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Optimized Design of Low Emission Zones in SUMO: A Dual Focus on Emissions Reduction and Travel Time Improvement

Alvaro Paricio-Garcia[1]*, Miguel A. Lopez-Carmona[1], Pablo Manglano-Redondo[1]

[1]Universidad de Alcala, Alcala de Henares, 28805, Madrid, Spain

*Correspondence: Alvaro Paricio-Garcia, alvaro.paricio@uah.es

Abstract: Focusing on the critical challenge of air pollution in urban areas, primarily caused by vehicular emissions, this study proposes an innovative process for Low Emission Zones (LEZ) design within the Simulation of Urban Mobility (SUMO) framework. Our primary focus is on enhancing urban mobility through the strategic design of LEZs, while simultaneously maintaining or even improving emission levels. The novel aspect of the approach lies in the use of LEZs with minimal geometric boundaries, strategically designed to balance the reduction of CO_2 emissions and the necessity of fluid urban transportation. LEZs are calculated using genetic algorithms that optimize a cost function balancing emissions and travel time while applying topological and specific constraints. Several experiments are simulated with SUMO to compare the efficiency of urban mobility under various LEZ configurations and different traffic demands. The results show the improvement of the approach in comparison with traditional LEZ design methodologies. The proposal not only preserves or even reduces the emission levels, but also actively improves urban mobility and traffic flow. This empirical evidence strongly supports the feasibility and effectiveness of the proposed solution in different urban scenarios. The design of the heuristic enables the possibility to create dynamic LEZs that may be changed depending on demand, weather, or any other varying conditions that affect traffic and emissions, preserving the mobility concerns of the users.

Keywords: Low Emission Zone, Urban Mobility, Transport Policy

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1 Introduction

In relation to the urban landscapes of our days, air pollution has become a pressing challenge [1] that hinders the sustainability and well-being of urban communities [2]. A significant contributor to this dilemma is the high emission of pollutants from vehicles that traverse the city street network [3]. The harmful effects of urban air pollution on public health, the environment, and the overall quality of urban life are undeniable, calling for an urgent call for innovative solutions.

Our research seeks to lead a forward-thinking approach that mitigates the adverse impacts of air pollution while optimizing urban mobility. Urban areas around the world are at a crossroads, grappling with the dual challenges of accommodating a growing population and the relentless march of urbanization [4]. As a result, the intricacies of urban mobility have become increasingly complex, demanding creative and sustainable solutions. Our research is motivated by the desire to find a balance between two seemingly conflicting goals: reducing air pollution caused by vehicle emissions and maintaining the flow and efficiency of urban transportation systems.

LEZs are areas where the most polluting vehicles are restricted to improve the air quality. This methodology is original from Sweden, which implemented environmental zones in 1996 [5]. Due to the observed results obtained after their first implementations, LEZs have been adopted by other European countries, with increasing recognition of their effectiveness in the EU Air Quality Standards [6].

The implementation of LEZ has a direct impact on mobility, as new constraints are added to the network and new routes must be considered. This situation may affect the user and system equilibrium as the travel times change considering the existing demands. LEZ implementation can be either static or dynamic by means of street/road signalling, taking into account the pollutant emissions values. As long as the emission levels are dynamically measured and/or forecasted, the LEZ shape may also be redesigned, considering the minimal impacts in travel times, while bounding the required emission rates.

SUMO [7] is an open-source microscopic and continuous traffic simulation environment, which is designed to handle large road networks. Although SUMO does not provide a native LEZ design module, its modular and flexible design allows the building of an external LEZ management module. This research focuses on the implementation and optimization of LEZs in SUMO.

We introduce a novel element in the LEZ domain through a new module integrated within the SUMO framework. This link of advanced technology and urban planning principles seeks to redefine the conventional approach to LEZ design. Our goal is to create LEZs with minimal geometric boundaries to achieve the required emission levels, taking full advantage of the SUMO framework's capabilities.

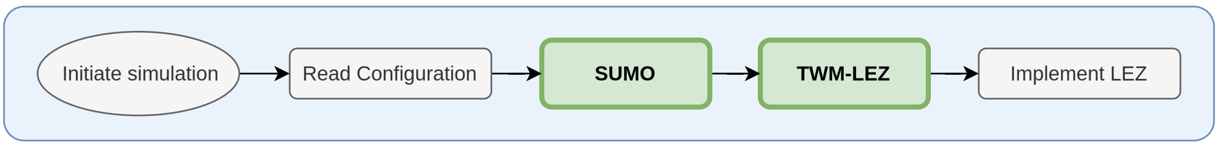


Figure 1. *Workflow of the optimization process.*

The LEZ module, referred to as TWM-LEZ, is part of the larger Traffic Weighted Multimaps (TWM) [8], [9] project which aims to enable differential traffic routing through traffic network multimaps. TWM-LEZ operates within the overarching traffic simulation framework in collaboration with SUMO to design and optimize LEZs. Following the simulation and data collection process by SUMO, TWM-LEZ applies specific constraints and employs a genetic algorithm to address optimization challenges. This involves selecting edges for optimal LEZ placement based on emissions and travel time. Establishing defined criteria is crucial for strategically locating and managing LEZs

In this work, we undertake a comprehensive exploration of the feasibility and efficiency of our approach. We present a series of experiments and robust data analysis to support our claims with evidence. Our results validate the potential of optimized LEZs (O-LEZ) against standard LEZs (S-LEZ) and underscore their advantage preserving, improving urban mobility and traffic flow, and contributing to the critical cause of contaminant emission reduction that can be seen in Figure 10, Section 5.

The experimental results are developed using a medium-sized Spanish city, Guadalajara[10], which is a Spanish provincial capital close to Madrid. This city has an autonomous service structure suitable for full activity-based traffic models (ABM) [11]. The historic core serves as the foundation for the development of a new LEZ configuration. In order to optimize Guadalajara LEZ and validate the results obtained, several simulations are carried out using the same demand matrix and various network configurations, thereby obtaining the corresponding heat maps, which represent emission volumes that allow the observation of the redistribution of traffic and the associated emissions. Additionally, using the additional files export options of SUMO, contrast graphs have been elaborated, showing the emissions obtained under the same demand conditions varying the restricted TAZ.

The main contributions of this work include:

- A formulation model oriented to LEZ optimization.
- Simulation studies on a real scenario in order to demonstrate the improvement made between S-LEZs and O-LEZs.
- Analytical validation methods to contrast the improvement obtained using O-LEZs

The structure of the study covers a total of six sections. In Section 2 reviews related literature and sets the theoretical framework for our research; Section 3 describes the methodology, including the design and integration of O-LEZs into SUMO; Section 4 details the experiments conducted and data analysis; Section 5 discusses the results and their implication for urban mobility and transportation policy; and Section 6 concludes the report, summarizing the findings and future research lines.

2 Related Works

The potential of geofencing in reducing emissions and energy consumption within predefined urban zones has been extensively explored by [12]. This work utilizes SUMO, a comprehensive traffic simulation tool, to model vehicle movements and traffic flows in Brighton and Hove, UK. The study includes the setup and calibration of SUMO to accurately represent various traffic elements such as bus routes, vehicle movements, traffic lights, and bus stops. A pilot trial with a fleet of taxi drivers in Brighton demonstrated the practical application of geofencing technology, employing specialized geofence apps and driver dashboards for real-time operational feedback. Preliminary results showed promising reductions in emissions within geofenced zones, with NOx emissions decreasing by approximately 10% and PMx emissions by 23%.

Several notable studies on LEZs and their environmental impacts warrant attention. [13] projects the environmental outcomes of implementing an LEZ in Warsaw, Poland, highlighting significant air quality improvements. Similarly, [14] evaluates the London ultra-low emission zone (uLEZ) through state-space modeling, revealing tangible air quality enhancements. Research by [15] provides a comprehensive analysis of the broader effects of LEZs on urban pollution and congestion. [16] examines the influence of urban LEZs on individual and organizational behavior from a behavioral operations management perspective. Additionally, [17] assesses hypothetical LEZ scenarios in Greater Paris, emphasizing the exposure reduction and the health benefits.

Many studies, including those within the iTETRIS project [18], leverage SUMO for contaminant emissions and travel time optimization, expanding its functionalities for noise, pollutant emissions, and fuel consumption modeling. Connectivity is crucial for urban mobility, as demonstrated by [19] with the introduction of LiDaSim, a simulation framework designed for ITS-G5 protocol stack VANETs. [20] provides an overview of the SUMO suite, highlighting research topics such as vehicular communication [21], route choice and dynamic navigation [22], traffic light algorithms [23], and traffic surveillance systems [24]. A systematic literature review of SUMO's first decade is available in [25], offering insights into research trends and statistics.

Regarding traffic emission research, [26] addresses pollution awareness through a traffic flow estimation approach implemented in Zaragoza, Spain, using SUMO, real city roadmaps and traffic data. The study evaluates various simulation strategies and trajectory generation techniques to regulate traffic patterns effectively.

3 Design of Optimal Urban LEZ

The optimization problem consists in designing and implementing a LEZ with minimum geometry, which is achieved by selecting as few edges as possible, favorable for urban mobility and capable of reducing emissions according to current regulations [27]. To achieve this reduction, a weighted sum between emissions and travel times is made, thus selecting those edges whose emissions and congestion are higher.

This section provides an optimization strategy based on removing the most polluting and congested edges of the net. Edges are compared to the rest of the network, and based on the constraints applied to emissions, urban mobility and localization criteria, the edges are chosen for the O-LEZ.

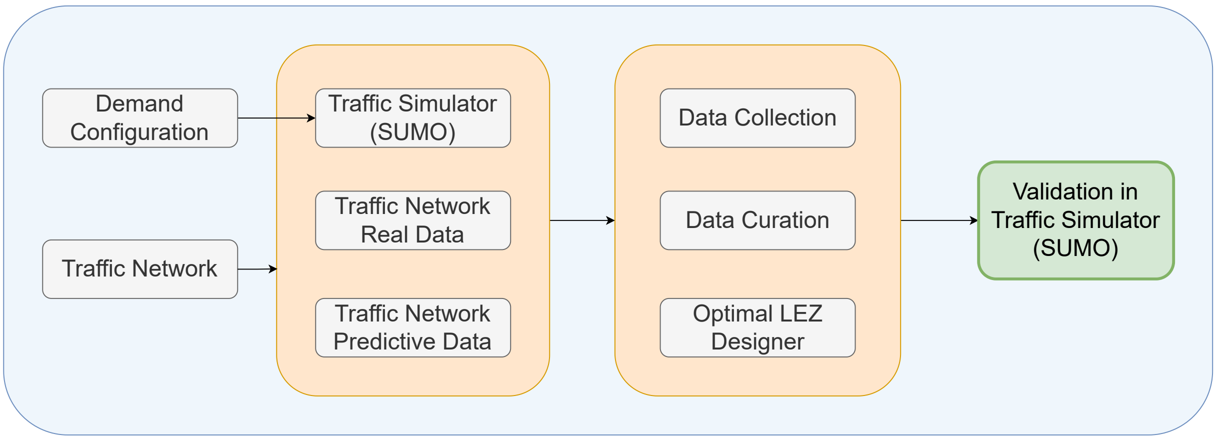


Figure 2. *Procedural Diagram For The Optimization Framework.*

Figure 2 outlines a structured process for integrating a traffic simulation system with the deployment of O-LEZs. The workflow initiates with the *Demand Configuration*, where the simulation parameters are set up, including the Origin-Destination matrix. This matrix is crucial for generating trip information and is complemented by additional data inputs such as detectors, new vehicle types (electric vehicles), and TAZ definitions.

Following the initial setup, a simulation is executed to collect the traffic measures related to a no-LEZ traffic distribution. We use SUMO in this case. Here, vehicles are introduced into the simulation, and the traffic dynamics are emulated to capture the intricate flow and interactions within the traffic network. Simultaneously, data on traffic network usage is meticulously collected, producing both real-time and predictive metrics per edge, related to travel time, emissions, and waiting times. They will be used later to score the optimization algorithm.

Upon completion of the simulation, the process transitions into *Data Collection*. In this phase, the simulation data undergoes a curation process to ensure its integrity and relevance. The curated data is then utilized by the *O-LEZ Designer*, which is tasked with establishing the LEZ configuration. The designer evaluates various constraints, including the target reduction rate, the geographic scope of the LEZ, and other operational metrics, to construct an optimization model. The solution to this model dictates the O-LEZ configuration.

The final step in the workflow is the validation, where the proposed LEZ design is re-integrated into the simulation environment. This validation step is crucial for assessing the efficiency of the LEZ strategy and ensuring that the desired environmental outcomes are achievable within the simulated traffic conditions.

3.1 Data Collection

Simulation data was collected using SUMO, with calls made every 60 time units and information accessed through TRACI.

The simulation tool, SUMO, is configured to log a variety of data points at every step of the simulation process. Key parameters, such as individual vehicle speeds, route choices, travel times, and queue lengths at intersections are recorded into XML files. This is complemented by the collection of aggregate metrics, such as overall traffic density, flow rates, and network-wide travel time improvements or delays. Data are collected under different traffic conditions, varying the volume and type of vehicles, to encompass a range of realistic traffic scenarios.

The thorough data collection is twofold. Firstly, it provides the raw material necessary for a thorough evaluation of current traffic management systems. Secondly, it generates a rich dataset that can be leveraged to train the genetic algorithm for O-LEZ Design, which require large amounts of detailed training data to produce accurate and reliable results.

3.2 Data Processing

Once collected, the data undergoes a rigorous data processing stage, wherein raw simulation outputs are transformed into actionable insights. The main objective of this stage is to distill large amounts of data into an adequate format for analysis, visualization, and the subsequent development of LEZ configurations.

The processing pipeline begins with data cleaning, which involves the removal of outliers, the fixing of errors, and the filling of gaps in the dataset. This process ensures the integrity and reliability of the data before any analysis is performed. After that, data is normalized and standardized to allow for comparisons across different simulations and to facilitate the application of statistical methods.

Further processing includes aggregation of data points to calculate performance metrics, such as average travel time, congestion levels, and route fairness indices. This step is crucial as it translates raw data into meaningful metrics that can be used to gauge the performance of traffic networks and the effectiveness of management strategies.

The rationale behind the extensive data processing is to enable a deeper understanding of the complex interactions within traffic systems. It allows us to identify bottlenecks, understand the impacts of various traffic management schemes, and ultimately inform the design of more efficient and equitable traffic systems. The processed data thus becomes a cornerstone for decision-making and policy formulation in urban traffic management.

3.3 O-LEZ Design

An initial approach was built trying to apply a linear programming model to the LEZ calculation process, but it proved inadequate due to the struggling challenge of ensuring edge continuity within the LEZ. To overcome this issue, a second approach was built using a genetic algorithm (GA). GA excels in exploring a vast solution space, accommodating non-linear constraints.

Metaheuristic algorithms are one of the most used methodologies to face optimization problems with large search spaces. In spite of these type of algorithms do not assure the finding of the best solution, they provide an efficient way to obtain optimal solutions in an assumable computational time. Within the population-based algorithm, the genetic algorithm is one of the most popular metaheuristic used to address optimization problems. The standard framework of the GAs was proposed by J. Holland [28], following the crossover and selection processes described in several evolution theories [29]. The GA's workflow is described in Figure 3.

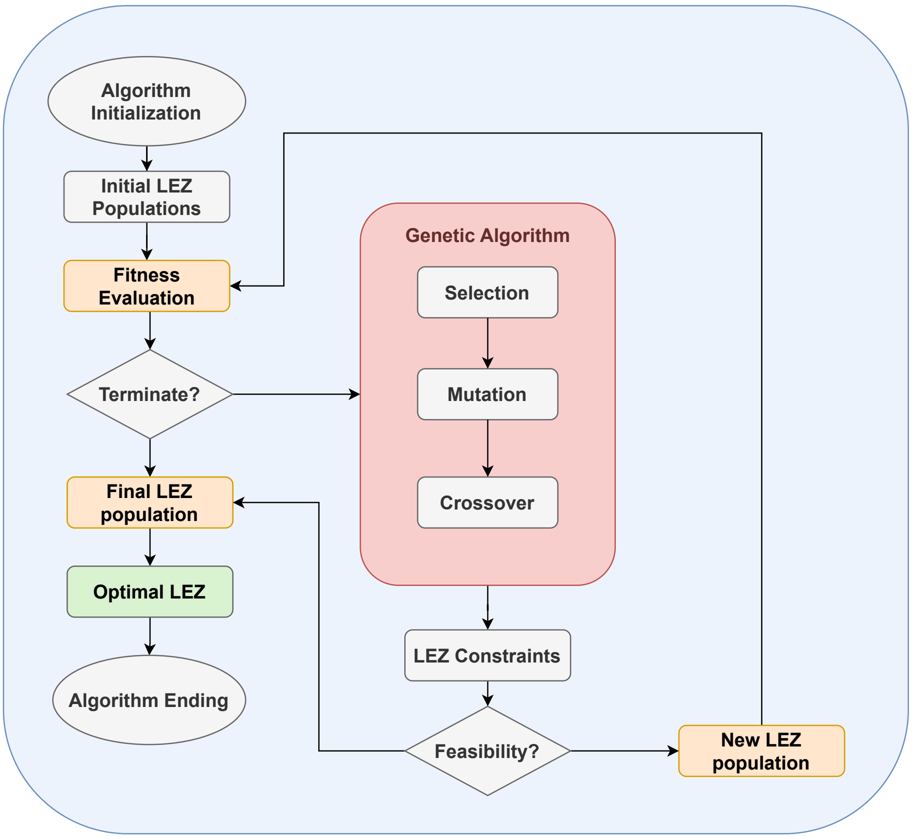


Figure 3. *Flowchart Describing a Genetic Algorithm For Optimal Solution Finding.*

The adoption of a GA for optimizing LEZ stems from its capability to address the complexities inherent in the design process. By leveraging genetic operators such as crossover and mutation, the GA can evolve and refine solutions iteratively, gradually converging towards optimal or near-optimal configurations. This approach facilitates the incorporation of various factors influencing LEZ design, including emission levels, spatial distribution, and traffic flow dynamics, enabling the identification of solutions that balance emissions reduction targets with an improved urban mobility.

Genes represent the selection status of an individual edge within the proposed LEZ. The entire solution, or chromosome, is an array of such genes, each encoded as a binary value, 1 indicates the edge is selected as part of the LEZ, and 0 means the edge is not included. The complexity of the algorithm depends on the edge volumes of the traffic network.

Not all the genes are suitable for the LEZ calculation problem as some constraints can be applied:

- Topological connectivity constraint: the edges considered for a LEZ must be connected between them. The dispersed unconnected edges set is not a valid LEZ solution.
- Topological bound and/or anchoring: the LEZ is usually associated to a certain area (around it), or even bounded by a geographical perimeter.
- Volume bounding: the LEZ is usually limited to a certain amount of the traffic network.
- Emissions bounding: the LEZ must achieve the target emissions, either by imposing a percentage reduction on initial emissions or by limiting emissions to a certain ratio.

In order to achieve the previously mentioned selection of the most polluting and congested edges, a fitness function is designed to harmonize various environmental and logistical objectives for the delineation of an effective LEZ. The LEZ fitness function, shown in Equation (1), makes a weighted aggregation of the emission ratio (ER), see Equation (2), and the waiting time ratio (WTR), see Equation (3), both referred to the original simulation that used no-LEZ. By quantifying total emissions and waiting times, the function aims to concurrently minimize the environmental footprint and alleviate traffic congestion.

$$fitnessValue = w_E \cdot ER + w_W \cdot WTR \tag{1}$$

$$ER = \frac{\displaystyle\sum_{i \notin C} emissions_i}{\sum_{\forall i} emissions_i} \tag{2}$$

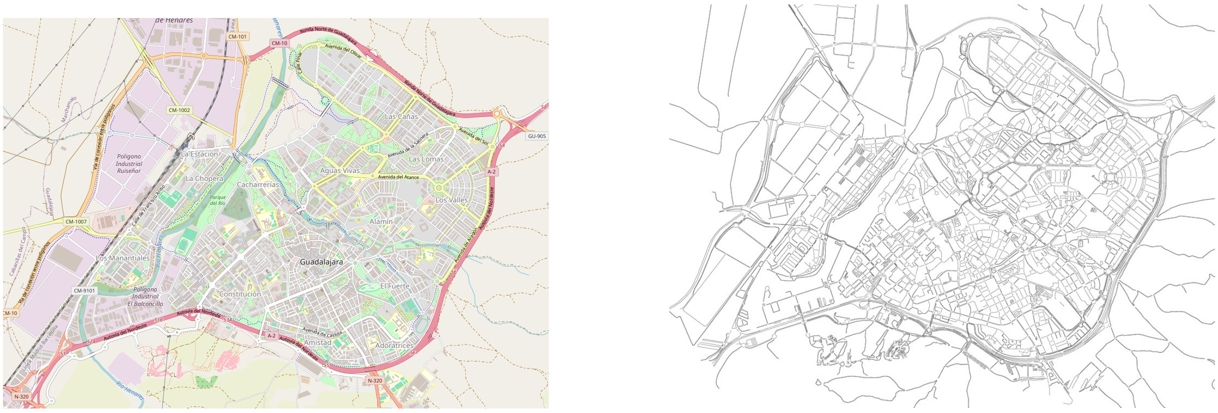
$$WTR = \frac{\displaystyle\sum_{i \notin C} waitingTime_i}{\sum_{\forall i} waitingTime_i} \tag{3}$$

4 Case Study

Guadalajara, a beacon of cultural and historical wealth, has an extension of 235.51 square kilometers in the center of Spain, housing a diverse population of 86,222 residents[10]. The city's transportation infrastructure is a testament to its strategic importance, featuring an extensive network of roads and railways that weave through the urban fabric. Guadalajara is only 50 kilometers from Madrid connected by the A-2 highway, which connects Madrid and Barcelona crossing the urban environment, where the industrial zones are pivotal to understanding Guadalajara's economic and logistic framework. The strategic importance of the city as a transportation nexus is further illuminated by its alignment with European mobility policies [30], positioning it as a central figure in the regional and national transit dialogue.

The experiments explore three distinct layouts of Guadalajara, which are subsequently compared. Initially, we examine the scenario with unrestricted traffic flow. Following this, we analyze the configuration depicted in Figure 5a, which represents the current restricted access zone approved by the Spanish Government. Finally, as shown in Figure 5b, we explore a version of the city that implements our proposed O-LEZ.

4.1 Supply Data: Guadalajara Road Network



***(a)** Road Network Before Conversion.*

***(b)** Road Network After Conversion.*

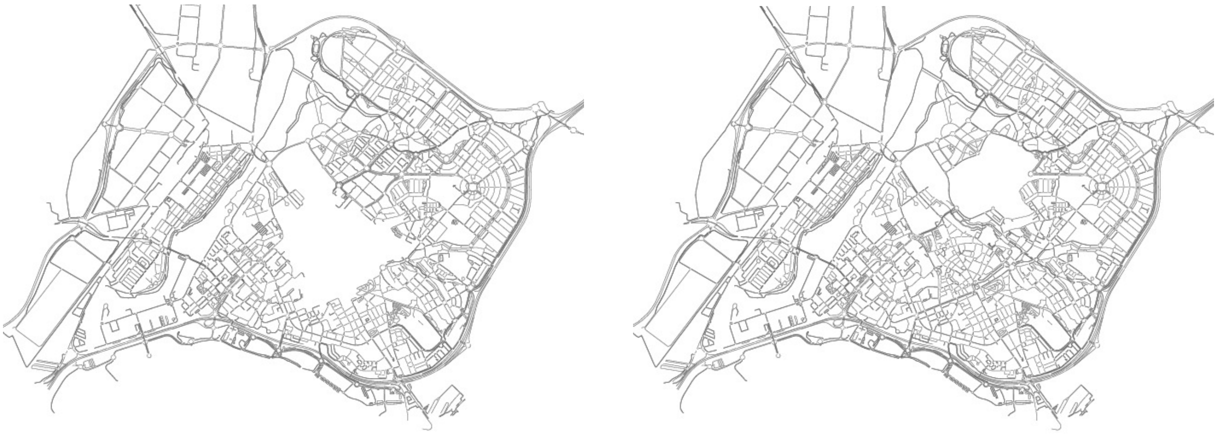
***Figure 4.** Guadalajara road network.*

In order to adapt a map from OSM to a format suitable for SUMO, a series of transformations are required to align the geographic data of OSM with the traffic simulation specifics of SUMO. Initially, the desired section of the OSM map is selected and downloaded, either directly from the OpenStreetMap website or through tools such as the OSM Export Tool, in the form of an '.osm' file.

Before the conversion, a preliminary cleanup and preprocessing of the OSM data is applied to only select road types we are interested in. Also, to ensure the network's integrity for simulation purposes, it is needed to remove non-essential elements or the fixing of any topological errors, such as poorly defined intersections or disconnected paths.

The core of the process involves using SUMO's netconvert tool [31] to transform the OSM data into a SUMO-compatible network file (*.net, *.xml). This conversion interprets the road types from OSM and adapts them to SUMO's requirements, setting up road attributes like speed limits and lane numbers, and generating intersections and lane connections.

With the scenario modelled, the LEZ is implemented, resulting in Figure 5a.



(a) *Guadalajara S-LEZ* ***(b)*** *Guadalajara O-LEZ*

Figure 5. *Guadalajara LEZ configuration.*

Table 1. *Detailed Information About Guadalajara Simulation Scenarios*

Scenario	**Edges**	**Nodes**
No LEZ	9030	4726
S-LEZ	8005	4189
O-LEZ	8497	4461

4.2 Demand Data: Guadalajara Travel Patterns

Climate change laws and policies elaborated by the EU have been followed by its members. In relation to the definition of LEZs in Spanish provinces, it is necessary to follow the Spanish policies related to the creation of LEZs [32]. According to the Climate Change and Energy Transition Law [33], the law requires the adoption of Urban Mobility Plans (UMP) by certain municipalities and territories by 2023, aiming to mitigate pollution and establish LEZs.

Our travel demand model relies on several key data sources to accurately represent travel patterns within Guadalajara. These sources include:

- Population Data: population figures for Guadalajara and its surrounding municipalities. This data is essential for understanding the demographics and distribution of the local population, which in turn affects travel demand.
- Distance Between Cities: geographical distances between cities in the Guadalajara region were calculated based on latitude and longitude coordinates. This information is crucial for modeling travel patterns and trip generation.
- Vehicle Implementation: SUMO calculates emissions using the HBEFA3 model [34]. The vehicle models employed in this study are SUMO's default options, including Passenger, Bus, Truck, Motorcycle, and Emergency vehicles. Additionally, an electric vehicle model [35] is integrated for simulation purposes.

Activity-based traffic models represent a sophisticated approach to traffic simulation, focusing on the intricate behaviors and patterns of individual agents. These models account for the activities and corresponding travel decisions at an specific region. This

Brown: $Balconcillo$ Blue: $Hospital$
Red: $Ejercito$ Pink: $Sanroque$
Yellow: $Manantiales$ Green: LEZ
Maroon: $Henares$ Purple: $Aguasvivas$

Figure 6. *TAZ Configuration.*

detailed modeling framework enables more accurate predictions of traffic patterns, congestion, and the potential impacts of transportation policies and infrastructure changes, making it an invaluable tool for urban planners and traffic engineers seeking to optimize transportation systems and enhance urban mobility. Therefore, different TAZs have been modeled for the simulation based on the predominant activity in these regions. The division has been carried out under the following criteria.

- **Industrial Area**: Henares, Balconcillo.
- **Residential Area**: Ejercito, Manantiales, Sanroque.
- **Low Emission Zone**: LEZ.
- **Hospital Area**: Hospital.

Where each TAZ is made up of edges characterizing it on the map. Figure 6 contains a graphical representation of each of these areas, Table 2 provides a quantitative description of each zones size.

Table 2. *Detailed Information About Guadalajara Simulation TAZs.*

TAZ	Edges
LEZ	2101
Ejercito	1241
Balconcillo	218
Henares	286
CComercial	468
Manantiales	831
Sanroque	1678
Aguasvivas	2207

Through these TAZs, the traffic demand is generated. This is created by means of traffic between TAZs, evenly distributed temporally. The demand data is created synthetically, thus obtaining the benefit of studying the behavior of the network under different levels of stress.

Table 3. *OD Matrix No LEZ Configuration*

	LEZ	Ejercito	Balconcillo	Henares	Hospital	Manantiales	Sanroque	Aguasvivas
LEZ	50	50	50	50	50	50	50	50
Ejercito	50	50	50	50	50	50	50	50
Balconcillo	50	50	50	50	50	50	50	50
Henares	50	50	50	50	50	50	50	50
Hospital	50	50	50	50	50	50	50	50
Manantiales	50	50	50	50	50	50	50	50
Sanroque	50	50	50	50	50	50	50	50
Aguasvivas	50	50	50	50	50	50	50	50

To make a fair comparison, the same amount of vehicles is simulated in all net configurations. Therefore, by eliminating the TAZ *LEZ*, the traffic is compensated by increasing it in other TAZs.

Table 4. *OD Matrix LEZ Configuration*

	Ejercito	Balconcillo	Henares	CComercial	Manantiales	Sanroque	Aguasvivas
Ejercito	67	67	67	67	67	67	67
Balconcillo	67	67	67	67	67	67	67
Henares	67	67	67	67	67	67	67
Hospital	67	67	67	67	67	67	67
Manantiales	67	67	67	67	67	67	67
Sanroque	67	67	67	67	67	67	67
Aguasvivas	67	67	67	67	67	67	67

4.3 LEZ Optimization Algorithm configuration

The design LEZ constraints for Guadalajara are:

- Topological connectivity constraint: all the edges considered for a LEZ must be connected between them.
- Topological bound: the LEZ must be inside a geographical zone covering the lat/long coordinates of latitude 40.630253 40.639958 and longitude -3.149262 -3.178892. Behind this requirement states that the LEZ must not cross the A-2 highway, so a maximum perimeter is fixed.
- Volume bounding: the LEZ should not cover more than a 10% of the network total size.
- Emissions bounding: the LEZ must achieve the target emissions reduction of 15% over the initial total emissions.

In the design of the dynamic LEZ algorithm, a meticulous approach to parameterization is critical to achieving a balance between environmental impact and practical implementation.

The LEZ algorithm for Guadalajara is started with a random population that complies with the design LEZ constraints. The algorithm starts with a population size of 500, which is chosen to provide a broad genetic diversity while maintaining computational efficiency. This size is sufficient to explore the solution space but not so large as to significantly increase computational demand.

The number of generations is set to 25, reflecting a commitment to a more exhaustive search process and a finer evolutionary progression. This allows for a more gradual and nuanced optimization process, giving the algorithm ample opportunity to refine solutions over a larger number of iterations, which is particularly important given the larger population size and the complex nature of designing effective LEZs.

The crossover rate of 0.8 ensures that a substantial portion of the population undergoes genetic recombination, promoting the exploration of new solutions by mixing genetic information from different individuals, which is crucial to avoid local optima and to encourage diversity in the solution space.

The individual selection method used is Tournament Selection. In Tournament Selection a subset of individuals is randomly chosen from the population and the individual with the highest fitness within this group is selected as a parent. This process is repeated until the required number of parents is selected. In this implementation, a tournament size of 3 is employed, balancing the trade-off between selection pressure and maintaining genetic diversity. This method ensures that individuals with higher fitness have a higher probability of being selected as parents, thus favoring the propagation of advantageous genetic traits. However, due to the random nature of tournament group selection, it also allows individuals with lower fitness to be occasionally selected, which contributes to maintaining genetic diversity within the population. This diversity is essential for preventing premature convergence to sub-optimal solutions and for ensuring a comprehensive exploration of the solution space.

The mutation rate is carefully set at 0.01 to introduce random alterations in the genotype, which is essential to introduce variability and prevent premature convergence. However, it is kept low enough to avoid disrupting advantageous genetic structures.

Each parameter is carefully selected and fine-tuned to align with the algorithm goals: to create dynamic, effective and practical LEZs that contribute to emission reduction.

5 Experimental results

The histogram in Figure 7 illustrates the distribution of percentage travel time enhancements, with a focus on individual trips. The distribution is markedly leptokurtic, indicating a frequency concentration around the mean, which is close to 0%. This suggests that for a significant number of trips, the travel time remains relatively unchanged.

A small number of trips exhibit travel time enhancements of both extreme reductions (left of the mean) and increases (right of the mean). Notably, there is a asymmetry with a longer tail on the positive side, indicating that while most trips experience little to no change, some trips see an increase in travel time as they need to circumvent the LEZ.

Figure 8 illustrates the comparison of the number of running vehicles over time under three different LEZ adopting scenarios: no-LEZ (Normal), S-LEZ and O-LEZ. The no-LEZ scenario, depicted by the black line, shows a steady increase in running vehicles, indicating typical traffic flow without restrictions. This reflects the principle that as the number of vehicles on the road increases, the number of waiting vehicles decreases, leading to smoother traffic flow. The S-LEZ scenario, shown in blue, displays a similar trend but with a reduced number of running vehicles, suggesting that the implementation of a LEZ does have a measurable impact on traffic flow, potentially reflecting restrictions or rerouting to reduce emissions. Notably, the O-LEZ, represented by the yellow line, consistently exhibits a higher count of running vehicles over time, suggesting better traffic flow compared to S-LEZs.

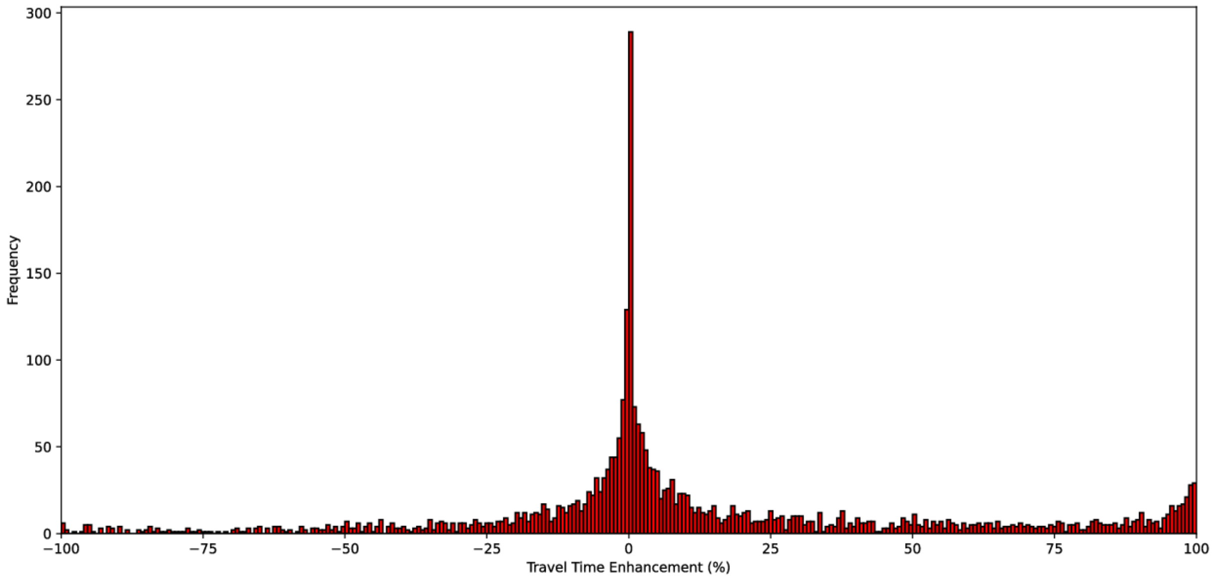


Figure 7. *Individual Travel Time Relative Comparison O-LEZ / no-LEZ Simulation.*

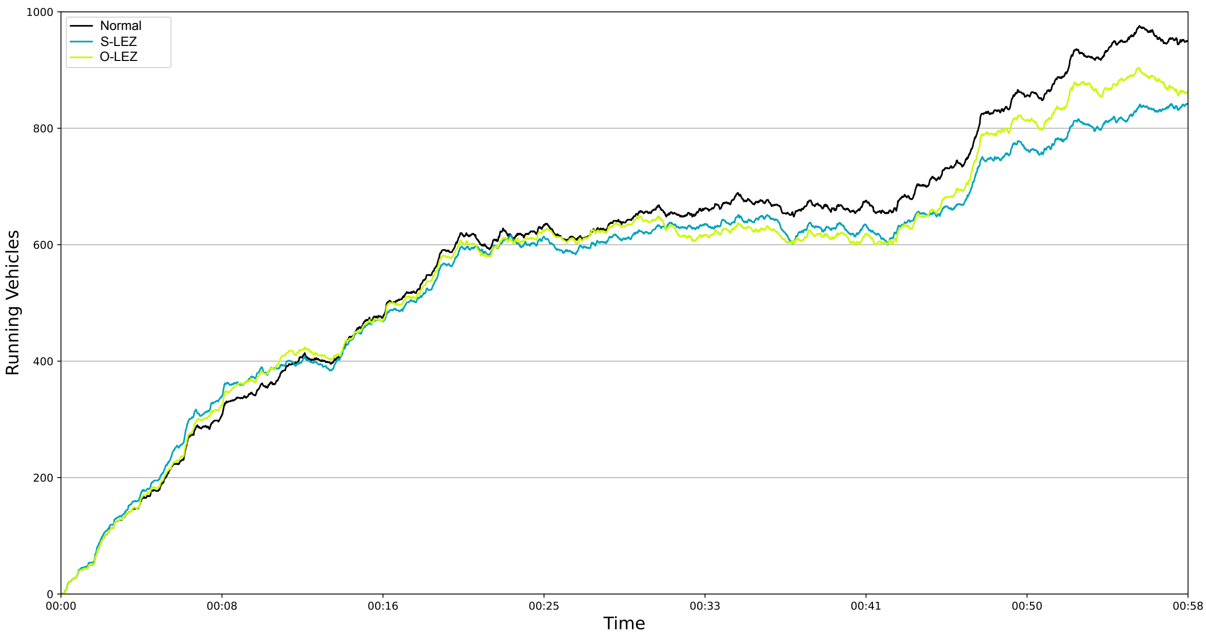


Figure 8. *Evolution of Number of Running Vehicles Under Three Scenarios: no-LEZ, S-LEZ and O-LEZ.*

The histogram in Figure 9 illustrates the comparison of relative travel time enhancement across two different scenarios: a S-LEZ implementation versus a non-LEZ scenario (red), and an O-LEZ versus a non-LEZ scenario (green). The green bars, representing the O-LEZ, typically show a greater frequency of instances clustered around the zero mark, suggesting that the optimized configuration results in travel times that are more consistently close to the non-LEZ scenario, implying minimal disruption to travel times. Furthermore, the distribution of green bars is slightly skewed towards positive values, indicating that the O-LEZ may lead to improvements in travel time for a subset of travelers.

In contrast, the red bars, depicting the S-LEZ implementation, show a similar clustering around the zero mark but with a less pronounced peak. This indicates that while the S-LEZ also performs closely to the non-LEZ scenario, it is not as effective as the O-LEZ in maintaining or improving travel times.

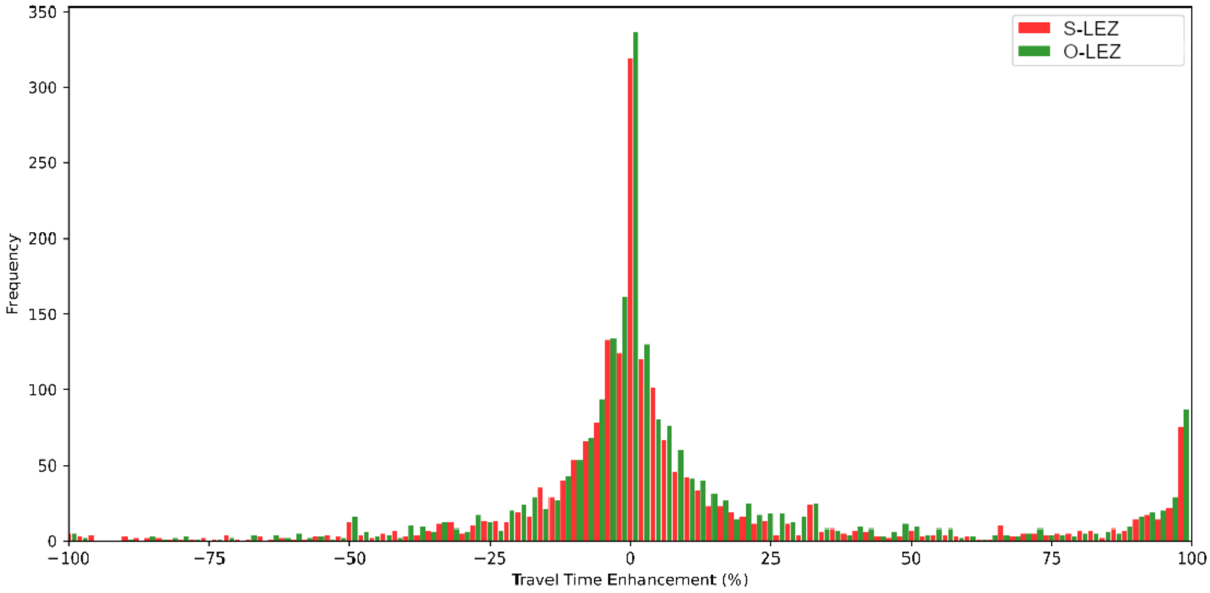


Figure 9. *Individual Travel Time Relative Comparison Between S-LEZ and O-LEZ.*

The sharp spikes near zero for both scenarios suggest that for most individuals, the LEZ implementations do not drastically alter travel times. However, the relatively higher peak and narrower distribution of the green bars demonstrate that the O-LEZ is more effective in enhancing travel efficiency when compared to the S-LEZ setup. This illustrates the benefits of optimization in LEZ design, potentially offering a superior balance between environmental objectives and travel time considerations. In this comparison, edges represented by bars to the left, which show a negative percent change, indicate an increase in emissions due to the LEZ implementation, whereas bars to the right with a positive percent change indicate a decrease in emissions relative to the no-LEZ scenario.

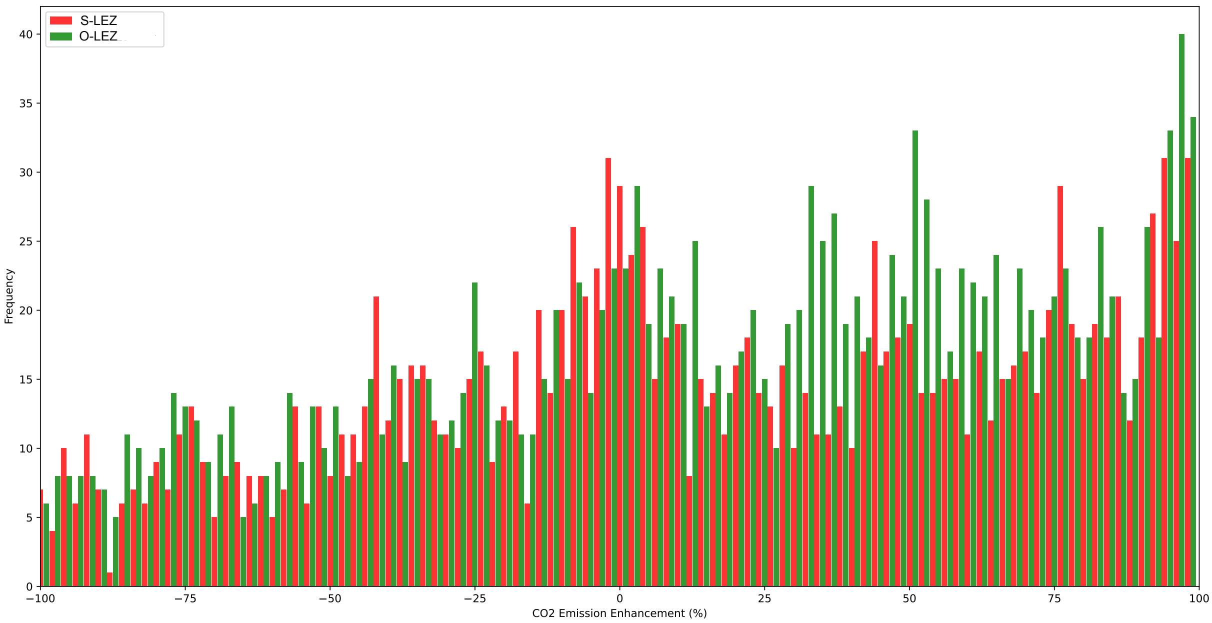


Figure 10. *Relative CO2 Emissions Improvement Between S-LEZ / O-LEZ.*

The histogram in Figure 10 shows the relative CO2 emissions improvement between non-optimal and O-LEZs. It can be observed that both LEZ implementations have edges that outperform the no-LEZ scenario as well as edges that underperform. However, the green bars, representing the O-LEZ, are more frequent in the positive region than the red bars, suggesting that the optimized configuration tends to be more effective at reducing emissions across the network of edges. This implies that the O-LEZ is better at enhancing environmental performance compared to the S-LEZ setup.

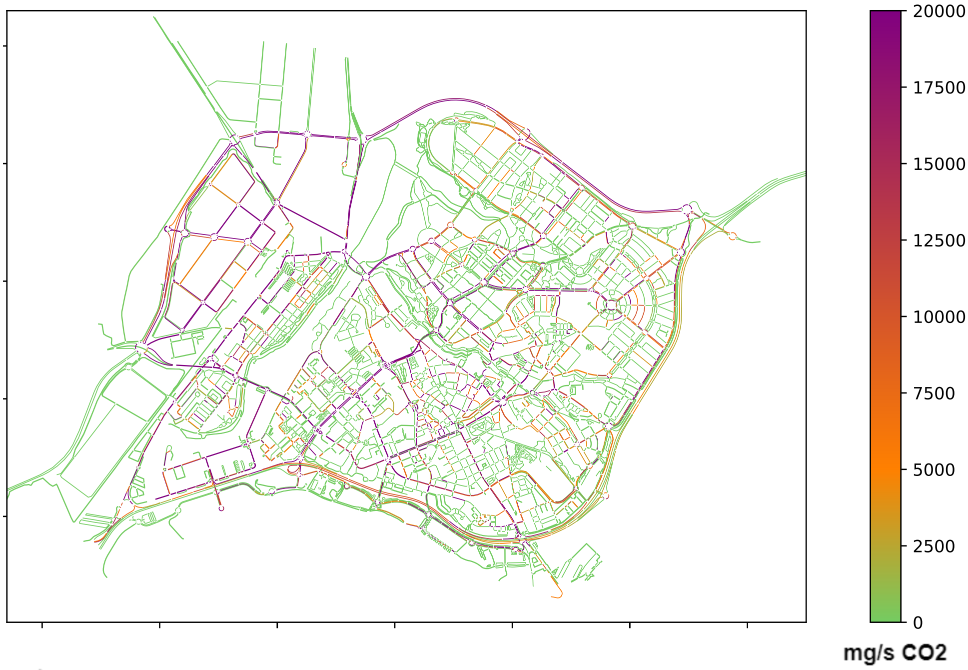


Figure 11. *Heatmap CO2 Emissions Without LEZ.*

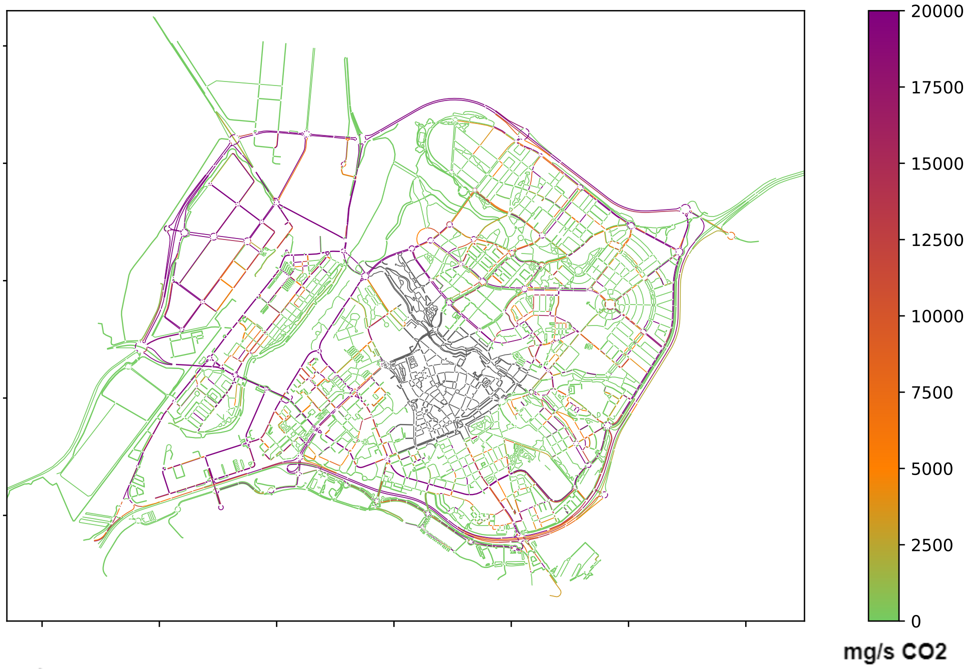


Figure 12. *Heatmap CO2 Emissions With S-LEZ.*

Figures 11, 12, and 13 illustrate the CO2 emissions densities per edge in the three scenarios considered. In Figure 12, representing the S-LEZ configuration, we observe a distribution of colors that suggests a varied impact on CO2 emissions across the network. Some areas, particularly those in purple and red, show high emission values,

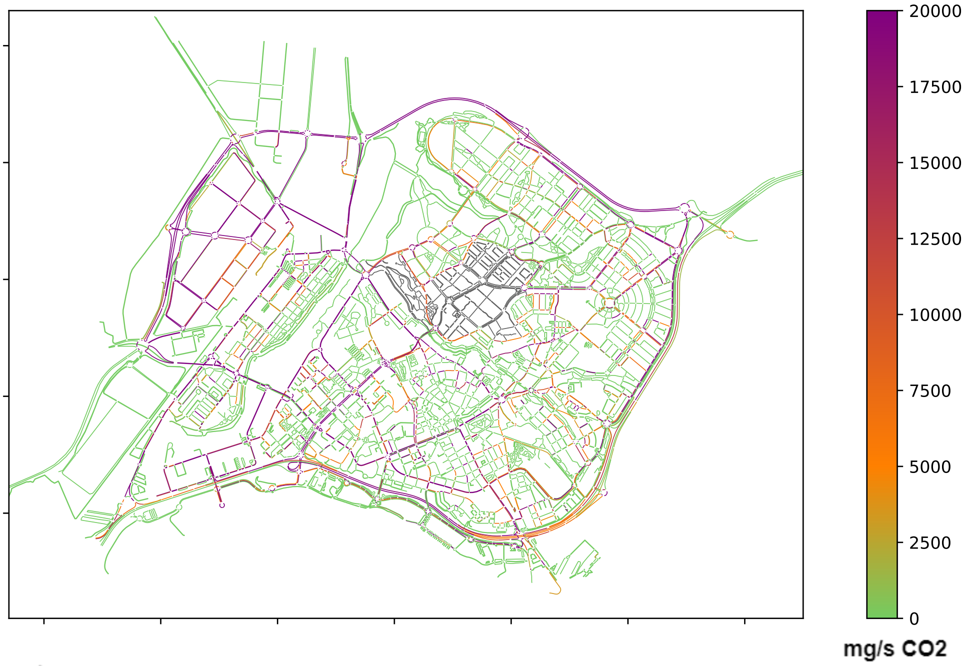


Figure 13. *Heatmap CO2 Emissions With O-LEZ.*

indicating zones where the LEZ is less effective. In contrast, areas with green to orange gradients indicate moderately lower emissions. The gray areas mark zones where emissions are zero, indicating that only electric vehicles are permitted to enter.

In Figure 13, depicting the O-LEZ configuration, shows a notably different pattern. The predominance of green and yellow hues across the map indicates a general reduction in emissions, with fewer instances of red and purple, suggesting that the optimized configuration leads to lower emissions in more areas compared to the S-LEZ.

Comparatively, the O-LEZ heatmap displays a more uniform distribution of low to moderate emission levels, implying a more effective overall strategy in reducing emissions. The reduction of high-emission zones (red and purple areas) in the O-LEZ heatmap demonstrates the effectiveness of the optimization process in mitigating CO2 output across the urban network.

When comparing Figure 11 with the previously analyzed LEZ and O-LEZ configurations, it becomes apparent that the implementation of LEZ strategies has a mitigating effect on emissions. The 'No LEZ Configuration' heatmap serves as a baseline to underscore the improvements brought by the S-LEZ and O- LEZ scenarios. While the S-LEZ shows a moderate reduction in high-emission zones, the O-LEZ heatmap exhibits a more substantial decrease in these areas, indicating a more effective strategy for emission reduction.

The demand data outlined in Table 5 introduces a sizing framework for LEZs, classifying them into five categories: XS, S, M, L, and XL, with 'M' established as the base reference size. This table delineates a straightforward multiplication factor for scaling the impact of each LEZ size category, setting 'M' at 1, with XS at half the impact of M, and XL threefold.

Figure 14 is a scatter plot that maps the trade-off between the relative waiting time impact and CO2 emissions. This plot represents O-LEZ and S-LEZ configurations under the demand configurations described in Table 5. There is a discernible pattern

Table 5. *Adjustment Factors for Each Size Relative to Size M.*

Size	**Factor**
XS	$\frac{1}{3}$ of M
S	$\frac{1}{2}$ of M
M	1 (Base Size)
L	2 times M
XL	3 times M

where larger LEZs are associated with more pronounced enhancements in emission reduction and reduction in travel time efficiency. Notably, there is a clear improvement in performance between the O-LEZ and S-LEZ configurations, with O-LEZs having a smaller impact on travel time and a greater reduction in CO2 emissions.

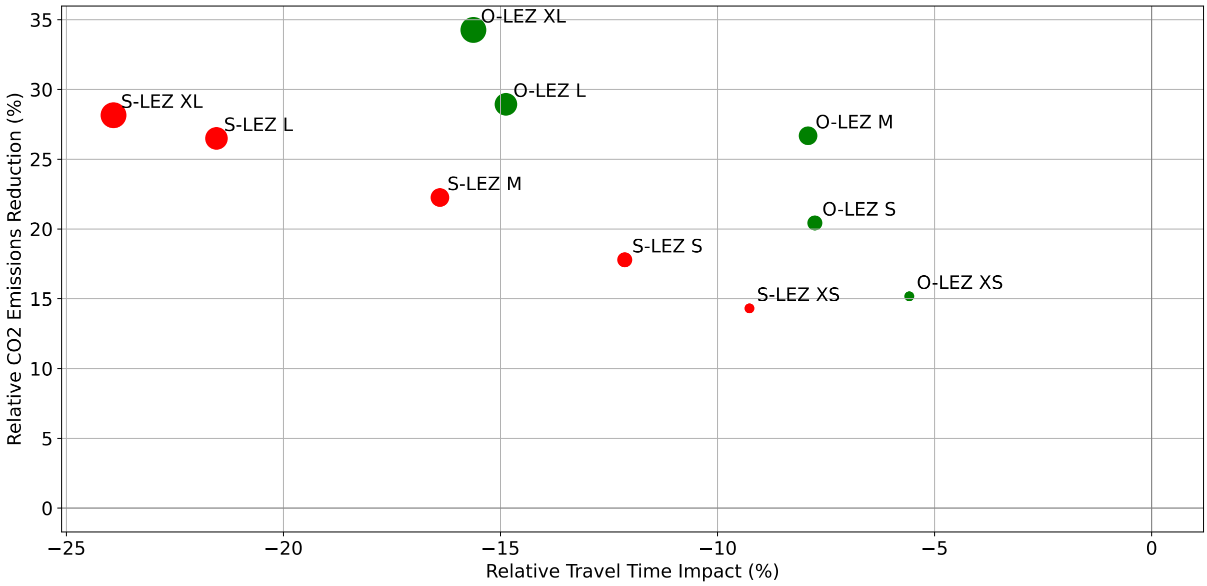


Figure 14. *Relative Improvement in Emissions and Travel Time Across Different LEZ Configurations and Demand Sizes.*

Table 6 provides a quantitative comparison of the differential effects of LEZ configurations on travel time and CO2 emissions in percentage terms. The implementation of O-LEZ configurations has a uniformly more positive impact, reducing travel times and CO2 emissions more effectively than S-LEZ configurations across all LEZ sizes.

Table 6. *Impact Comparative O-LEZ and S-LEZ.*

Size	**O-LEZ Travel Time (%)**	**S-LEZ Travel Time (%)**	**O-LEZ CO2 (%)**	**S-LEZ CO2 (%)**
XS	- 5.58	- 9.26	15.18	14.31
S	- 7.76	- 12.14	20.43	17.79
M	- 7.91	- 16.40	26.68	22.26
L	- 14.87	- 21.54	28.94	26.49
XL	- 15.62	- 23.91	35.27	28.15

Overall, the comparison demonstrates the value of LEZ configurations in managing urban emissions.The O-LEZ, in particular, shows a marked improvement in environmental performance over the baseline scenario under various demand sizes, highlighting the potential benefits of such optimization measures in urban planning and sustainability efforts.

6 Results and Contributions

This work embarked on an in-depth investigation into the integration of LEZs within the SUMO framework, aimed at mitigating urban air pollution caused predominantly by vehicular emissions. Through the strategic design of LEZs with a minimal edge count, optimized via the SUMO framework, our study has showcased an improvement in urban mobility and reduction in emission levels.

The broader implications of our findings extend beyond the immediate benefits of improved traffic flow and reduced emissions. By facilitating a healthier urban environment, O-LEZs contribute to the well-being of urban populations, potentially reducing healthcare costs associated with air pollution-related ailments. Moreover, the adoption of such innovative traffic management solutions can enhance the overall quality of urban life, making cities more livable and attractive to residents and visitors alike.

However, the implementation of O-LEZs is not without challenges. The adoption of new technologies and the restructuring of urban landscapes require significant investment and stakeholder buy-in. Public acceptance and compliance with LEZ regulations are also critical to the success of such initiatives. Thus, effective communication strategies and stakeholder engagement are paramount in advancing the LEZ concept from theory to practice.

In conclusion, this study significantly contributes to the discourse on sustainable urban mobility and environmental preservation. By presenting an O-LEZ model that aligns with stringent emission standards and enhances traffic efficiency, our research offers a viable pathway towards achieving healthier, more sustainable urban environments. As cities worldwide continue to grapple with the complexities of urbanization and environmental degradation, the insights garnered from this research can inform future urban planning and policy-making, heralding a new era of urban mobility management.

6.1 Future research lines

In future research, we aim to implement dynamic access policies for LEZs, allowing access to various fleets of vehicles based on real-time data and evolving traffic conditions. This dynamic approach will allow LEZs to adapt flexibly to changes in traffic patterns and environmental conditions, optimizing the balance between emission reduction goals and urban mobility needs.

Furthermore, our future work will involve the calibration of traffic flows to accurately reflect real-world scenarios. By calibrating traffic models with empirical data, we strive to create simulations that closely resemble actual traffic conditions. This calibration process ensures that the performance evaluation of LEZs is based on realistic traffic dynamics, enhancing the reliability and applicability of our findings in practical urban settings.

Data availability statement

All available data has been included in the paper.

Author contributions

Pablo Manglano-Redondo contributed to the conceptualization of the study, developed the methodology, conducted the investigation, wrote the original draft, and created the visualizations. Alvaro Paricio-Garcia contributed to the conceptualization of the study, developed the methodology, validated the results, reviewed and edited the writing, provided supervision and managed the project administration. Miguel A. Lopez-Carmona contributed to the conceptualization of the study, validated the results, reviewed and edited the writing, provided supervision and managed the project administration.

Competing interests

The authors declare that they have no competing interests.

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