure 6.5: Emitted NO_2 over time in Calle del Barco (A) with 2-hours window.

- **Calle de Gran Vía (B):** Gran Vía is a principal street and it is bidirectional, so it will be studied in both directions. It is expected that the higher the percentage of routing based on exposure to pollution, the lower the pollution emitted, as there will be a tendency to go less along this street as it is a main street. Figures 6.6 and 6.7 show the results for both directions. In the first, the difference is more noticeable while in the second it is somewhat less, but the theory is still true.

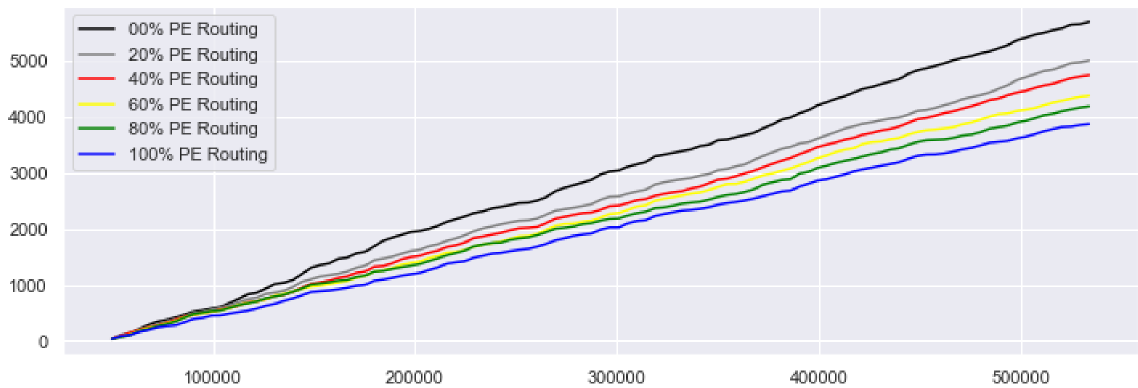


Figure 6.6: Emitted NO_2 over time in Calle de Gran Vía (B) in east-west direction with 2-hours window.

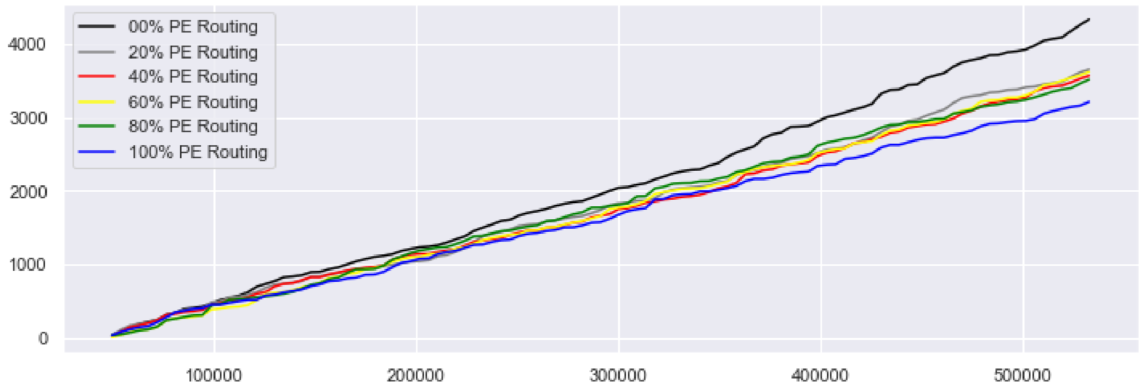


Figure 6.7: Emitted NO_2 over time in Calle de Gran Vía (B) in west-east direction with 2-hours window.

- **Calle de Paseo del Prado (C):** This street is also considered a main street but it is also a peripheral street. This makes it a street that vehicles tend to choose when they do not want to go through the center of the map. In other words, it is expected that this type of street in most cases is not the shortest route. Therefore, it is a road that will tend to be used by vehicles with alternative routing based on pollution exposure to avoid the more polluted streets in the center of the map. This theory is reflected in the data shown in Fig. 6.8.

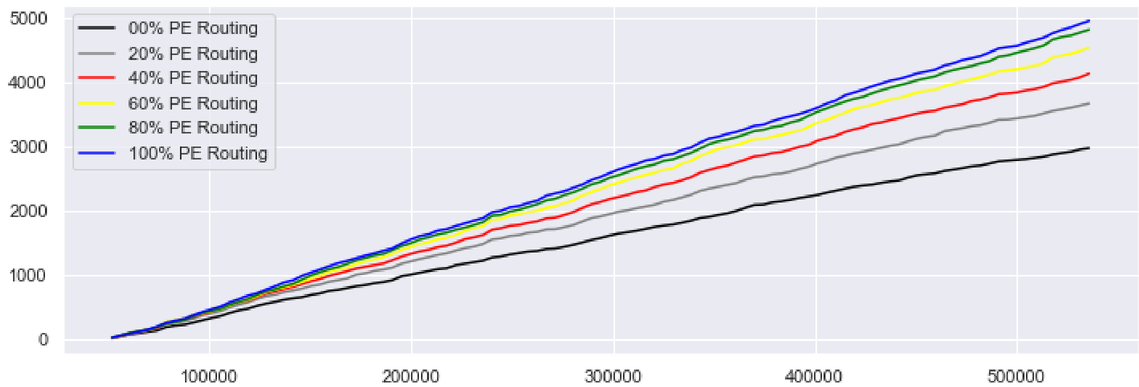
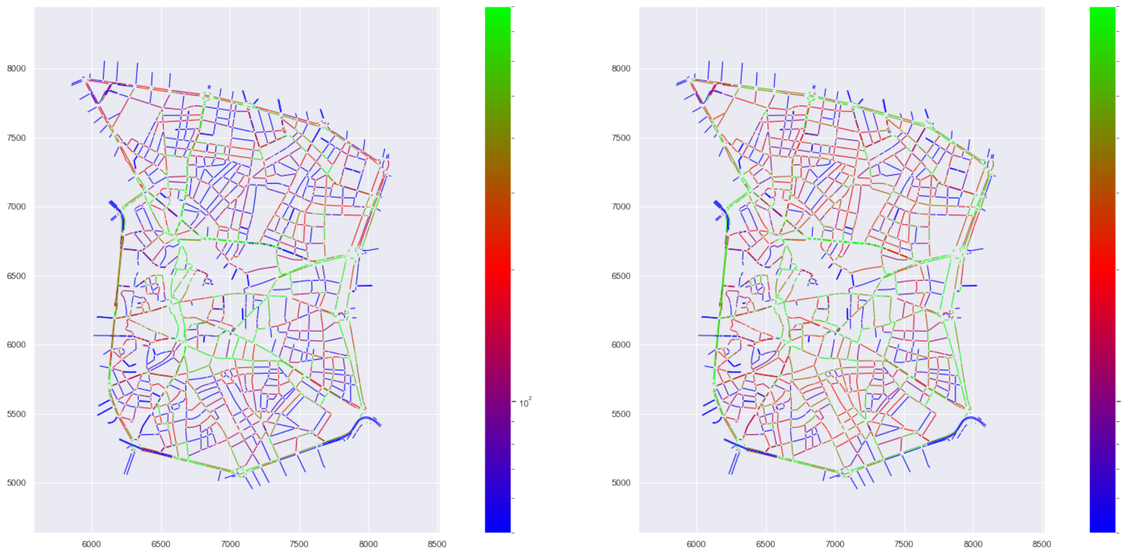


Figure 6.8: Emitted NO_2 over time in Calle de Paseo del Prado (C) with 2-hours window.

6.3.1.5 NO_2 final emissions distribution in Madrid Central network

In this section we are going to use the Plot Net Dump tool provided by SUMO (Section 3.2.5) and a customized version of it that we have created (Section 4.2.4.12). This tool will be used to visualize the pollution state at the end of the simulations in our Madrid Central network.

Thus, in Fig. 6.9 we show a comparison of the NO_2 accumulation in the network between the 0% scenario with routing based on pollution exposure and the 100% scenario for the two-hour window - the results in the other windows are similar. In this way, and following the color code, it can be seen that, as we have seen previously, the 100% scenario presents more NO_2 , since it barely contains edges with blue colors, while these abound in the 0% scenario. At the same time, it can be seen that the so-called main streets have more green tones in the 0% scenario. However, since these appreciations are not so visible to the naked eye, this tool has been customized to make the comparison.



(a) 0% PE routing scenario

(b) 100% PE routing scenario

Figure 6.9: Comparison between NO_2 final emissions distribution in Madrid Central network in scenarios 0% and 100 % PE routing with 2-hours window with SUMO Plot Net Dump

Therefore, in Fig. 6.10 we carry out a comparison in which the 0% routing scenario based on pollution exposure and the 100% scenario for the two-hour window are also analyzed. The edges shown in green are those with higher NO_2 concentrations in the 100% scenario, i.e., in this scenario more pollution accumulates in these streets than in the other scenario. On the other hand, the red color indicates just the opposite: the edges with this color have more pollution in the 0% scenario than in the other scenario. Thus, we can see that there is a clear trend: in those scenarios with our alternative routing, there is a tendency to go along secondary edges, distributing pollution to a greater extent. Whereas the scenarios with the time-based routing tend to go through main edges, accumulating the pollution on those edges.

Figure 6.10: Comparison between NO_2 final emissions distribution in Madrid Central network in scenarios 0% and 100 % PE routing with 2-hours window with customized Plot Net Dump.

6.3.2 Characteristics of the trips

In this section, a comparison will be made between the trips made by the agents in different scenarios. Thus, the mean duration, the mean distance traveled, and the speed at which they do it... will be studied.

Subsequently, a comparison of both routing types with these parameters from the same point A to the same point B (flows) as explained in Section 4.2.4.3 will be made.

6.3.2.1 Mean duration of trips

First, the average duration of all scenarios will be compared. Fig 6.11 shows the evolution of the average duration between the different windows and between the different percentages of pollution-based routing. It can be seen that it follows a trend very similar to the one shown for the total system pollution in Fig. 6.2 above. In fact, both graphs have practically the same shape. This supports the theory that the total sum of pollution produced is due to vehicles making slower trips on average. Thus, the behaviour after 60% routing due to pollution exposure is very similar.

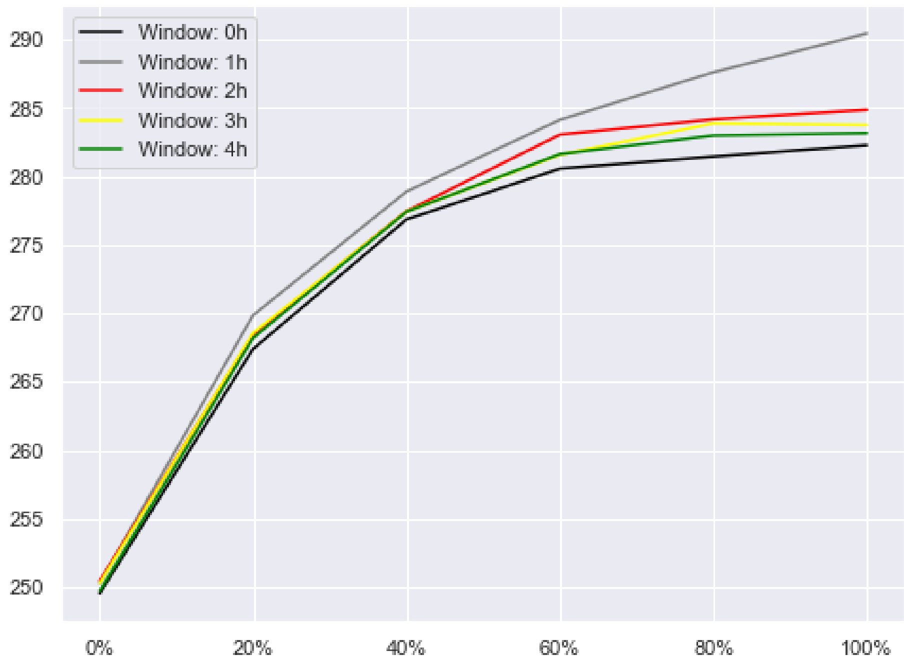


Figure 6.11: Mean trips duration in the 30 scenarios.

In turn, Table 6.2 shows the percentage increase compared to the scenario without alternative routing (0%) of the average distance in 2-hours window. As the behaviour is similar regardless of the window, the table with the remaining values for the other windows can be found in Section A.2 of Appendix A. It is interesting to compare the scenarios of 0%

and 100% routing by exposure to pollution, where in all windows it is found that there is approximately 13% more average duration of cars following this routing. Therefore, we can conclude that, on average, the alternative routing due to pollution exposure is approximately 13% slower.

Window	**Agents with PE routing**	**Mean trip duration**	**Percentage over base scenario**
2h	0%	250.48s	-
2h	20%	268.44s	7.17 %
2h	40%	277.47s	10.78 %
2h	60%	283.06s	13.01 %
2h	80%	284.18s	13.46 %
2h	100%	284.87s	13.73 %

Table 6.2: Duration mean increase compared to the base scenario in 2-hours window.

6.3.2.2 Mean distance of trips

As for the average distance traveled in the 30 scenarios, it has a behavior similar to that of the duration. Thus, the average duration increases up to 60% of routing based on exposure to pollution, but in this case, except in the 1-hour window, it decreases as we increase this percentage, as shown in Fig. 6.12. Among the windows themselves, we continue to find that the 1-hour window continues to have a more atypical behavior.

One thing to note is Table 6.3, and that is that the increase in distance in the case of the 2-hour window, is up to 6%, while the duration was up to 13%. This is due to the fact that the routing due to exposure to pollution actually takes alternative paths that are slightly longer, but these detours take more time due, surely, to the characteristics of the network. That is, due to the fact that in these detours there will be traffic lights, crossings, waits... etc. This behavior is also reproduced in the rest of the windows, reaching up to 7.29% in the case of the one-hour window. The table with all the values can be found in Appendix A in Section A.2.2.

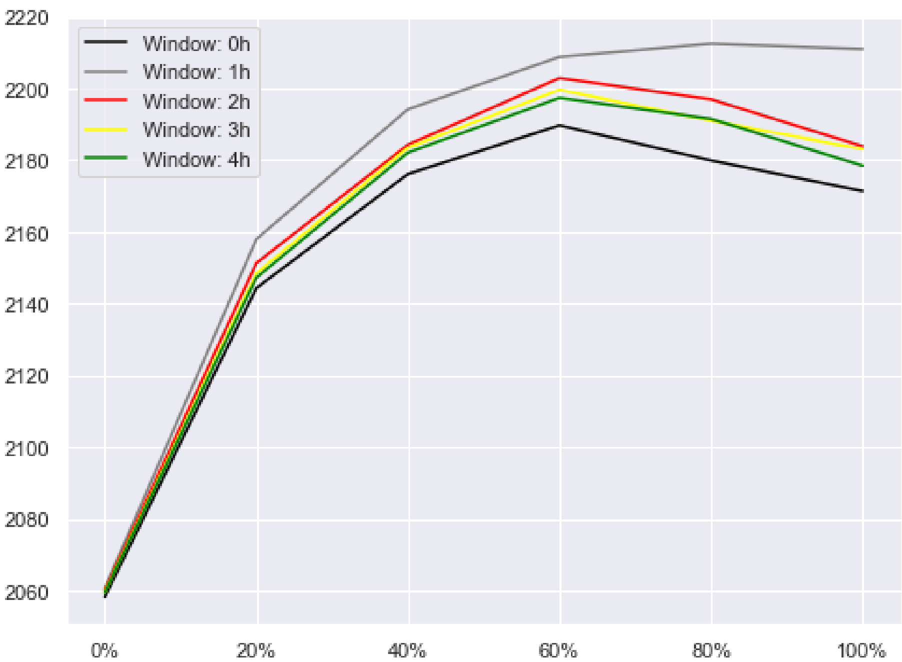


Figure 6.12: Mean trips distance in the 30 scenarios.

Window	**Agents with PE routing**	**Mean trip distance**	**Percentage over base scenario**
2h	0%	2060.21m	-
2h	20%	2151.35m	4.42 %
2h	40%	2184.33m	6.02 %
2h	60%	2202.92m	6.93 %
2h	80%	2196.99m	6.64 %
2h	100%	2183.9m	6.0 %

Table 6.3: Distance mean increase compared to the base scenario in 2-hours window.

6.3.2.3 Mean speed of trips

On the other hand, and as a consequence of the behavior with respect to distance and trip length, it is also interesting to study the average speed of the trips. As expected, the speed decreases as we increase the number of alternatively routed vehicles in the network, this can be seen in Fig. This decrease is as much as approximately 6.5% as can be seen in Section A.2.3 in the Appendix A.

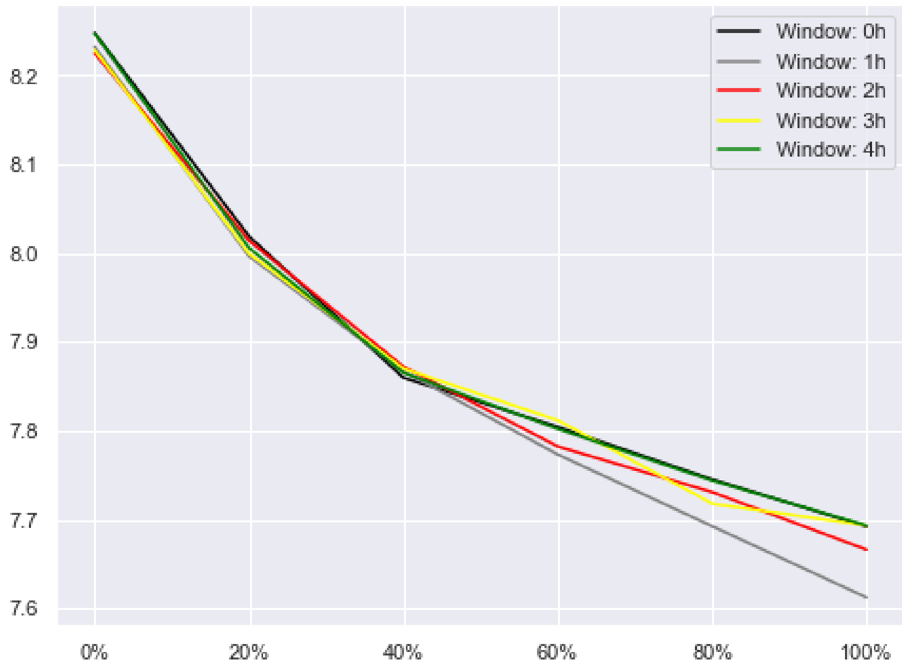


Figure 6.13: Mean trips speed in the 30 scenarios.

6.3.2.4 Comparison of flows

As mentioned above in Section 4.2.4.3, for all simulations, flows of agents were created that departed from the same origin A to the same destination B every 300 seconds during the entire simulation. However, each of them followed a different routing. The location of these points can be seen in Fig. 4.7, as we have shown previously. As we can see, these are two points that are far apart, thus, there are several routes connecting these points. This has been done on purpose to test the behavior of the routing based on pollution exposure over the longest possible distance. In this way we will study and analyze the comparison of both routing, in terms of distance and duration.

Regarding the duration, Fig. 6.14 shows the evolution of the time taken by the vehicles to go from point A to B. Thus, the time taken in all windows by the time-based routing is on average practically the same. Therefore, only one of them is shown in the graph. With

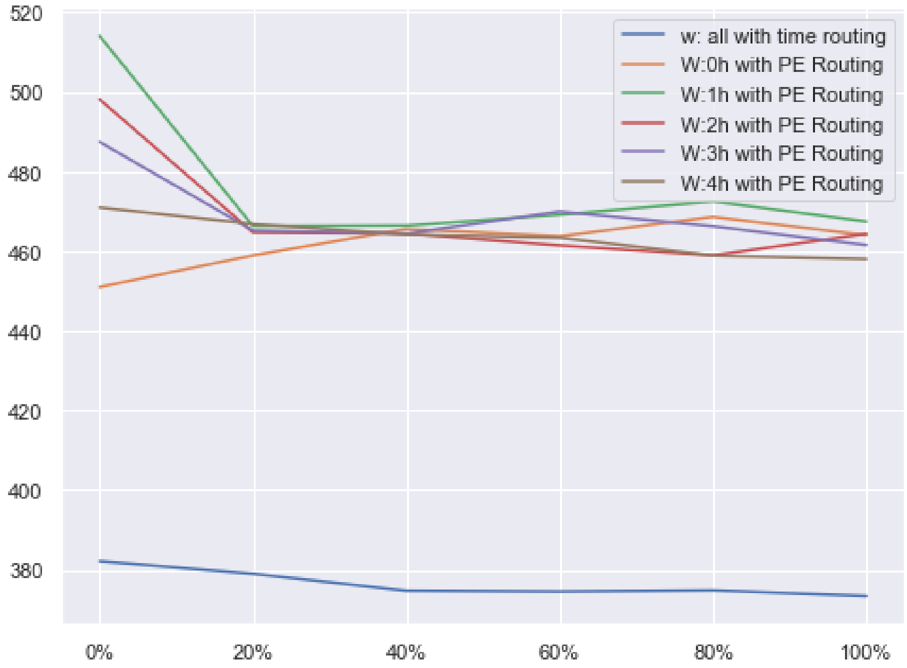


Figure 6.14: Average time [s] taken for the flows to travel from A to B.

respect to the routing based on pollution exposure, it is shown for all five windows. The behavior is similar except for 0%. This happens because these scenarios do not have other cars that are routed by pollution exposure. The only one that follows this routing is the flow itself every 300 seconds so it is the only one that tends to regulate the network by the operation of the weights. This causes it to take too long routes on certain trips. For this reason, it makes sense that the larger the window, the less time the flow takes in the case of 0%, since the weights have less impact throughout the simulation the larger the window. This is equally true for the distance, as can be seen in Fig. 6.15.

Finally, in Appendix A and specifically in Section A.2.4, the comparative tables with respect to the time and duration of the flows are shown. Thus, we can see that approximately, in a very long path such as from A to B, the duration of the path with routing due to exposure to pollution is 23% longer, while the distance is approximately 24% longer. On the other hand, the distribution of flow durations by scenario for 2-hours window, as well as those of distances, are also included in Fig. A.21 and Fig. A.22.

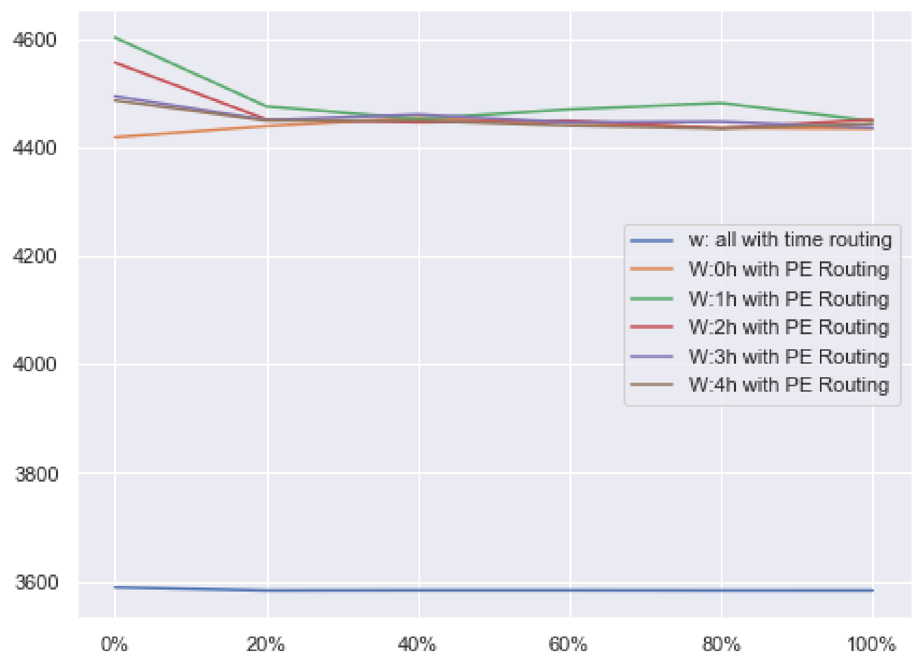


Figure 6.15: Average distance [m] taken for the flow to travel from A to B.

6.3.3 Pollution exposure

In this section we will study and evaluate how the pollution exposure of the simulations varies according to the routing being used. Thus, in the first instance, a comparison will be made of the average pollution exposure received by the vehicles among all the scenarios. Subsequently, a comparison will be made between the exposure received by flows from A to B, as in the previous case.

6.3.3.1 Average pollution exposure

Fig. 6.16 shows the variation of the average pollution exposure in the 30 scenarios with respect to their base scenarios (scenarios with 0% routing based on pollution exposure). It should be noted that the exposure of all vehicles in the simulation is being measured. In turn, we can observe that the behavior in all windows is very similar. Also, it can be observed that as we increase the percentage of vehicles with routing based on pollution exposure, the percentage decreases. That is, with only 20% of vehicles following our alternative routing, a 15% decrease in pollution exposure is achieved for all vehicles in the network, and with 40% of vehicles, the percentage reaches a decrease of 25%.

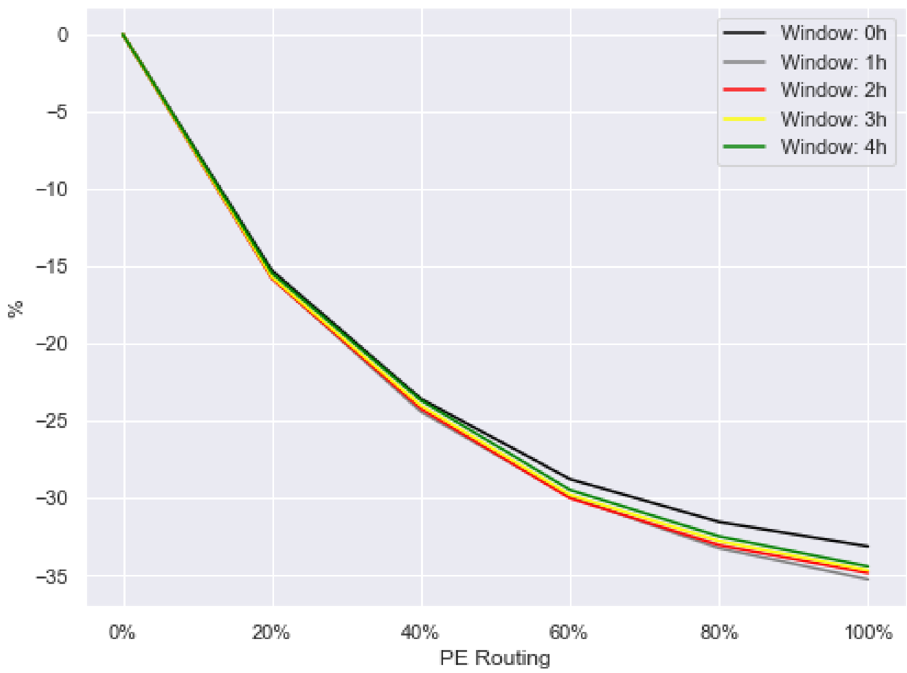


Figure 6.16: Percentage of pollution exposure with respect to the base scenario for the 30 scenarios.

Finally, if we compare the scenarios of 100% with 0% alternative routing, a 35% reduction in all vehicles is achieved. This makes this type of routing very interesting and very useful, and is undoubtedly one of its strengths. The pollution exposure values recorded can be seen in the Table A.6 in Section A.3.1.

6.3.3.2 Comparison of flows

Now, we are going to perform a study in which we will compare the pollution exposure in the flows explained in Section 4.2.4.3. How the pollution exposure varies in these flows can be seen in Fig 6.17 and Fig 6.18. Thus, in the first one, the average pollution received in each window of each of the flows is shown. The dashed lines are the flows that follow the pollution exposure routing, while the solid lines are those that follow the standard routing. As can be seen, in all windows, proportionally, the behavior is the same. Thus, in each window the more percentages of vehicles are routed based on pollution exposure, the more the PE routing flow - dashed line - pollutes. This makes sense as pollution is becoming more distributed, so alternative routing cannot be leveraged as much in comparison. That is, as more cars follow your routing, the streets with less pollution end up being distributed sooner.

In turn, the more exposure routing there is, the pollution received by vehicles with normal routing is drastically reduced. So the agents with alternative routing are helping the agents with normal routing to become less polluted.

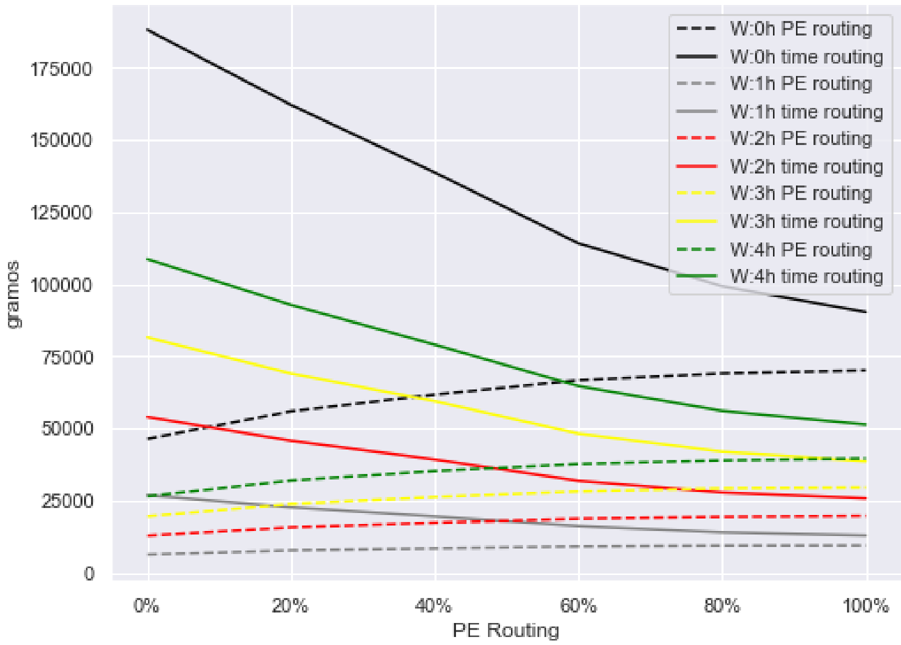


Figure 6.17: Evolution of the pollution exposure in flows in the 30 scenarios.

Fig. 6.18 shows the difference in percentage of pollution exposure received between the flow with alternative routing and the flow with normal routing. Recall that both have the same origin and the same destination. Thus, in a 0% scenario, the flow with alternative routing has up to 400% less exposure to pollution, this is because it is the only agent in the system that seeks the least polluted routes, so although we have seen in trips, its trip lasts much longer, it compensates by receiving less pollution. As we increase the percentage of vehicles with alternative routing, the percentage of pollution saved decreases, reaching up to -130%.

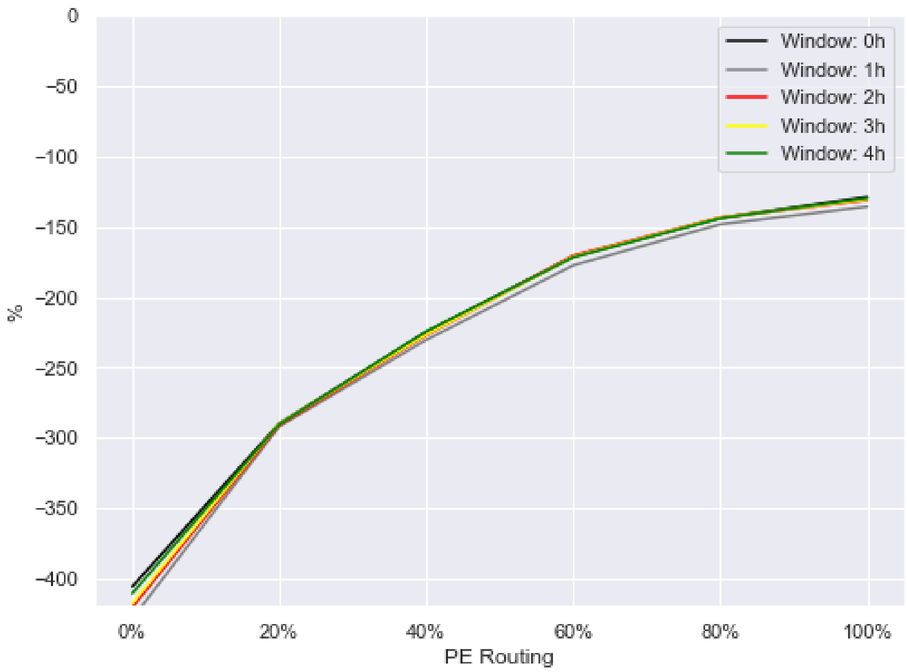


Figure 6.18: Evolution of the difference in percentage of pollution exposure received between flow with time routing and flow with PE routing.

Finally, it is useful to know for vehicles that follow pollution-based routing how much of the emissions they are saving. That is, the percentage compared to the route they would have taken if they had followed standard routing. The same is shown in Fig. 6.19. The very low value in the 0% case is due to the fact that the only vehicles with such a routing are those in the flow. Thus, in this case, the flow is receiving a quarter of the pollution it would have received. In the rest of the simulations, the vehicles with our alternative routing are exposed to between 80% and 95% of the pollution they would have received.

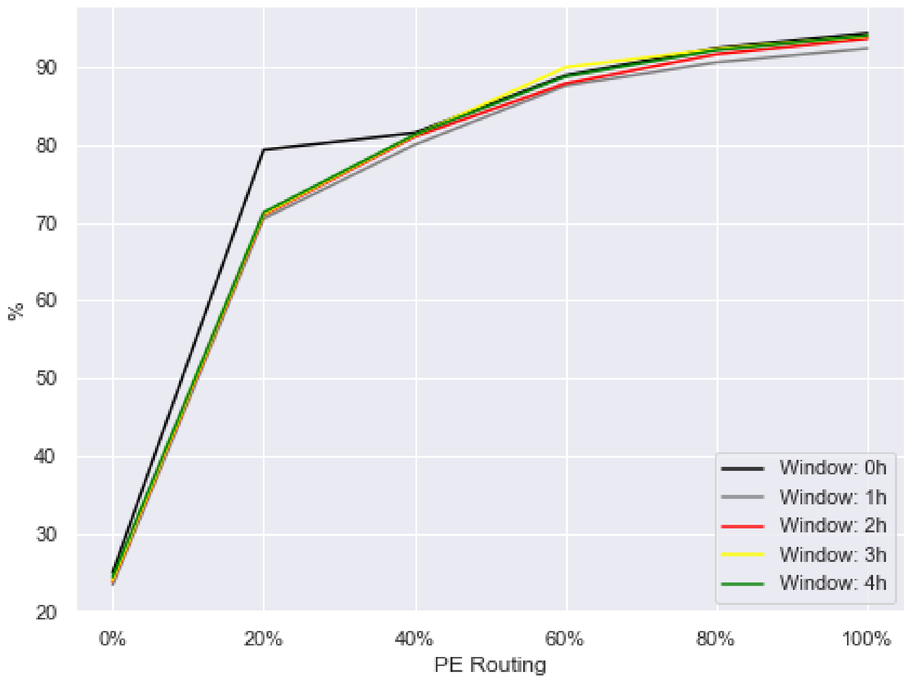


Figure 6.19: Emissions saved by vehicles with PE routing in the 30 scenarios.

Finally, section A.3.2 of the appendices shows the table with flows data obtained with respect to pollution exposure.

6.3.4 Conclusions Experiment 1

This section will report the conclusions of the evaluation and analysis of experiment 1.

In terms of the pollution emitted, we have seen that routing based on exposure to pollution emits more NO_2 into the atmosphere, up to 9% more. However, the distribution of NO_2 emitted is much more homogeneous with our alternative routing, as secondary streets are more used by the agents, to the detriment of the main ones. Thus, main streets with the standard routing comprise high concentrations of pollution, while small streets have hardly any high concentrations. This is reversed by routing based on pollution exposure, making the emissions map more homogeneous across the city.

In regard to trip characteristics, routing based on pollution exposure causes the average trip length to be longer, being up to 13% slower. Even for longer trips, journey times can be up to 23% slower. On the other hand, the average distance travelled with our alternative routing is up to almost 7% longer on average. For longer trips it can be up to 24% longer. At the same time, the average speed of vehicles with such routing is up to 7% lower. All these values are mainly the result of detours from main routes to generally slower secondary routes.

Finally, in terms of pollution exposure of the agents during the simulations, pollution exposure-based routing achieves a reduction of up to 35%. In turn, it is noteworthy that with 20% of vehicles with this routing, the pollution exposure of the whole system is already reduced by 15%. A direct comparison of the two routing scenarios shows a reduction in NO_2 exposure of up to 400% in scenarios with only standard routing (except for evaluation trips where the impact is negligible), and up to a 130% reduction in simulations with only alternative routing. Furthermore, the more exposure routing there is, the pollution received by vehicles with normal routing is drastically reduced. So the agents with alternative routing are helping the agents with normal routing to become less polluted.

Finally, regarding the behaviour of the pollution windows in the different simulations, it should be noted that the larger the window, the lower the incidence of each vehicle in the network, as the cost function will have higher values. Thus, it has been observed that in the 1-hour window, there is a somewhat erratic behaviour of vehicles with routing based on exposure to pollution with respect to distance and time taken. On the other hand, the 4-hour window makes the incidence of each agent in the simulation very low, approaching values where there is no pollution window. This is why it has been determined that the best performing windows are the 2-hour window in the first instance, or the 3-hour window in the second instance.

6.4 Experiment 2

In this section we will show the results obtained from the second experiment. As mentioned at the beginning of the chapter, this experiment consists of six new simulations in which the traffic on the network has been increased to create a certain degree of congestion. To achieve this, three times as many vehicles have been introduced into the network for a 2-hour window in the simulations with 0%, 20%, 40%, 60%, 80%, and 100% of vehicles with routing based on pollution exposure. The choice of this window is linked to the conclusions of Experiment 1, where we concluded that the best results are obtained in this window. The idea of this experiment is to find out how such scenarios may affect alternative routing. In this way, a comparison will be made with the corresponding simulations with a two-hour window of normal traffic.

The six new simulations created have a duration of 8 hours. However, comparisons between the two sets of six simulations will be made from the second hour of simulation. Thus, we will have five hours of comparison of the two groups. Contrary to the previous experiment, in this comparison, the origin-destination pairs are not the same in all groups, as the number of vehicles varies.

In the congested traffic simulation group, there are many traffic jams. Due to the limitations of SUMO and the map, the number of teleports in these cases is quite accentuated, as some vehicles are more likely to be stuck. Still, despite the fact that these errors occur from time to time, a successful evaluation and analysis could be carried out, but it is something to keep in mind at all times.

To perform this experiment, the same procedure will be followed as in the previous experiment. Thus, the pollution emitted by these vehicles will be analysed, including, of course, the final emission maps, the characteristics of the trips, and the pollution exposure of the network agents.

However, for this experiment we will not go into as much detail with respect to the analysis as in the previous experiment, so the most interesting data and graphs will be presented, as there are many concepts that are repeated from the previous experiment. Thus, during the evaluation of this experiment, parts of the previous experiment will be referenced.

As for the nomenclature in this evaluation, we will call the sets of six simulations of each traffic type traffic groups. That is, there will be two traffic groups, one with the dense traffic simulations, and one with the normal traffic simulations. As in Experiment 1, we will use the name base scenario to refer to the scenario without vehicles with pollution exposure routing at all times. In turn, the term PE routing will be used in the graphs to refer to the pollution exposure-based routing itself.

6.4.1 Pollution emissions: NO_2

For the total emitted pollution in the system, there is a difference between the two sets of simulations. Thus, Fig. 6.20 shows the percentage of pollution that is emitted in excess of the baseline scenario (0% scenario without pollution exposure-based routing). Thus, in the simulations with normal traffic, the percentage increases logarithmically, whereas in the case of dense traffic, the percentage always increases somewhat irregularly, but always less than the percentage of normal traffic. This irregular shape is due to the congestion that occurs in these scenarios. We have shown this in percentages because the comparison in absolute pollution values shows that the pollution is three times higher in dense traffic, which is quite logical as there are three times as many vehicles.

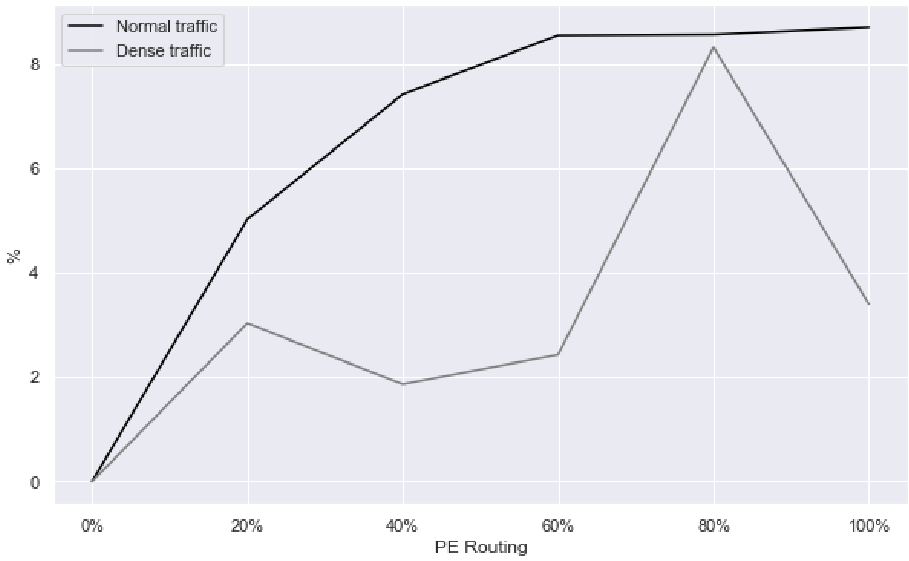


Figure 6.20: Comparison of the percentage of pollution that is emitted in excess of the baseline scenario (0%) between normal traffic and dense traffic.

On the other hand, the pollution distribution at the end of the simulation is quite similar in both cases, with the result that in the cases where there are no vehicles with routing based on pollution exposure, the number of edges with very low pollution values is higher. This follows the same behaviour as in Fig. 6.3 of the previous experiment.

In turn, the behaviour on the different streets throughout the simulation behaves in the same way with dense traffic as with normal traffic. This is true for Calle del Barco, for Calle Gran Vía in both directions, and for Calle Paseo del Prado.

Regarding the final emission status at the end of the Madrid Central network, it can be seen that the increase of pollution with dense traffic is noticeable in Fig. 6.25. This figure shows the four final pollution emission scenarios when all vehicles are routed based on time and when all vehicles are routed based on pollution exposure for normal traffic and for dense traffic. Thus it can be seen that the final pollution in the two dense traffic scenarios is higher, as expected.

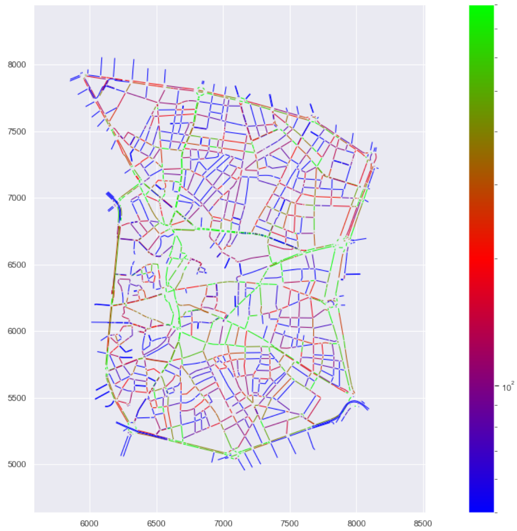


Figure 6.21: 0% PER & Normal traffic.

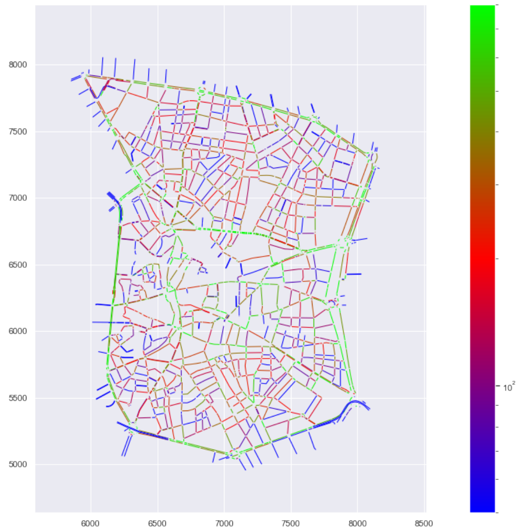


Figure 6.22: 100% PER & Normal traffic.

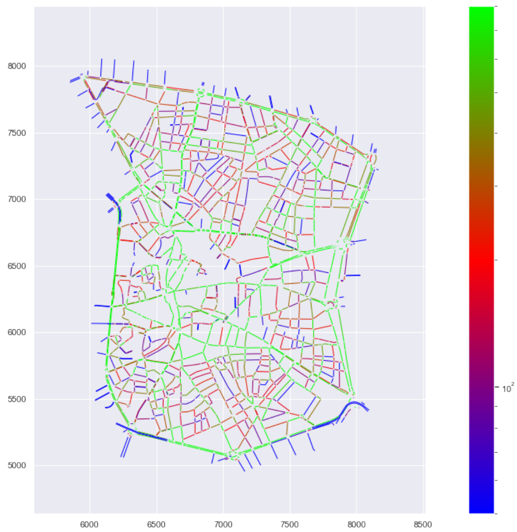


Figure 6.23: 0% PER & Dense traffic

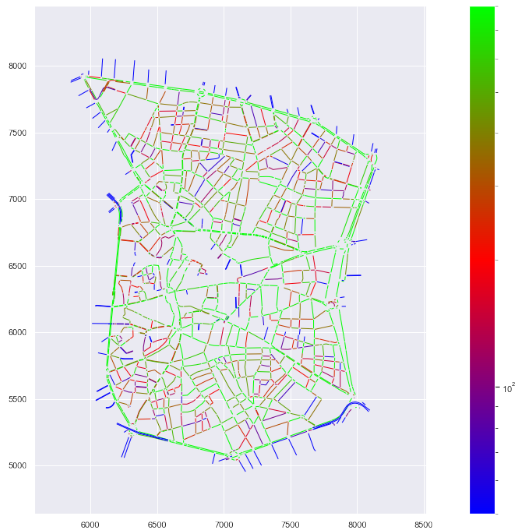


Figure 6.24: 100% PER & Dense traffic

Figure 6.25: Comparison between NO_2 final emissions distribution in Madrid Central network in scenarios 0% and 100 % PE routing with normal traffic and dense traffic.

As for the comparison between the two types of routing for dense traffic with the customised tool we have developed (Section 4.2.4.12), it follows the same behaviour as for normal traffic, with a clear tendency in the scenarios with time-based routing to occupy and pollute the main lanes, while the secondary lanes are more polluted in the cases of routing based on exposure to pollution. This can be seen in Fig 6.9 from the previous experiment.

6.4.2 Characteristics of the trips

This part will explain the main and interesting characteristics of the trips in this Experiment 2.

Thus, with respect to the duration of the trips, it has increased as expected. Fig. 6.26 shows the average time per simulation in each traffic group. It can be seen that, in general, the behaviour is similar between both groups, except for the 80% peak in dense traffic. This is due to the fact that specifically in this simulation there was a large amount of congestion in the network. The variation of each traffic group with respect to its base scenario of 0% is similar.

However, one thing to note is that as we increase the percentage of alternative routing in the scenarios, the percentage increase in duration over the base scenario in dense traffic is less than that in normal traffic. In other words, in congested networks, when there is high routing based on exposure to pollution, it decongests the network to some extent, as many vehicles opt for alternative routes and the main lanes are not as congested.

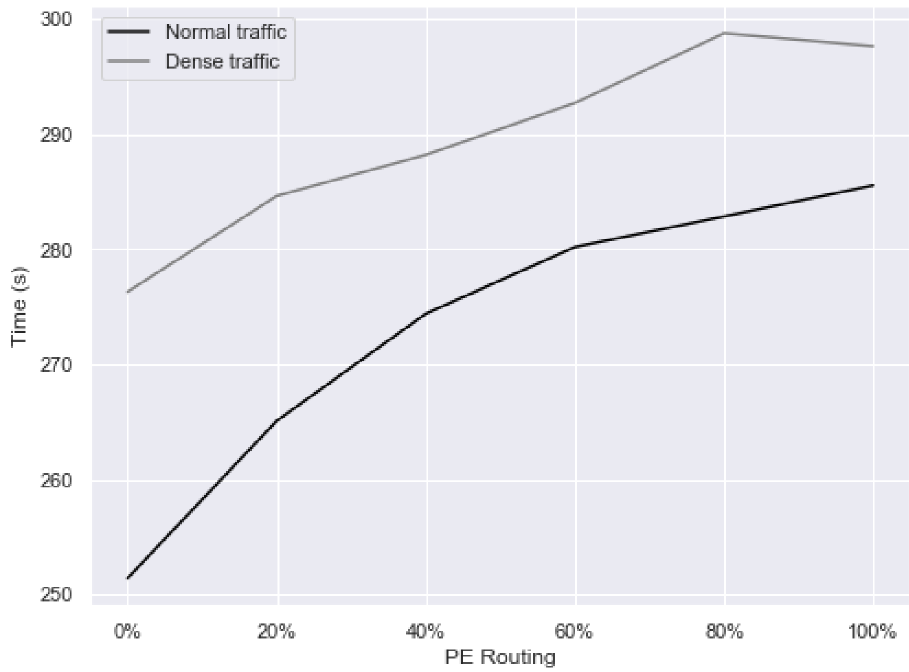


Figure 6.26: Mean trips duration in the 12 scenarios.

As for the length travelled, it is practically the same for dense traffic as for normal traffic, Fig. 6.12 of Experiment 1 shows how it behaves. This shows that vehicles in both simulations take on average the same routes, but take significantly longer due to network congestion.

With regard to the comparative study of flows, we would like to highlight the duration of journeys. Thus, Fig. 6.27 shows the duration of the two flows of each traffic group. Recall that the flows were two batches of vehicles leaving every 300s from the same origin A to the same destination B quite far apart following the pollution exposure routing and the time-based routing respectively (Section 4.2.4.3,). The location of these points A and B can be seen in Fig. 4.7,

Thus, we can observe that in the case of normal traffic, the flow following the standard routing (blue colour) lasts about 370 seconds on average in all simulations, and its respective in the pollution exposure based routing (orange colour) is higher by about 23%, as seen in Experiment 1 in Section 6.3.2.4.

In turn, in the cases of high traffic density, the duration of flow vehicles routed by exposure to pollution (red colour) follows the same behavioural trend, with slightly longer times due to congestion. However, the time it takes for time-based routed flow to reach the destination in the different scenarios decreases as we increase the percentage of vehicles with our routing in the system. This is because, in the 0% and 20% scenarios, the majority of vehicles tend to go on the main roads, which are more congested than the secondary roads. As a consequence, long journey times, such as flows, ending up being closer in duration to the routing based on pollution exposure. Thus, for the 80% and 100% scenarios, the flow duration decreases because the network becomes less congested due to the increase of cars on side streets.

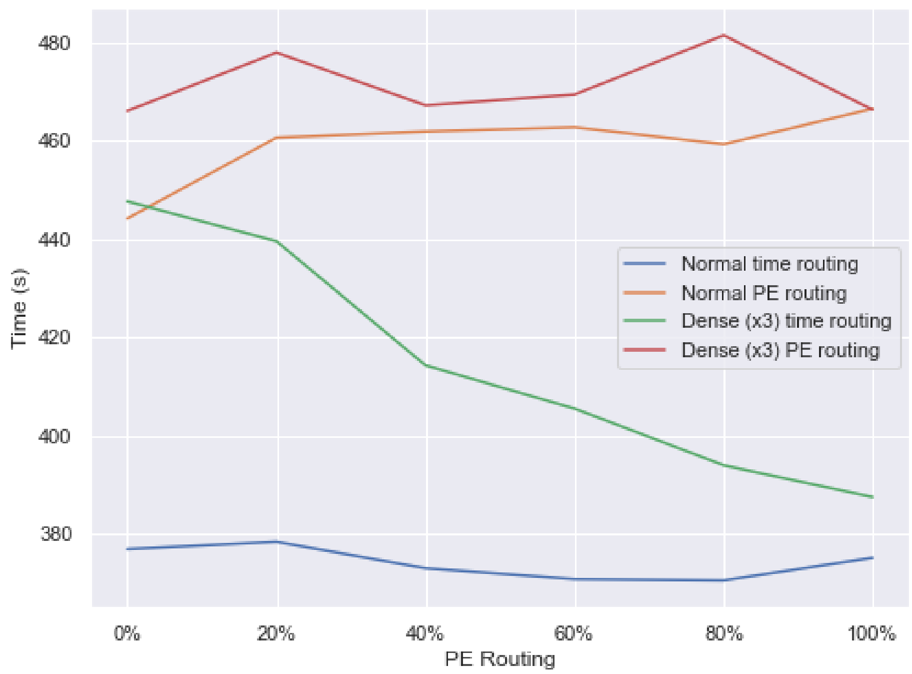


Figure 6.27: Average time [s] taken for the flows to travel from A to B.

On the other hand, the distance and speed in the flows between dense traffic and normal traffic have a similar behavior, which makes sense, following the line we have been seeing so far.

6.4.3 Pollution exposure

With regard to pollution exposure, the same trend is followed in normal traffic as in dense traffic. This can be seen in Fig. 6.28, which shows the evolution of the percentage of pollution exposure with respect to the baseline scenario for each simulation. It is shown in percentage to see that the behaviour is the same, but it should be noted that as there is approximately three times as much pollution as we have seen above, the pollution exposure is also three times higher in dense traffic than in normal traffic.

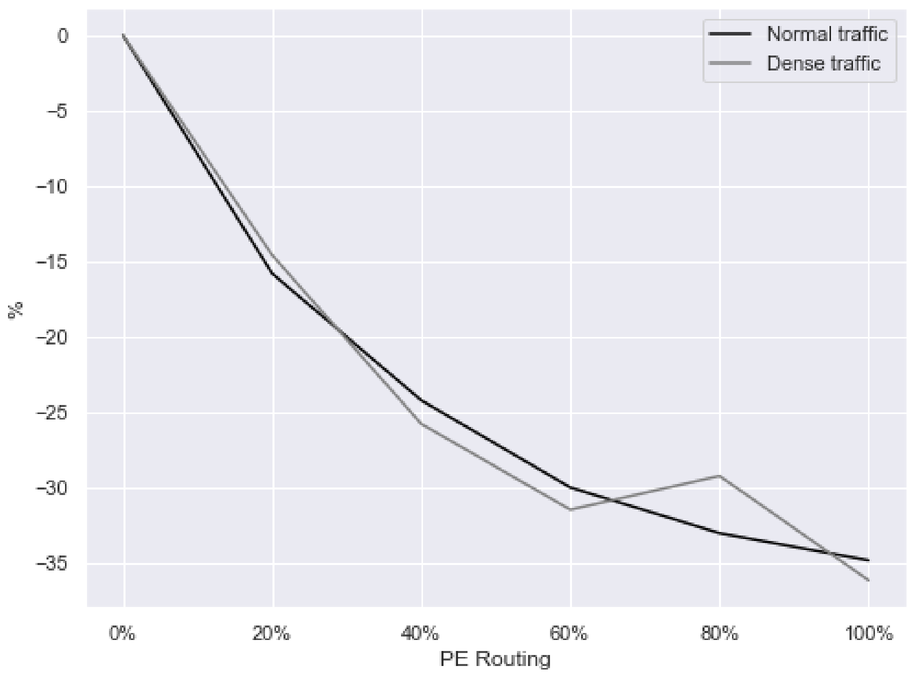


Figure 6.28: Percentage of pollution exposure with respect to the base scenario.

Finally, with regard to the pollution exposure of flows from A to B, Fig 6.29 shows the difference in percentage of pollution exposure received between the flow with alternative routing and the flow with normal routing. Thus, in a 0% scenario, the flow with alternative routing in dense traffic has up to 300% less exposure to pollution, meanwhile in normal traffic this value is 400% less. This difference between the two traffic groups is due to the fact that because there are more vehicles, and therefore more congestion, both flows receive values approximately three times as high. As congestion is higher, the impact of the flows on the cost function is reduced, i.e. with higher pollution values, the ability of each agent to influence the network decreases, as was the case in the window comparison. This causes the dense traffic function to be shifted to the left as a percentage of the normal traffic function. The behavior in both, anyway, is similar, as we increase the percentage of vehicles with alternative routing, the percentage of pollution saved decreases, reaching up to approximately -130% in both cases.

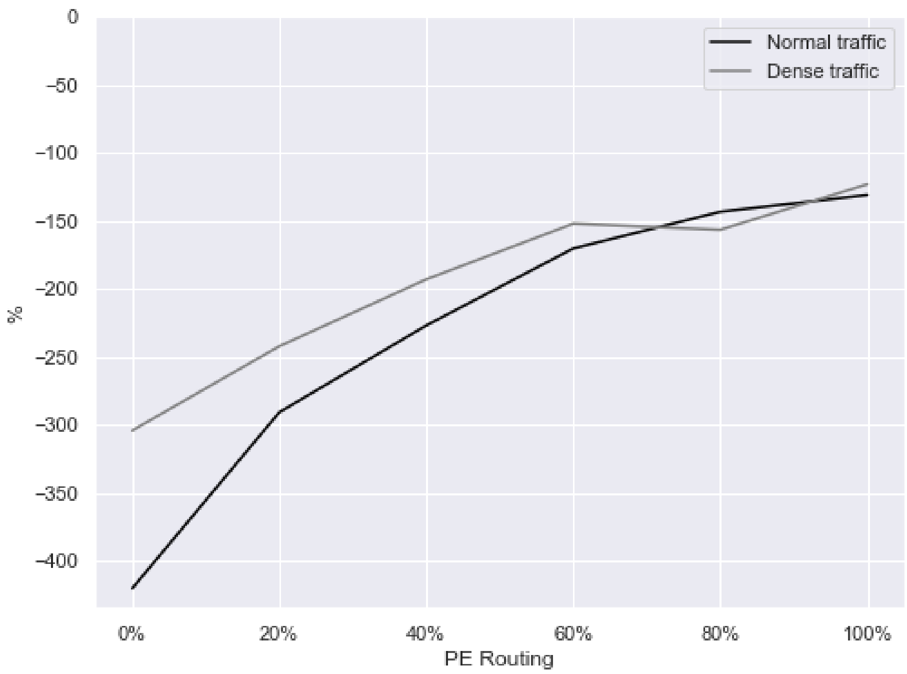


Figure 6.29: Evolution of the difference in percentage of pollution exposure received between flow with time routing and flow with PE routing in normal traffic and dense traffic.

6.4.4 Conclusions Experiment 2

Having done all the evaluation and analysis of this Experiment 2 in which we compared dense traffic with normal traffic for a two-hour window and the six simulations of percentage routing based on pollution exposure, we will present in this section the conclusions of the experiment.

With respect to emitted pollution, the fact that dense traffic has three times the number of vehicles than normal traffic makes the overall emitted pollution approximately three times higher. The overall behaviour of the emitted pollution does not vary much depending on the number of vehicles.

With regard to trip characteristics, the average trip length in dense traffic is longer due to congestion than in normal traffic. However, as the number of vehicles routed based on pollution exposure increases, the percentage increase in trip length is lower in dense traffic than in normal traffic. This means that when a high majority of vehicles are routed with our algorithm in dense traffic, vehicles tend to use more secondary and less congested streets. This causes the network to become somewhat less congested, which allows vehicles following the time-based routing to decrease their trip lengths, as shown in Fig. 6.27. On the other hand, generally the distance travelled is independent of the amount of traffic.

Finally, the exposure to pollution in dense traffic is higher, this is obvious because there is about three times as much pollution; however, percentage-wise, the exposure to pollution in dense traffic is higher. In other words, the effectiveness of routing in terms of minimising pollution exposure of vehicles is somewhat diminished in dense traffic.

CHAPTER 7

Conclusions

This last chapter will detail the conclusions of this project, as well as the objectives achieved, and the future work.

7.1 Achieved Goals

Following the objectives set at the beginning of the project, this section will detail whether and how they have been achieved.

- **Design of a traffic agent-based simulation in Madrid:** Thanks to the use of SUMO, the tools provided by this simulator, TraCI and Jupyter Notebook, it has been possible to design a simulation environment based on agents whose modelled behaviour is influenced by the state of the network at all times. In this way, a complex architecture has been designed that allows the correct operation and future evaluation of the simulations. Thus, through a routing algorithm, the behaviour of these agents can be modelled during the simulation, creating several output files that will allow the future study of the simulations. Thus, a map of Madrid Central has also been designed, which through certain transformations, allows the use of this network in the simulations.

- **Design of an algorithm that minimises exposure to NO_2:** At the same time, a mathematical algorithm based on a cost function dependent on time and accumulated pollution has been created. In this way, this cost function has been integrated into the agent-based simulation environment to create a map of weights in the network to enable routing based on pollution exposure in the simulations. In this way, this algorithm will be the basis of the network modelling that will influence the agent modelling.

- **Design of different simulation scenarios:** At the same time, the necessary tools have been created and provided for the creation and design of different scenarios depending on the input parameters to be introduced in the simulations. Thus, it has been possible to simulate up to 36 different simulations for a total of 348 simulated hours. For these scenarios, a temporal interpolation model of pollution has been created in the form of pollution windows.

- **Analysis and evaluation of the effect of pollution exposure routing on the city of Madrid:** Finally, an exhaustive evaluation and analysis of the consequences of routing based on exposure to pollution has been carried out, drawing positive and negative conclusions about the effect of this routing on passengers and on the network itself.

7.2 Conclusion

Our project has managed to meet the objectives set at the beginning of its development, so this section will detail the conclusions of the entire project.

First, we have observed that routing based on pollution exposure influences the network differently depending on the pollution window used, the percentage of vehicles in the whole simulation that follow this routing, and traffic density.

Thus, it has been observed that this type of routing causes the pollution of the whole system to be slightly higher, because vehicles do not take the shortest or fastest paths. However, it results in a more homogeneous distribution of NO_2 in the city, causing the high pollution accumulated in the main streets to decrease while the low pollution accumulated in the side streets rises. This means that certain NO_2 concentration thresholds are not exceeded at any point in the city. In the case of Madrid, which, as we have seen, is the city with the highest concentration of NO_2 in Europe, this is especially important, since, as it is more homogeneous and certain peaks are not reached, the probability of the appearance of illnesses due to this particle decreases.

In terms of pollution exposure of vehicles, the more vehicles with pollution exposure-based routing there are, the pollution received by vehicles with standard routing is drastically reduced. So the agents with alternative routing are helping the agents with normal routing to become less polluted as shown in Fig. 6.17. In turn, with only 20% of vehicles with this pollution exposure-based routing, the pollution exposure of the whole system is already reduced by 15%.

The cost of achieving this homogeneity of NO_2 in the city is that journeys are around 13% slower, while the distance travelled is up to 7% longer.

On the other hand, in dense traffic scenarios, the routing behaviour due to pollution exposure varies too much. Thus, one thing to note is that, this routing means that vehicles following this routing tend to go on side streets more often. This means that in scenarios where traffic density is high and there are a large number of vehicles following this routing, some traffic congestion occurs as shown in Figure 6.27. At the same time, it is worth mentioning that the effectiveness in minimising pollution exposure in heavy traffic is reduced.

In view of the above, we conclude that routing based on pollution exposure is a type of alternative routing to be taken into account, as it offers multiple advantages for the city and for the drivers themselves in terms of pollution exposure.

7.3 Future Work

Although this thesis has covered a multitude of technologies, there is always room for improvement of the project. Thus, this section will detail future lines of research.

- On the one hand, it would be interesting to create a hybrid routing that is able to discern between following the route through a routing based on exposure to pollution or based on time. That is, depending on parameters such as the estimated time, the route taken, the estimated distance, the state of the network, etc., it could decide which routing to follow.

- On the other hand, a clear line of research would be the creation of a model of temporal and spatial dispersion of pollution. That is, the accumulation of pollution that occurs in the streets has an impact on nearby streets, as well as the temporal propagation of pollution also occurs.

- A clear improvement that could be made is to simulate on the map the whole of Madrid or a larger city and study the behaviour of the simulations in these cases. This has not been done partly because of the computational capacity required for simulations with large maps, but mainly because of the errors in the maps. Thus, the transformation that would have to be done to make the map of the whole of Madrid error-free would be an arduous task.

- Also, it would also be interesting to simulate scenarios based on real traffic, studying the variation of routing in different time zones and see how routing based on exposure to pollution can be affected.

- Finally, the inclusion of cyclists and pedestrians could also be carried out to see how they may be affected by pollution emitted on the network when routing based on pollution exposure. Thus, cyclists themselves could also be routed with our routing, thus reducing their exposure to pollution.

APPENDIX A

Evaluation Experiment 1

In this appendix, some graphs of interest regarding the simulation results and their analysis are shown.

A.1 Pollution

A.1.1 NO_2 distribution at the end of the simulation

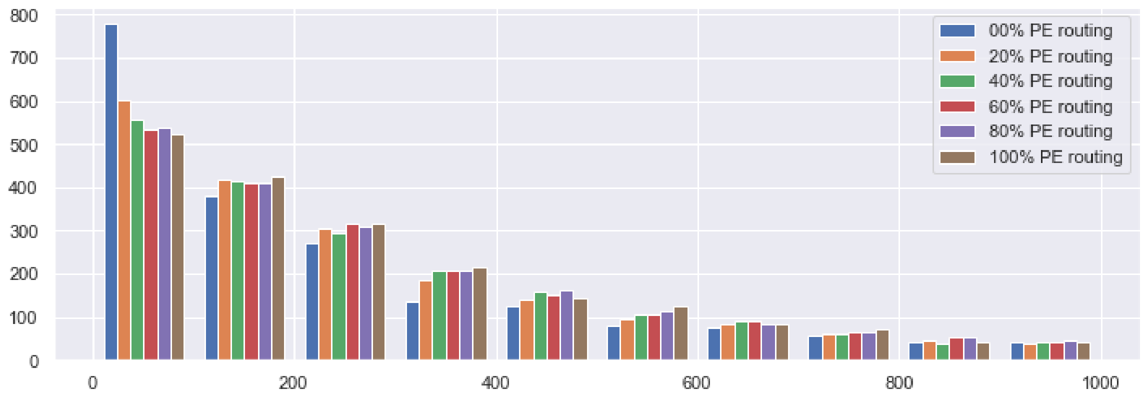


Figure A.1: Comparison of the evolution of NO_2 distribution at the end of the simulation with no window.

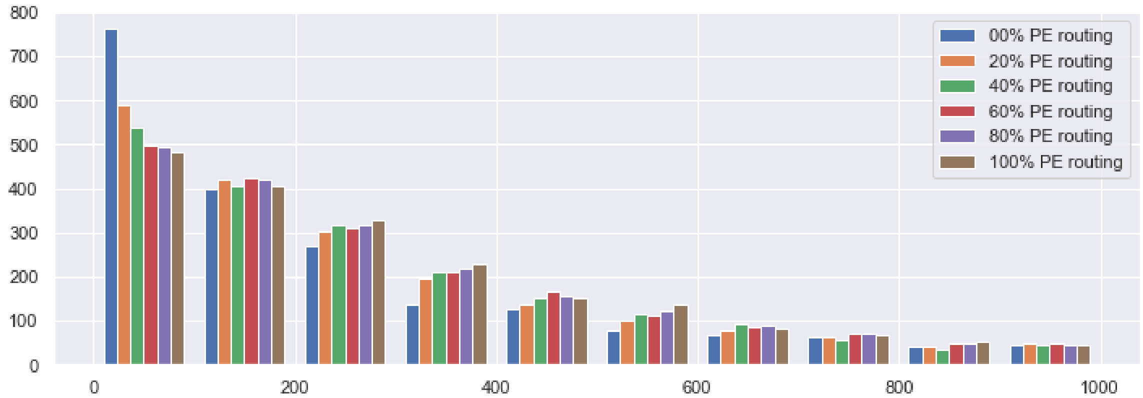


Figure A.2: Comparison of the evolution of NO_2 distribution at the end of the simulation with 1-hour window.

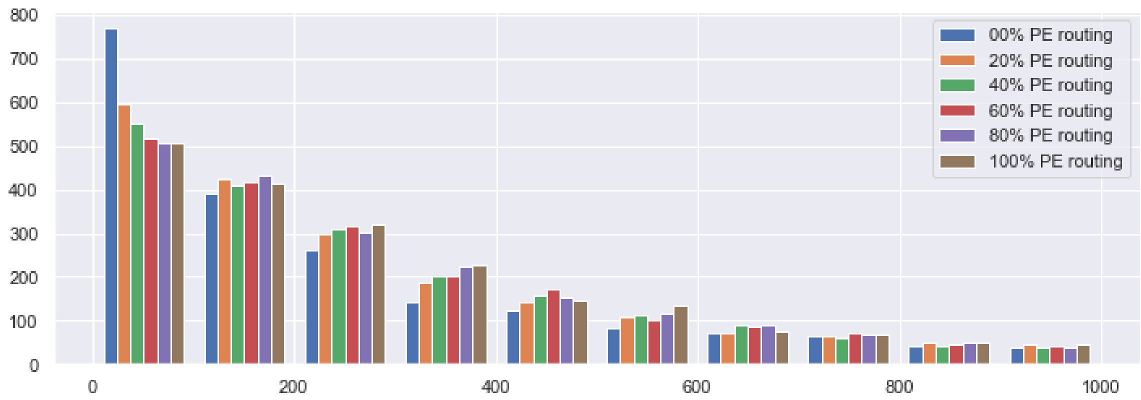


Figure A.3: Comparison of the evolution of NO_2 distribution at the end of the simulation with 2-hour window.

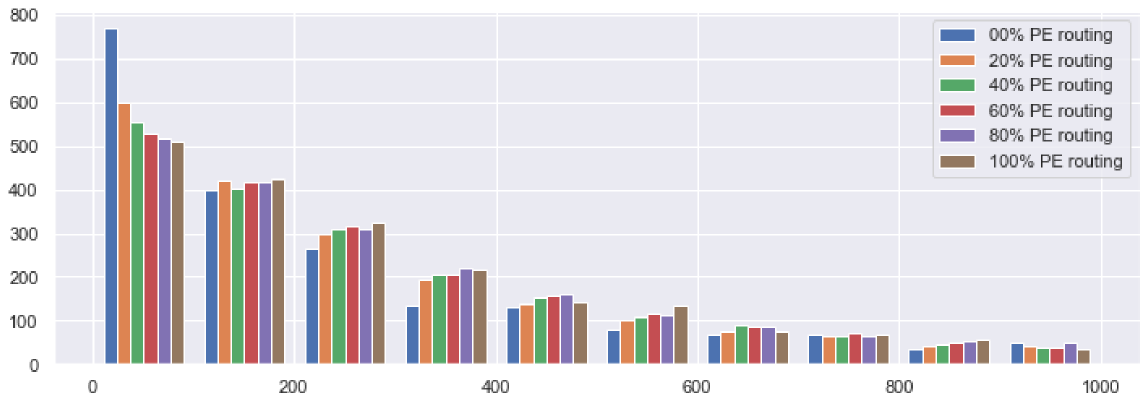


Figure A.4: Comparison of the evolution of NO_2 distribution at the end of the simulation with 3-hour window.

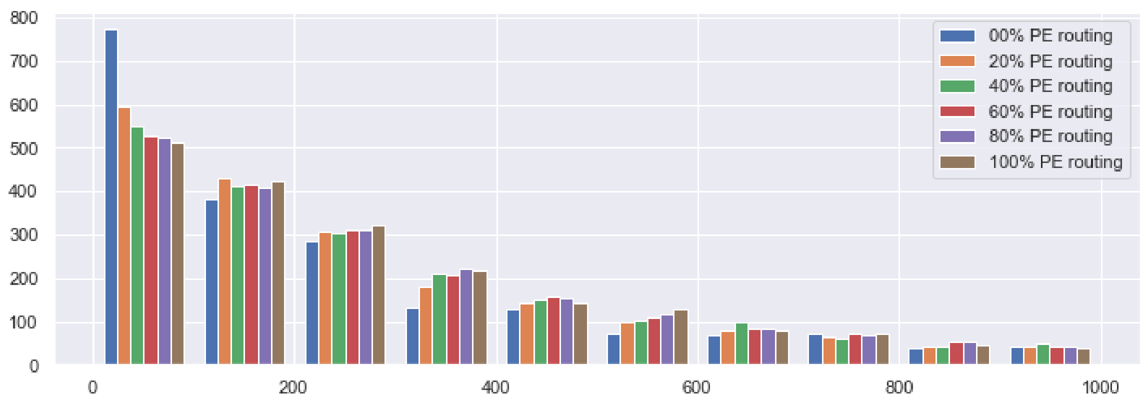


Figure A.5: Comparison of the evolution of NO_2 distribution at the end of the simulation with 4-hour window.

A.1.2 NO_2 emissions over time in different streets

- **Calle del Barco (A):**

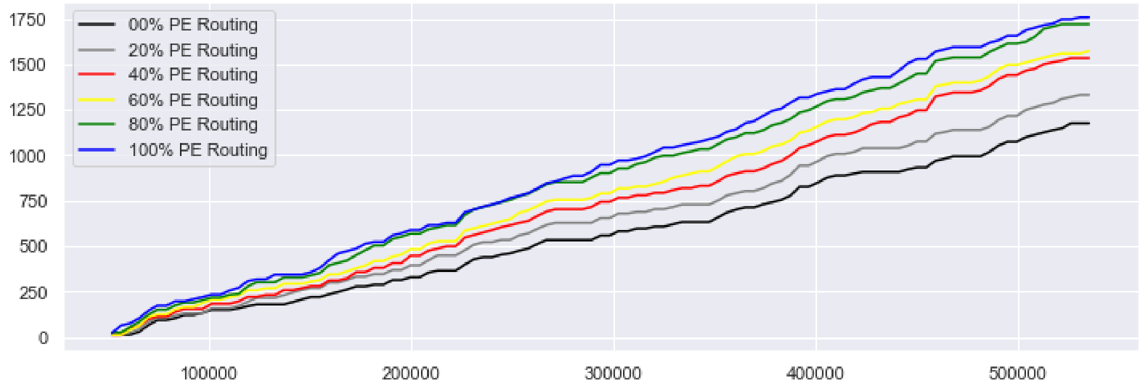


Figure A.6: Emitted NO_2 over time in Calle del Barco (A) with no window.

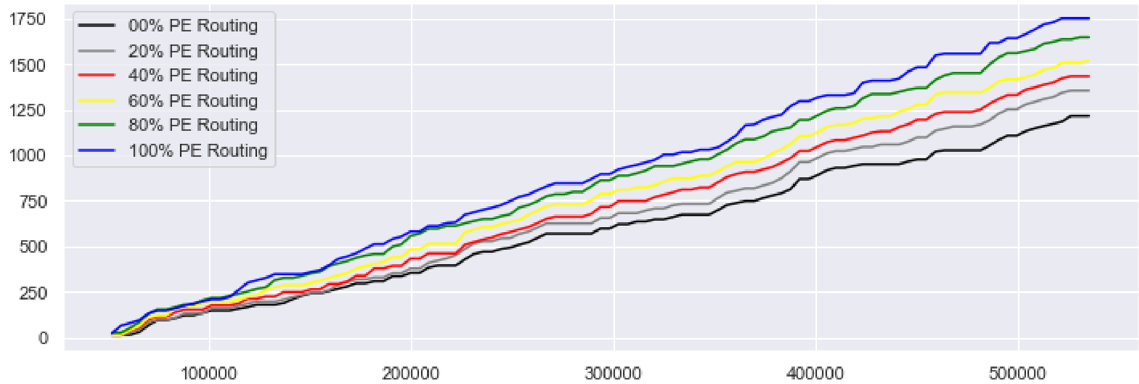


Figure A.7: Emitted NO_2 over time in Calle del Barco (A) with 1-hour window.

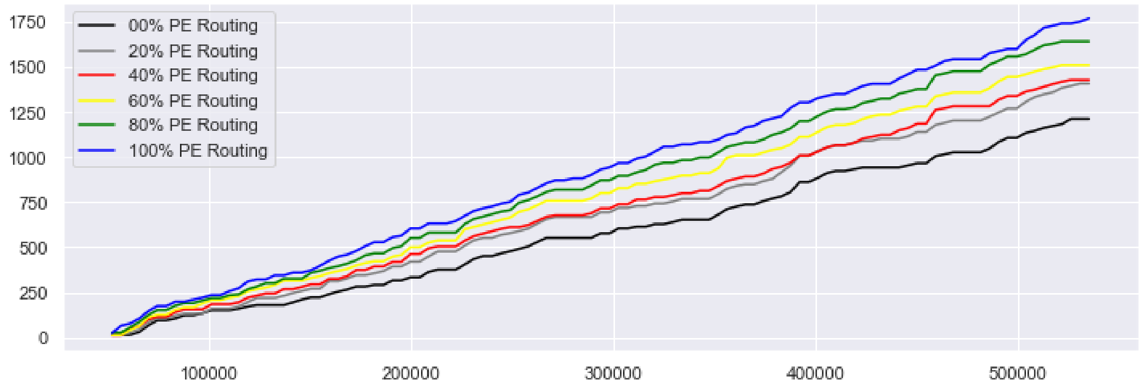


Figure A.8: Emitted NO_2 over time in Calle del Barco (A) with 2-hours window.

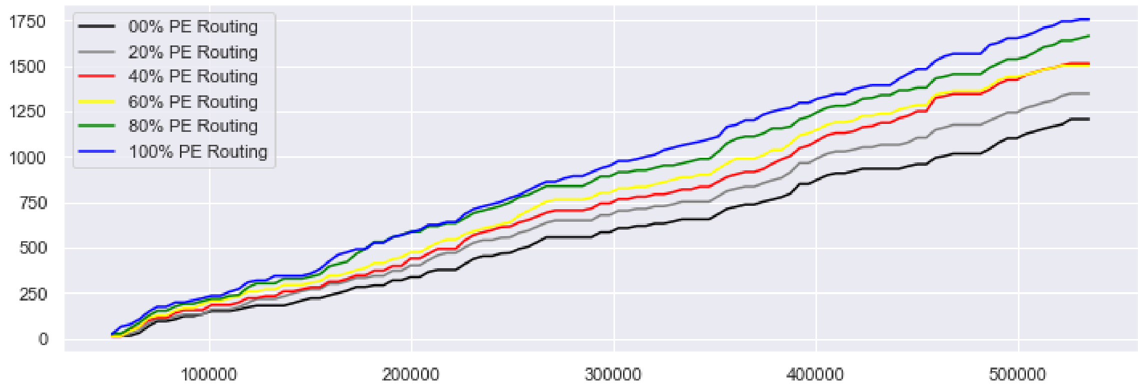


Figure A.9: Emitted NO_2 over time in Calle del Barco (A) with 3-hours window.

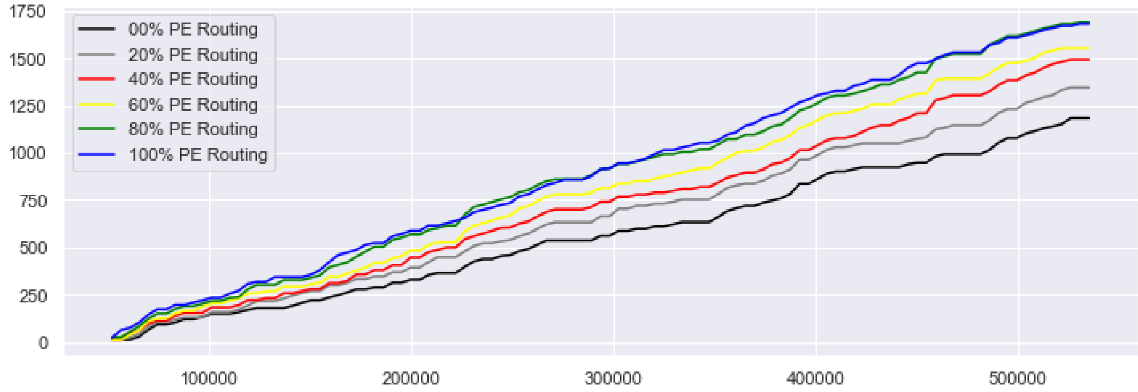


Figure A.10: Emitted NO_2 over time in Calle del Barco (A) with 4-hours window.

- **Calle de Gran Vía (B):**

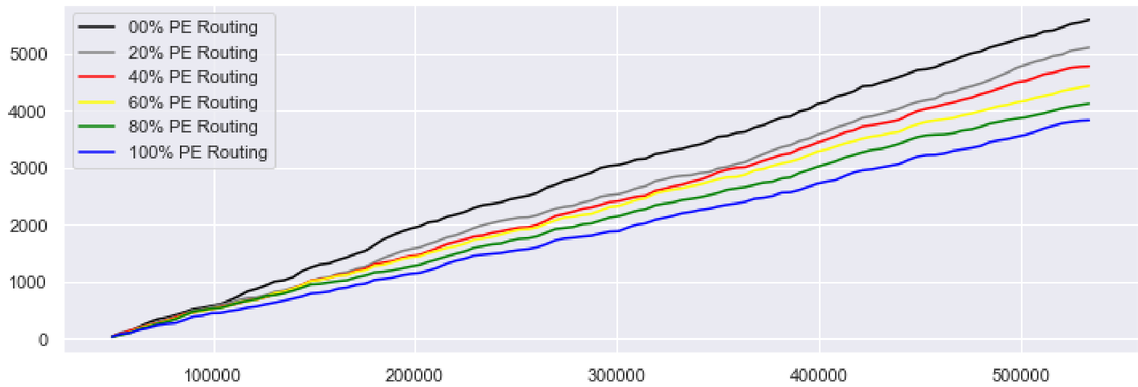


Figure A.11: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 1 with no window.

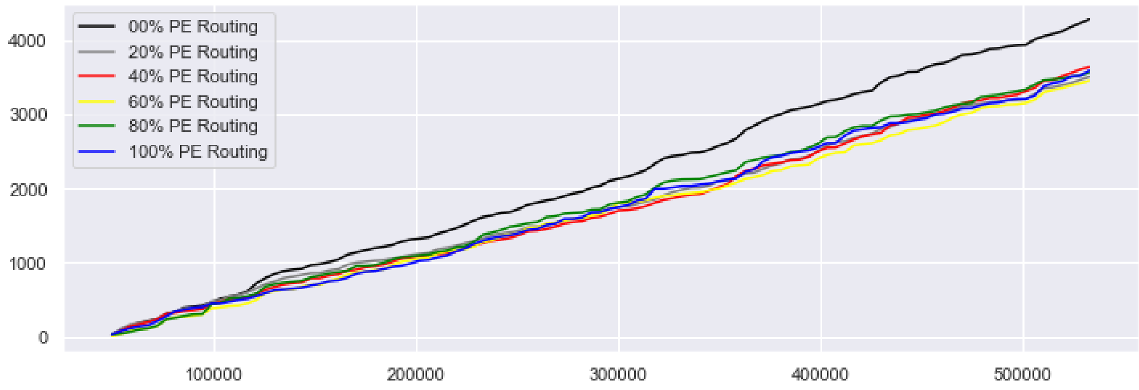


Figure A.12: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 2 with no window.

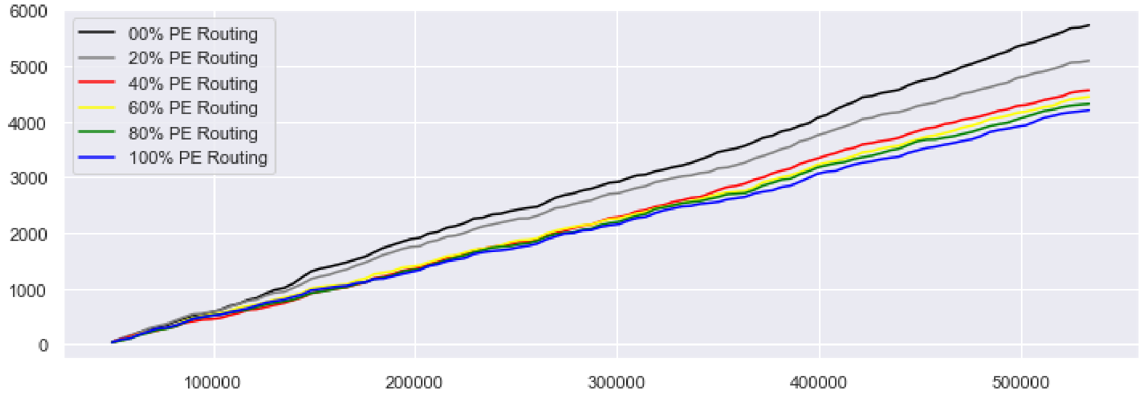


Figure A.13: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 1 with 1-hour window.

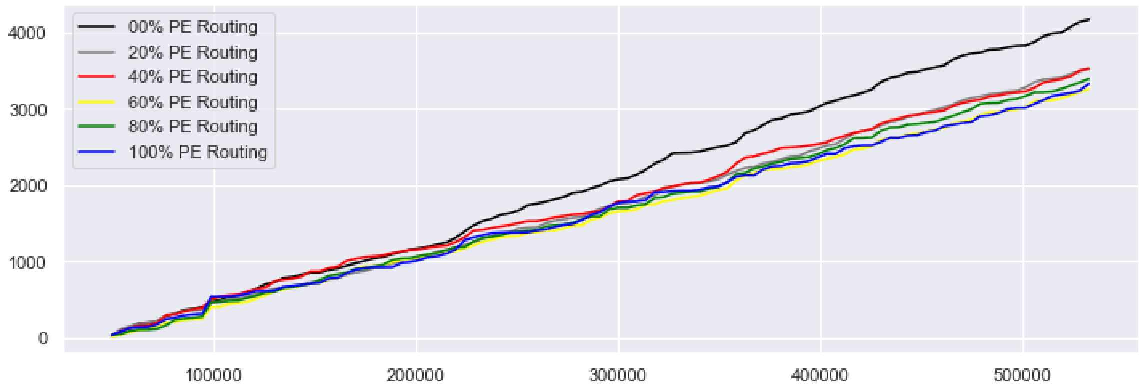


Figure A.14: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 2 with 1-hour window.

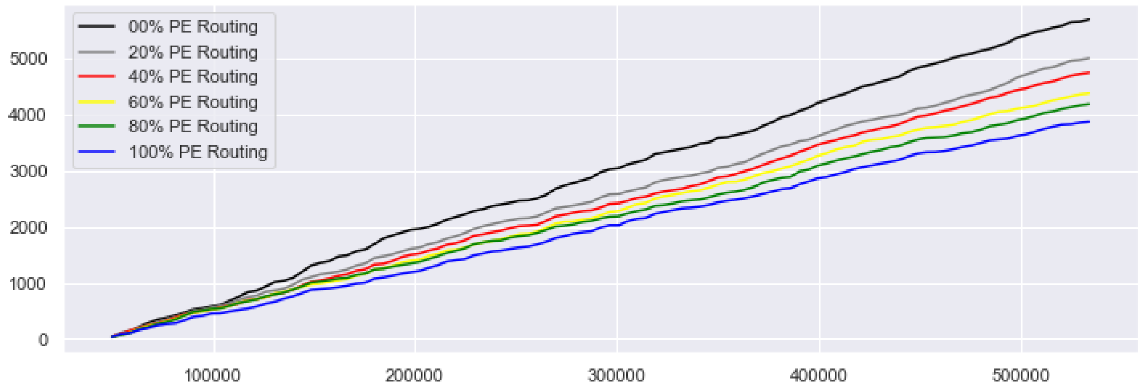


Figure A.15: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 1 with 2-hours window.

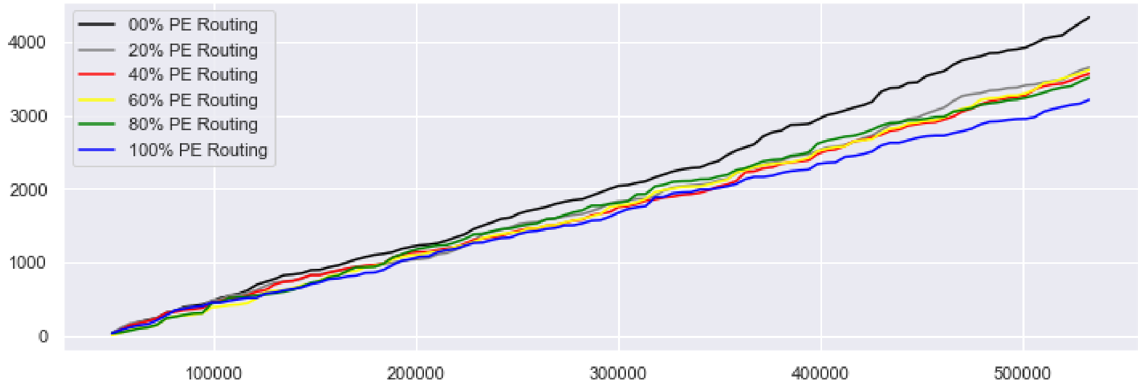


Figure A.16: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 2 with 2-hours window.

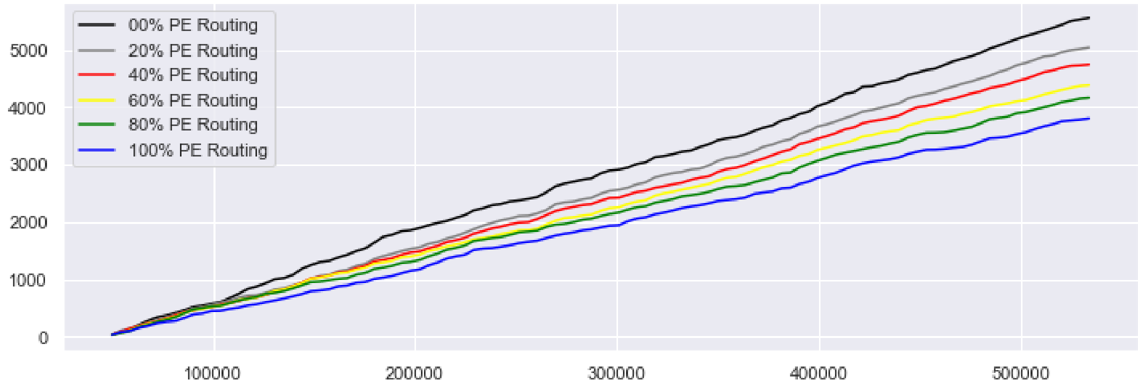


Figure A.17: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 1 with 3-hours window.

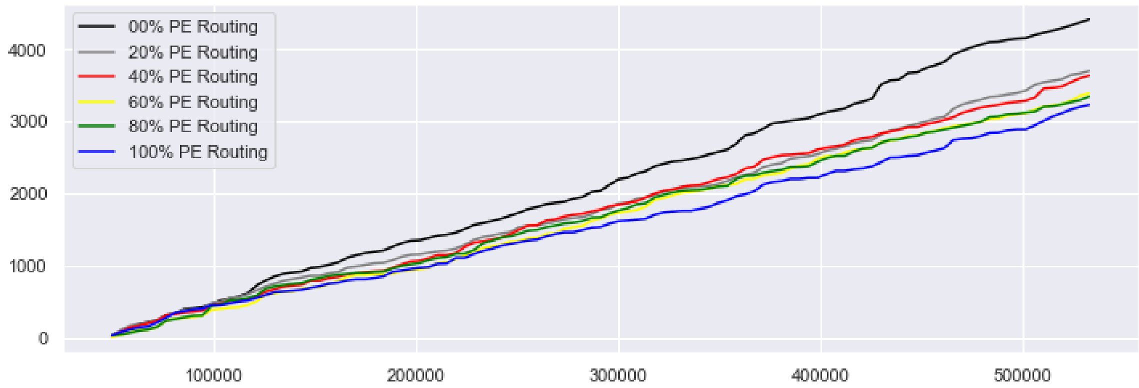


Figure A.18: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 2 with 3-hours window.

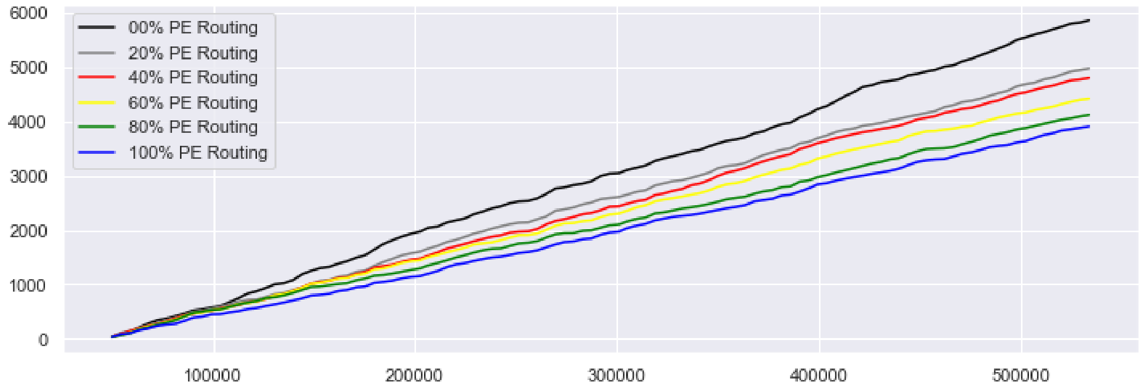


Figure A.19: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 1 with 4-hours window.

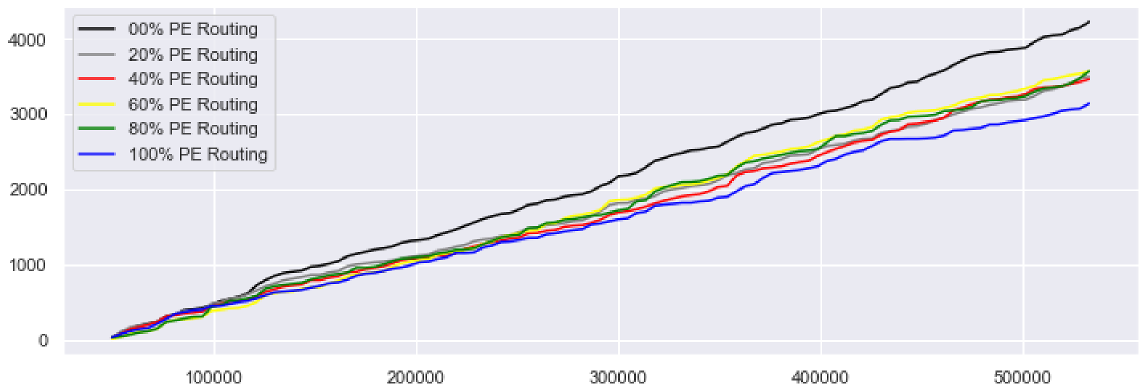


Figure A.20: Emitted NO_2 over time in Calle de Gran Vía (B) in direction 2 with 4-hours window.

A.2 Trips

A.2.1 Mean duration

Window	Agents with PE routing	Mean trip duration	Percentage over base scenario
0h	0%	249.54s	-
0h	20%	267.41s	7.16 %
0h	40%	276.87s	10.95 %
0h	60%	280.58s	12.44 %
0h	80%	281.46s	12.79 %
0h	100%	282.29s	13.12 %
1h	0%	250.32s	-
1h	20%	269.87s	7.81 %
1h	40%	278.91s	11.42 %
1h	60%	284.15s	13.52 %
1h	80%	287.62s	14.9 %
1h	100%	290.45s	16.03 %
2h	0%	250.48s	-
2h	20%	268.44s	7.17 %
2h	40%	277.47s	10.78 %
2h	60%	283.06s	13.01 %
2h	80%	284.18s	13.46 %
2h	100%	284.87s	13.73 %
3h	0%	250.3s	-

3h	20%	268.58s	7.3 %
3h	40%	277.45s	10.84 %
3h	60%	281.58s	12.5 %
3h	80%	283.89s	13.42 %
3h	100%	283.76s	13.37 %
4h	0%	249.73s	-
4h	20%	268.21s	7.4 %
4h	40%	277.44s	11.1 %
4h	60%	281.64s	12.78 %
4h	80%	283.0s	13.32 %
4h	100%	283.17s	13.39 %

Table A.1: Duration mean increase compared to the base scenario in each window.

A.2.2 Mean distance

Window	**Agents with PE routing**	**Mean trip duration**	**Percentage over 0% scenario**
0h	0%	2058.3m	-
0h	20%	2144.38m	4.18 %
0h	40%	2176.18m	5.73 %
0h	60%	2189.72m	6.38 %
0h	80%	2179.95m	5.91 %
0h	100%	2171.42m	5.5 %
1h	0%	2060.74m	-

1h	20%	2158.02m	4.72 %
1h	40%	2194.23m	6.48 %
1h	60%	2208.8m	7.18 %
1h	80%	2212.52m	7.37 %
1h	100%	2211.0m	7.29 %
2h	0%	2060.21m	-
2h	20%	2151.35m	4.42 %
2h	40%	2184.33m	6.02 %
2h	60%	2202.92m	6.93 %
2h	80%	2196.99m	6.64 %
2h	100%	2183.9m	6.0 %
3h	0%	2059.71m	-
3h	20%	2148.48m	4.31 %
3h	40%	2183.53m	6.01 %
3h	60%	2199.64m	6.79 %
3h	80%	2191.01m	6.38 %
3h	100%	2183.1m	5.99 %
4h	0%	2059.6m	-
4h	20%	2147.29m	4.26 %
4h	40%	2182.16m	5.95 %
4h	60%	2197.39m	6.69 %
4h	80%	2191.54m	6.41 %
4h	100%	2178.49m	5.77 %

Table A.2: Distance mean increase compared to the base scenario in each window.

A.2.3 Mean speed

Window	**Agentes with PE routing**	**Mean trip speed**	**Percentage over 0% scenario**
0h	0%	8.25m/s	-
0h	20%	8.02m/s	-2.78 %
0h	40%	7.86m/s	-4.71 %
0h	60%	7.8m/s	-5.38 %
0h	80%	7.75m/s	-6.1 %
0h	100%	7.69m/s	-6.74 %
1h	0%	8.23m/s	-
1h	20%	8.0m/s	-2.87 %
1h	40%	7.87m/s	-4.44 %
1h	60%	7.77m/s	-5.58 %
1h	80%	7.69m/s	-6.56 %
1h	100%	7.61m/s	-7.53 %
2h	0%	8.23m/s	-
2h	20%	8.01m/s	-2.57 %
2h	40%	7.87m/s	-4.29 %
2h	60%	7.78m/s	-5.38 %
2h	80%	7.73m/s	-6.01 %
2h	100%	7.67m/s	-6.8 %

3h	0%	8.23m/s	-
3h	20%	8.0m/s	-2.79 %
3h	40%	7.87m/s	-4.36 %
3h	60%	7.81m/s	-5.07 %
3h	80%	7.72m/s	-6.21 %
3h	100%	7.69m/s	-6.51 %
4h	0%	8.25m/s	-
4h	20%	8.01m/s	-2.93 %
4h	40%	7.87m/s	-4.63 %
4h	60%	7.8m/s	-5.4 %
4h	80%	7.74m/s	-6.1 %
4h	100%	7.69m/s	-6.72 %

Table A.3: Speed mean increase compared to the base scenario in each window.

A.2.4 Comparison of flows: trips

Window	**Agentes with PE routing**	**Mean duration time routing**	**Mean duration PE routing**	**Difference in percentage**
0h	0%	382.15s	451.0s	18.02%
0h	20%	379.02s	458.92s	21.08%
0h	40%	374.76s	465.56s	24.23%
0h	60%	374.54s	463.73s	23.81%
0h	80%	374.85s	468.58s	25.0%
0h	100%	373.42s	464.0s	24.26%

1h	0%	382.42s	514.02s	34.41%
1h	20%	381.07s	466.27s	22.36%
1h	40%	375.07s	466.41s	24.35%
1h	60%	377.25s	469.12s	24.35%
1h	80%	369.95s	472.46s	27.71%
1h	100%	372.75s	467.42s	25.4%
2h	0%	381.61s	498.1s	30.53%
2h	20%	379.12s	464.69s	22.57%
2h	40%	374.05s	464.41s	24.16%
2h	60%	372.83s	461.42s	23.76%
2h	80%	370.08s	458.93s	24.01%
2h	100%	375.02s	464.34s	23.82%
3h	0%	382.15s	487.41s	27.54%
3h	20%	379.46s	465.17s	22.59%
3h	40%	376.03s	464.39s	23.5%
3h	60%	371.54s	469.93s	26.48%
3h	80%	372.1s	466.24s	25.3%
3h	100%	373.85s	461.53s	23.45%
4h	0%	383.19s	470.93s	22.9%
4h	20%	376.92s	466.81s	23.85%
4h	40%	379.05s	464.15s	22.45%
4h	60%	373.54s	463.37s	24.05%
4h	80%	372.66s	458.88s	23.14%

4h	100%	372.22s	458.02s	23.05%

Table A.4: Average duration [s] taken for the flow to travel from A to B in the 30 scenarios

Window	**Agentes with PE routing**	**Mean distance time routing**	**Mean distance PE routing**	**Difference in percentage**
0h	0%	3589.4m	4419.01m	23.11%
0h	20%	3583.46m	4439.52m	23.89%
0h	40%	3583.82m	4454.72m	24.3%
0h	60%	3583.78m	4445.6m	24.05%
0h	80%	3583.46m	4436.3m	23.8%
0h	100%	3583.5m	4434.63m	23.75%
1h	0%	3583.7m	4602.82m	28.44%
1h	20%	3583.5m	4475.92m	24.9%
1h	40%	3583.62m	4452.92m	24.26%
1h	60%	3583.62m	4470.26m	24.74%
1h	80%	3583.58m	4481.95m	25.07%
1h	100%	3583.58m	4449.08m	24.15%
2h	0%	3583.42m	4556.7m	27.16%
2h	20%	3583.7m	4451.73m	24.22%
2h	40%	3583.66m	4446.72m	24.08%
2h	60%	3583.66m	4449.32m	24.16%
2h	80%	3583.7m	4435.75m	23.78%
2h	100%	3583.54m	4451.41m	24.22%

3h	0%	3583.46m	4494.65m	25.43%
3h	20%	3583.7m	4450.78m	24.2%
3h	40%	3583.9m	4460.87m	24.47%
3h	60%	3583.62m	4446.38m	24.08%
3h	80%	3583.74m	4447.58m	24.1%
3h	100%	3583.7m	4436.59m	23.8%
4h	0%	3583.54m	4486.91m	25.21%
4h	20%	3583.5m	4449.51m	24.17%
4h	40%	3589.52m	4449.55m	23.96%
4h	60%	3583.74m	4440.44m	23.91%
4h	80%	3583.78m	4434.93m	23.75%
4h	100%	3583.58m	4443.95m	24.01%

Table A.5: Average distance [m] taken for the flow to travel from A to B in the 30 scenarios

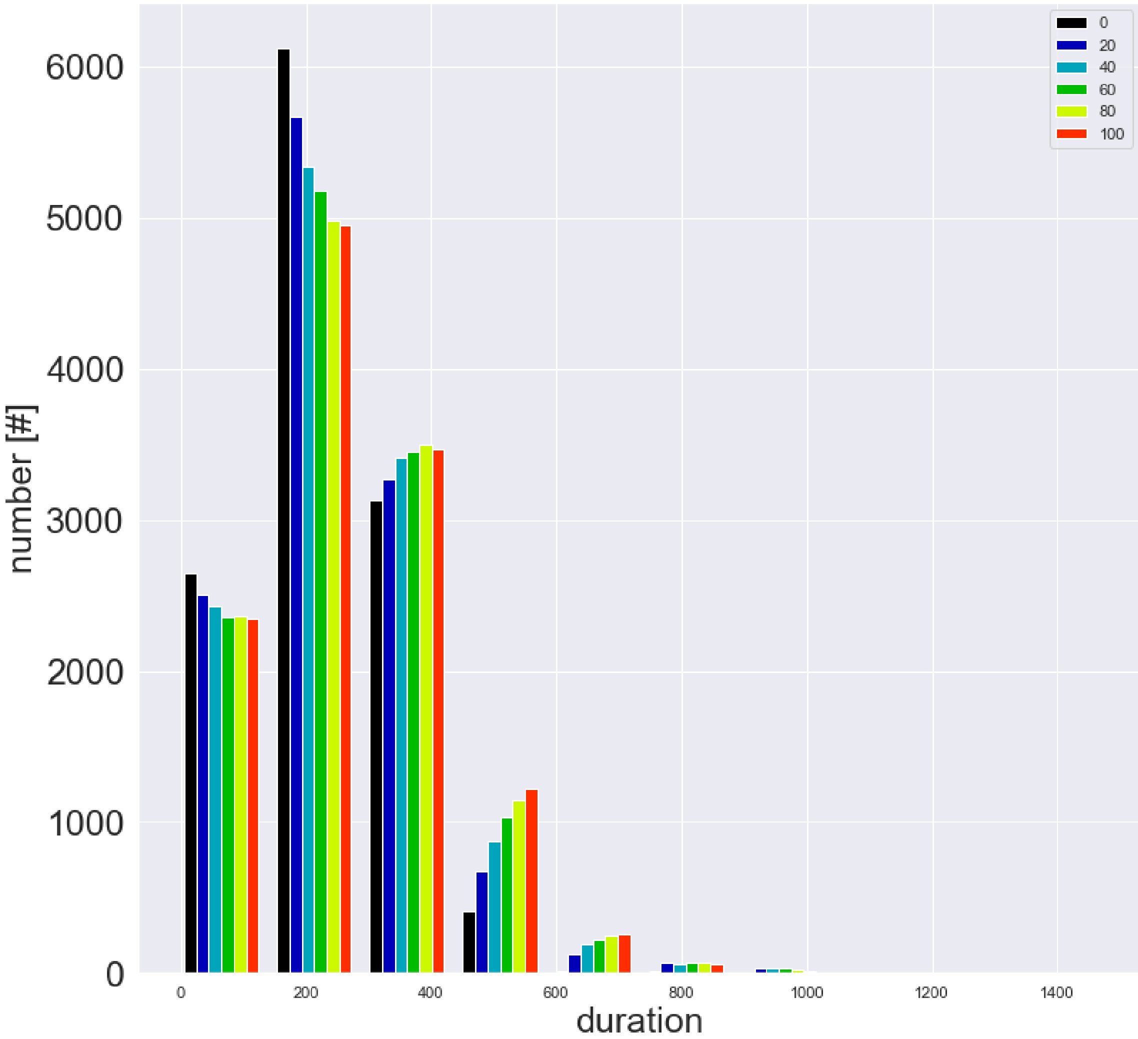


Figure A.21: Distribution of flow durations by scenario for 2-hours window,.

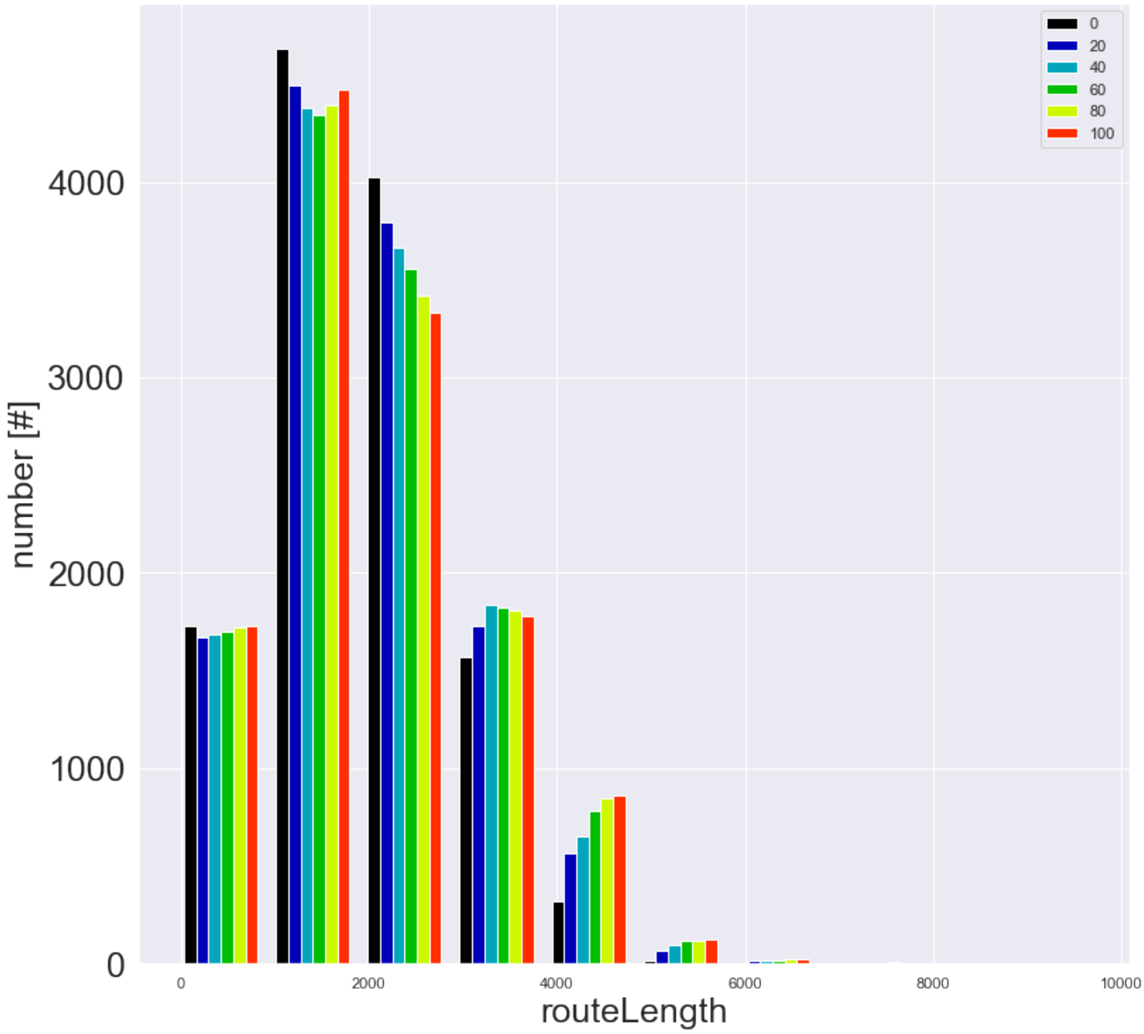


Figure A.22: Distribution of flow route lenghts by scenario for 2-hours window,.

A.3 Pollution exposure

A.3.1 Average pollution exposure

Window	Agentes with PE routing	Mean Time time routing	Mean time PE routing
0h	0%	61230.38g	-
0h	20%	51881.78g	-15.27%
0h	40%	46798.97g	-23.57%

0h	60%	43619.2g	-28.76%
0h	80%	41922.53g	-31.53%
0h	100%	40956.56g	-33.11%
1h	0%	8813.51g	-
1h	20%	7424.81g	-15.76%
1h	40%	6662.45g	-24.41%
1h	60%	6177.24g	-29.91%
1h	80%	5884.76g	-33.23%
1h	100%	5707.47g	-35.24%
2h	0%	17601.74g	-
2h	20%	14821.41g	-15.8%
2h	40%	13339.92g	-24.21%
2h	60%	12322.01g	-30.0%
2h	80%	11788.63g	-33.03%
2h	100%	11471.36g	-34.83%
3h	0%	26375.32g	-
3h	20%	22234.12g	-15.7%
3h	40%	20040.05g	-24.02%
3h	60%	18521.02g	-29.78%
3h	80%	17732.9g	-32.77%
3h	100%	17232.11g	-34.67%
4h	0%	35075.44g	-
4h	20%	29657.08g	-15.45%

4h	40%	26770.91g	-23.68%
4h	60%	24742.69g	-29.46%
4h	80%	23689.43g	-32.46%
4h	100%	23006.79g	-34.41%

Table A.6: Mean pollution exposure values in the 30 scenarios.

A.3.2 Comparison of flows: pollution exposure

Window	Agents with PE Routing	Mean pollution exposure with time routing	Mean pollution exposure with PE routing	Difference in percentage
0h	0%	188206.14g	46401.83g	-405.6%
0h	20%	162160.44g	55964.35g	-289.76%
0h	40%	138738.26g	61754.48g	-224.66%
0h	60%	114181.44g	66728.14g	-171.11%
0h	80%	99328.42g	69111.45g	-143.72%
0h	100%	90364.71g	70169.24g	-128.78%
1h	0%	26881.2g	6275.7g	-428.34%
1h	20%	22675.19g	7771.55g	-291.77%
1h	40%	19504.81g	8468.5g	-230.32%
1h	60%	16186.09g	9127.42g	-177.33%
1h	80%	14003.92g	9448.05g	-148.22%
1h	100%	12917.06g	9515.72g	-135.74%
2h	0%	54005.48g	12850.93g	-420.25%

2h	20%	45766.27g	15735.01g	-290.86%
2h	40%	39263.72g	17298.29g	-226.98%
2h	60%	31875.63g	18708.21g	-170.38%
2h	80%	27789.88g	19375.64g	-143.43%
2h	100%	25806.11g	19685.69g	-131.09%
3h	0%	81567.79g	19532.85g	-417.59%
3h	20%	69067.44g	23828.85g	-289.85%
3h	40%	59472.36g	26262.6g	-226.45%
3h	60%	48207.04g	28160.64g	-171.19%
3h	80%	41991.32g	29259.76g	-143.51%
3h	100%	38613.83g	29562.36g	-130.62%
4h	0%	108724.81g	26496.44g	-410.34%
4h	20%	92850.07g	31986.44g	-290.28%
4h	40%	79049.41g	35248.76g	-224.26%
4h	60%	64716.12g	37703.74g	-171.64%
4h	80%	56105.74g	38964.5g	-143.99%
4h	100%	51373.18g	39657.35g	-129.54%

Table A.7: Evolution of the pollution exposure in both flows in the 30 scenarios.

APPENDIX B

Project Impact

This appendix will discuss the social, economic, environmental and ethical impact of this project, going into detail in each of the sections.

B.1 Context

This project has been developed at the Cabify Chair of the Escuela Técnica Superior de Ingenieros de la Telecomunicación (ETSIT) at Universidad Politécnica de Madrid (UPM) in collaboration with the Intelligent System Group (GSI) of the Department of Telematic Systems Engineering (DIT) of the same school.

The idea of carrying out this project is in line with Cabify's objectives as a company, which are to improve sustainability in cities, improving mobility and reinventing it, making it sustainable, accessible and efficient.

The following sections will cover the different types of impact of the project.

B.2 Social Impact

The social impact is partly related to the environmental impact, since having a city with more homogenised pollution and without pollution peaks can have effects on people's health.

Thus, as we have seen, NO_2 is a particle that is quite harmful to health and can cause itchy eyes, nose and throat, as well as irritation of the bronchial tubes with coughing, phlegm and difficulty breathing and even death in exceptional cases. Thanks to routing based on exposure to pollution, the inhalation of NO_2 is reduced, which decreases the chances of catching a NO_2-induced disease.

In turn, this project can cause a raising awareness which would affect the way people move through a city, opening up a new paradigm in which the priority is not to minimise distance or time, but to prioritise people's health.

B.3 Economic Impact

In terms of economic impact, there is no major advantage or disadvantage to this project. We would simply like to mention that if alternative routing for pollution exposure were to be implemented in different routing applications, this could lead to increased profits for the company developing the application because it could attract a larger number of users.

B.4 Environmental Impact

The environmental impact of this project is very important as it affects the environmental pollution of the city. That is, thanks to the routing by pollution exposure, a greater homogeneity in the pollution map of a city is achieved. As a consequence, pollution peaks are not reached in some main streets. Thus, secondary streets with low concentrations would see an increase in the amount of pollution, but main streets with high emissions would see a decrease in pollution concentration, so it would be regulated.

On the other hand, as we have seen, total system pollution is increased as a result of generally taking longer routes, and although exposure to this pollutant decreases as we move around, it is something to consider.

Finally, to make possible the development of our project and run all simulations, it is necessary to have specialized equipment such as computers, servers, and other computer materials, which need energy to run. As a consequence, this could produce a huge charge on our electricity networks and, at the end, contributing to greenhouse gas emission.

B.5 Ethical Impact

Finally, as far as the ethical impact of this project is concerned, there is nothing to mention. We have not used personal data which could cause impact related with privacy, and there is not any ethic conflict which could be caused by this project.

APPENDIX C

Project Budget

In this appendix we will detail the economic budget for the realization of this project. The main parts of this budget will be explained in the following sections.

C.1 Project structure

First of all, we will present the structure of the project. In this way we will have an idea of the hours that have been invested to carry out the project and the time it has taken to do it. In total 180 days (36 weeks) have been spent, at an average of 5 hours per day. This makes about 900 hours in total.

Activity	**Duration (days)**
Searching for related articles and the technology available	15
Learning the tools and techniques available	15
Development of initial architecture	8
Map transformation	8
Searching for other lines of research	5
Development of agents, detectors and main parts of simulation	6
Deployment and Analysis of 1st generation of simulations	14
Deployment and Analysis of 2nd generation of simulations	14
Deployment and Analysis of 3rd generation of simulations	10
Deployment and Analysis of 4th generation of simulations	15
Deployment of final generation of simulations	25
Comprehensive analysis of final generation of simulations	15
Report writing	30
Total	**180**

Table C.1: Project structure by activity

C.2 Physical Resources

In order to carry out this project, a high computational capacity has been required to support agent-based simulations with a multitude of agents and large scenarios, handling a large amount of data produced during the simulation. Thus, the resources can be divided into two: software and hardware.

- **Software:** This part includes everything related to the software tools necessary for the development of the project. The software is mainly composed of SUMO, its tools, TraCI and Jupyter Notebook. All of them are Open Source Software (OSS), which means that they are free and there is no need to pay for their use.

- **Hardware:** With regards to the hardware necessary for the development of this project, it has been mainly a computer whose characteristics are:

  - *RAM:* 16 GB
  - *CPU:* Intel Core i7, 2,5 Ghz x 4
  - *Hard disk:* 500 GB

Thus, the approximate cost of a computer with the above characteristics is about 1,000€.

C.3 Human Resources

In this section, we will detail the part of the budget that consists of the cost of the human resources. This project has been carried out by one person with a salary of 550€ per month. As the duration of the project has been approximately 8 months, the total cost has been 4,400€.

C.4 Indirect Costs

On the other hand, there are indirect costs that also need to be taken into account. These include both electricity and internet connection.

- **Internet:** Internet connection in Spain costs approximately €30 per month, guaranteeing about 100 Mbps. This internet connection has not been used only by us, so we will estimate that 10% of it corresponds to this project. Thus, finally, this is about 24€for the whole project

- **Electricity:** In Spain, the price of electricity is approximately €0.118 per kilowatt. 900 hours have been spent on this project, but the computer has been consuming more hours while doing the simulations, the estimated running time is approximately 1500 hours. A computer consumes on average 300 watts per hour. So the total cost is approximately 53€.

C.5 Taxes

As far as taxes are concerned, it should be noted that they are included in all the prices described above. However, it is important to emphasise how much of the investment has been in taxes. Thus, with regard to the computer, Internet connection and electricity, 21% is applied, while for the salary it is approximately 10% as it is a research grant from the Cabify Chair itself.

C.6 Conclusion

This project has a **duration of 900 hours** with a **total cost of 5,477€**.

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