



Low emission zone and mobility behavior: Ex-ante evaluation of vehicle pollutant emissions

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ABSTRACT

Exposure of the population living in urban areas to an increasing level of air pollution has led local authorities to implement vehicle access restrictions to limit the circulation of pollutant vehicles and foster sustainable travel habits. With these aims, Low Emission Zones (LEZs) have been introduced in several European cities. Many previous works have evaluated the impacts of such regulation; however, they adopted pre-defined assumptions about new travels to access the regulated area and neglected potential behavioral changes induced by the measure. The aim of this paper is to quantify the effects of a LEZ on vehicle pollutant emissions, considering potential short-term variations of travel habits after its introduction (i.e., vehicle replacement, modal shift and destination change), and the associated uncertainty. The study area was the Municipality of Padova (Italy), where a LEZ is likely to be enforced. A holistic evaluation framework was applied combining a behavioral model and a traffic simulation model, calibrated using responses from a mobility survey administered to local stakeholders and traffic counts. The results highlighted the measure could contribute to induce fleet renewal and modal shift toward sustainable transportation means, that could be furtherly fostered by increasing the awareness of the benefits of the LEZ. Furthermore, the outcomes confirmed that the intervention could significantly reduce vehicle pollutant emissions within the area. Nevertheless, a spillover effect could occur outside the LEZ, due to the long detours that travelers deciding to avoid entering the zone have to perform.

1. Introduction

In many European countries, in 2022, air pollution concentrations have exceeded thresholds suggested by the World Health Organization (EEA, 2022), with severe consequences for human health and the environment. The problem is exacerbated in urban areas, where many people live (Fransen et al., 2023). At European level, road transportation is responsible for one-third of NO_x emissions, 23 % of Black Carbon, 18 % of CO and 9 % of Particulate Matter (2.5 and 10) (EEA, 2022); in addition, air quality studies during the Covid-19 pandemic have proven that the reduction of traffic flows can significantly mitigate pollutant concentrations (Gao et al., 2021; Jephcote et al., 2021; Querol et al., 2021; Ravina et al., 2021; Rossi et al., 2020). To meet air quality targets and increase livability in urban spaces, by promoting sustainable travel habits of travelers, several Transportation Demand Management policies have been proposed (Meyer, 1999). These can be divided into (Eriksson et al., 2008): (1) coercive measures, such as congestion/emission

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charging or license plate restrictions (Gu et al., 2018; Jia et al., 2017), aiming to mitigate or avoid specific mobility behaviors (Schmöcker et al., 2012), and (2) supportive measures, such as building bike lanes and pedestrian areas (Eriksson et al., 2008), aiming to promote sustainable mobility behaviors (Morton et al., 2021).

The European Commission proposed a harmonized approach to define these interventions, which were grouped as Urban Vehicle Access Regulations (UVAR) (European Commission, 2013). A Low Emission Zone (LEZ) is one of these policies (Fransen et al., 2023). A LEZ is an area where vehicle access is allowed depending on specific emission requirements (Ellison et al., 2013). Unlike other Travel Demand Management strategies, LEZ aims to reduce local pollutants' emissions generated in a delimited area and restricts vehicle access based on emission standard, rather than vehicle classes (Morton et al., 2021). The first LEZ was introduced in Sweden in the 1990s (Oltra et al., 2021) and, nowadays, many LEZs are enforced in several European cities, like Berlin (Cyrys et al., 2014), Lisbon (Ferreira et al., 2015), London (Ellison et al., 2013), Madrid (Peters et al., 2021) and Paris (André et al., 2018). The adopted regulatory schemes are site-specific and differ depending on (Gonzalez et al., 2023): the type of enforced restrictions (e.g., fuel types, EURO emission standards), the extension of the regulated area (e.g., specific area, full city), and the period of operation (e.g., during working hours, 24 h per day). Although a standardized LEZ framework has not been defined (Lurkin et al., 2021), the measure is often expected to improve air quality, reduce congestion and noise, and ultimately prompt the adoption of sustainable transportation modes and travel habits (Gonzalez et al., 2022; Peters et al., 2021; Rodriguez-Rey et al., 2022; Sánchez et al., 2021), with consequent benefits for environment, citizens and society (Malina and Scheffler, 2015).

In particular, some authors analyzed factors affecting the public acceptance of a LEZ, performing both ex-ante evaluations based on hypothetical scenarios (Morton et al., 2021) and ex-post assessments after the measure implementation (Oltra et al., 2021; Tarrío-Ortiz et al., 2021). Furthermore, many previous works have evaluated the impacts of the introduction of a LEZ, focusing on air quality changes (Tartakovsky et al., 2020) and effects on travel behaviors (Gonzalez et al., 2022). For instance, Ferreira et al. (Ferreira et al., 2015) observed that average annual concentrations of PM₁₀ and NO₂ respectively decreased by 23 % and 11 %, after the implementation of a LEZ in Lisbon (Portugal). Gonzales et al. (Gonzalez et al., 2023) focused on the introduction of a LEZ and parking management policies in Madrid (Spain); the authors observed a reduction in parking demand, particularly for the most polluting vehicles, and then concluded that the two measures could generate positive effects on transportation-related emissions. The same study area was investigated by Tarrío-Ortiz et al. (Tarrío-Ortiz et al., 2023), who reported a decrease on sales for retailers in the LEZ, due to a lower number of car trips toward the area. Considering that the effectiveness of Travel Demand Management policies could be prevented by a lack of public support (Jia et al., 2017; Zheng et al., 2014), other authors investigated the factors impacting the acceptance of the LEZ (Morton et al., 2021; Oltra et al., 2021). Furthermore, some authors pointed out that the introduction of a LEZ could induce changes in mobility behaviors of travelers impacted by the new regulation (Ellison et al., 2013; Gonzalez et al., 2022; Lurkin et al., 2021), which are often difficult to evaluate due to their complexity (Tarrío-Ortiz et al., 2022).

In order to estimate the effects of a LEZ implementation, the majority of previous works has carried out before/after analyses. In particular, data collected after the intervention were compared with those gathered before the introduction of the measure. Depending on the focus of the analysis, these data include air quality information (Ferreira et al., 2015), traffic flows (Malina and Scheffler, 2015), on-street parking records (Gonzalez et al., 2023), and vehicle registrations (Ellison et al., 2013). An assessment after the LEZ implementation allows to evaluate its actual impacts; on the other hand, ex-ante evaluations are needed to forecast the potential effect of the measure, thus providing sound elements to properly design the intervention (Sánchez et al., 2021). However, few works have applied this predictive approach (Poulhès and Proulhac, 2021; Sousa Santos et al., 2020), despite its importance for planning purposes (Lurkin et al., 2021).

Among the impacts generated by the LEZ implementation, short and long-term changes in the mobility habits of stakeholders can produce significant effects that should not be neglected in forecasting models (André et al., 2018; Tarrío-Ortiz et al., 2022). In particular, users impacted by the regulation could decide to replace their polluting vehicles to meet the required standards to access the LEZ (Ellison et al., 2013; Peters et al., 2021), thus altering the composition of the fleet circulating in the area, with consequent effects on emission estimates (André et al., 2018). Moreover, people could shift from private cars to more sustainable travel means, such as public transportation or active modes, in order to reach the regulated area, thereby reducing traffic flows and congestion (Gonzalez et al., 2022; Tarrío-Ortiz et al., 2022). In addition, travelers could decide to avoid entering the LEZ and park their vehicle outside the restricted zone, thus, a consequent increase in traffic flows and parking demand in the surrounding areas and streets could generate a spillover effect (Gonzalez et al., 2023; Lurkin et al., 2021).

Although there are many studies investigating the environmental impacts of a LEZ, most of them did not simulate the multiple and broad impacts that such a policy can induce on travel behaviors, significantly affecting the quantification of its effects (Rodriguez-Rey et al., 2022; Sánchez et al., 2021). Furthermore, the few works considering these issues applied predefined hypothesis, such as banning all non-compliant vehicles following the LEZ regulation (Dias et al., 2016; Poulhès and Proulhac, 2021; Sousa Santos et al., 2020) or assuming fixed numbers of modal splits (Host et al., 2020). In addition, the assessment of behavioral changes was not based on real data (Lurkin et al., 2021) and did not consider the potential uncertainty related to these variations. As described before, new potential mobility habits can lead to the success or failure of a LEZ, therefore a holistic ex-ante evaluation of their impacts is crucial for the design of an effective policy (Lurkin et al., 2021; Sánchez et al., 2021).

In this paper, a mobility behavioral model, a traffic simulation model and an emission model are used to perform an ex-ante estimation of the impacts on vehicle pollutant emissions after the foreseeable introduction of a LEZ in Padova (Italy). Unlike previous works, real traffic data are used to estimate traffic flows in the area and the results of a mobility survey administered to local stakeholders of the LEZ are analyzed to understand and quantify the potential behavioral changes induced by this new policy in a short-term period. Furthermore, a probabilistic estimation is carried out to consider the uncertainty associated with these modifications. For these reasons, the present work aims to provide policy makers with an integrated framework to assess how a LEZ can contribute to the

creation of a cleaner environment in sustainable cities.

The rest of the paper is organized as follows. In [Section 2](#) the implemented method and used data are described. The results of the work are reported in [Section 3](#) and discussed in [Section 4](#). Lastly, the main findings are summarized in [Section 5](#).

2. Methods and data

2.1. Case study

The study area was the Municipality of Padova, a 93-square-kilometer area located in Northern Italy, where about 200'000 people

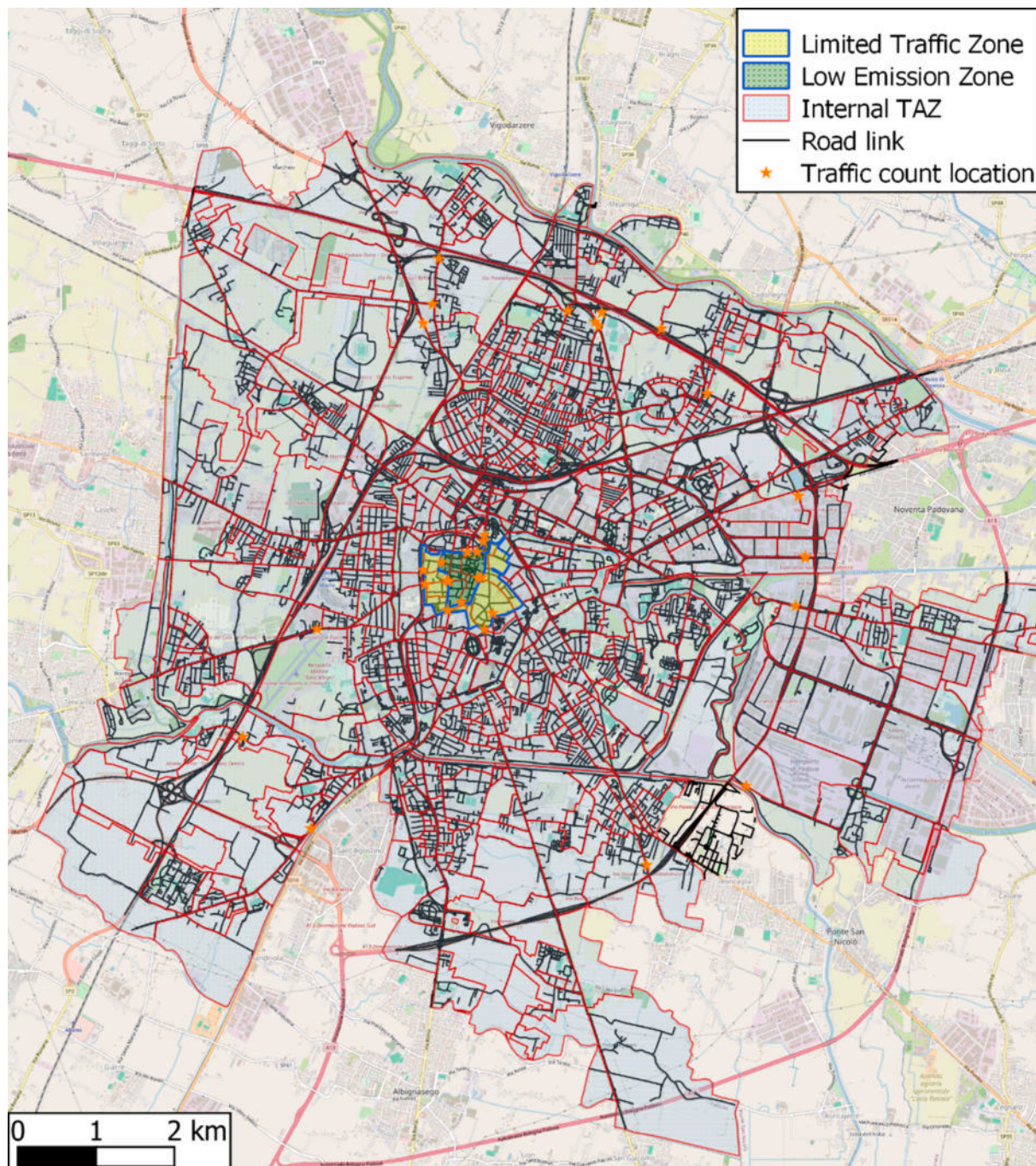


Fig. 1. Padova city center. Regulated areas, internal Traffic Analysis Zones (TAZs), road network and location of traffic counts.

live. Padova is a medium-sized city with a density of about 2'300 inhabitants per square kilometer. A Limited Traffic Zone (LTZ) has been enforced since 1989 in the central part of the city (about 0.95 km²) (Comune di Padova, 2022), which includes the historic city center, as reported in Fig. 1.

The existing transportation network in Padova consists of two layers: the suburban network and the urban network. The former includes rail and road public transportation services that ensure an efficient connection of the city with the surrounding municipalities, as well as with other areas at the regional and national level. The urban transit network has 23 lines for road vehicles and one tramline. The latter connects the northern and southern parts of Padova through the historic city center, where there are 10 tram stops. The main mobility hub is located next to the train station, about 800-meters far from the city center and represents the bus terminal of many suburban and urban lines. To promote the use of public transportation within the city, 6 park and ride facilities have been created along the boundary of the Municipality.

Currently, specific restrictions depend on the subzone where they are applied; however, they are based on types of vehicles and users, as well as time periods and days. In particular, in order to enter the area, a permanent or temporary permit is to be purchased. The former is assigned to defined user categories, such as residents, owners of a private parking lot in the area, retailers, doctors, workers in public administrative offices, hotel owners, journalists, and people with reduced mobility. The latter are granted for specific activities to be carried out in the area, such as loading/unloading of heavy, bulky or perishable goods, escorting people with reduced mobility or children in nursery and primary schools. Furthermore, a specific regulation is enforced for freight vehicles, delivering and collecting parcels, and participating in the local market in the area. These last access restrictions depend on vehicle's weight and fuel type and are applied during fixed time periods. Moreover, specific categories of motorized vehicles are permanently allowed to enter the area: police departments and firefighters, ambulances, garbage trucks and vehicles cleaning the streets, public transportation vehicles, car sharing vehicles, taxis, scooters, and motorbikes, and full electric vehicles. The compliance of the users is ensured through an automatic control system installed on the entries and administrative fines for transgressors. Specifically, gates located on road sections accessing the LTZ are equipped with cameras that record vehicle license plate. In the area, the speed limit is set at 30 km/h.

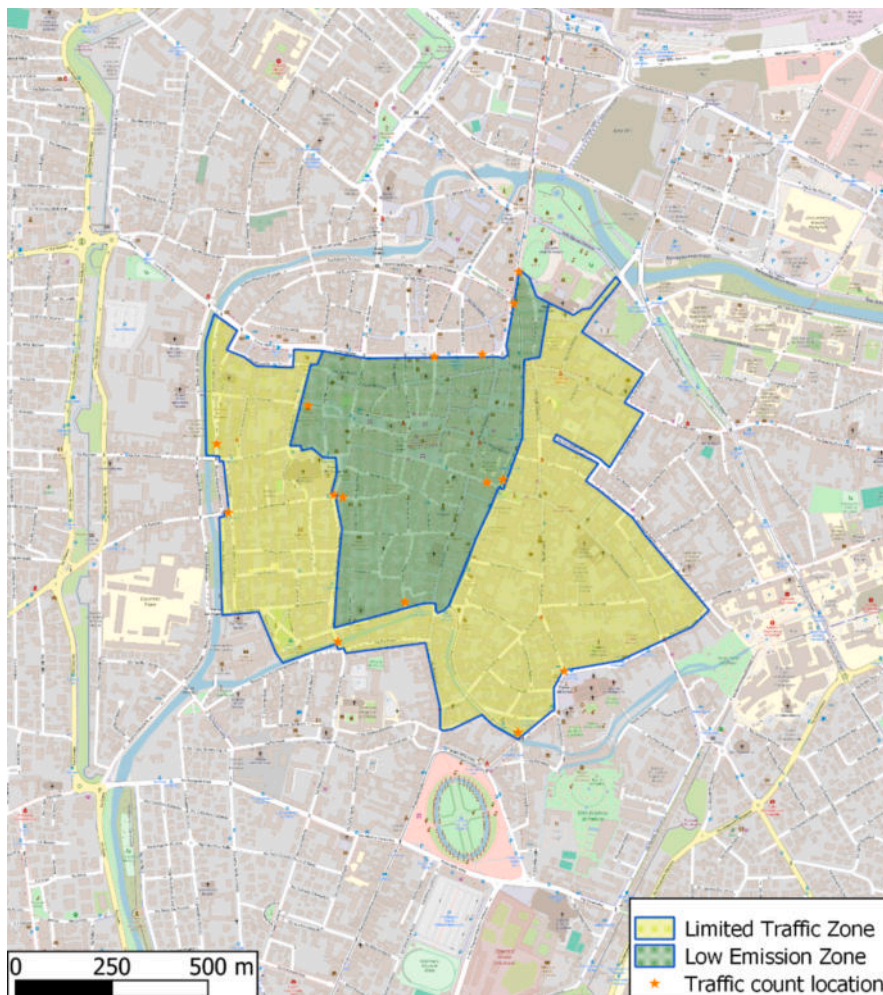


Fig. 2. Limited Traffic Zone, drafted Low Emission Zone and traffic count locations.

In the central part of the current LTZ, a new Low Emission Zone (LEZ) could be introduced (of about 0.3 km²), as shown in Fig. 2. The measure was included in the Sustainable Urban Mobility Plan (SUMP) of Padova as one of the interventions to improve sustainable and low-carbon mobility, e.g. by promoting the adoption of electric vehicles (Comune di Padova, 2019). In the document, a gradual enforcement of the LEZ was planned, by progressively imposing stricter restrictions to the access of pollutant vehicles. However, a first draft of the regulatory framework of the LEZ was designed during the ReVeAL project (Regulating Vehicle Access for Improved Liveability) (Lewald, 2022). In particular, during the project period (2019–2022), the Municipality of Padova defined the area of the new LEZ, as well as the first set of restrictions that could be applied, with the support of all the project partners. The logic of the future limitations is likely to be different than the current LTZ scheme. In particular, in line with the final goals of a LEZ, the access of vehicles in the area can be regulated considering their fuel type and emission standard. Specifically, only the following vehicle categories are likely to be authorized: electric, CNG, LPG Bifuel, CNG Bifuel, Petrol Hybrid or Diesel vehicles (only for freight vehicles) with a EURO emission standard greater than a specified threshold. These restrictions are planned to be applied every day for 24 h a day. Table 1 reports details about the vehicle and engine types allowed to access the new LEZ, based on the drafted regulation. In addition, dedicated exceptions are planned to be granted to residents, people with reduced mobility, those working for emergency and waste management services, and freight vehicles used by the local market (during specific time windows). Lastly, the automatic number plate recognition system required by the project has been recently installed on both entries and exists of the current LTZ to monitor vehicle compliance. At the time of writing, the drafted regulation related to the LEZ has been submitted for the political discussion and approval. Following the comprehensive view of mobility adopted in the SUMP, the LEZ is part of an integrated set of measures to improve sustainable mobility in the area. In particular, complementary policies and interventions planned in the document include two new tramlines, parking management interventions, such as a new pricing scheme and park-and-ride facilities, new cycle paths to improve the current bike network connectivity, pedestrian zones in the central part of the city, and streets with a speed limit of 30 km per hour (Comune di Padova, 2019). In line with the scope of the ReVeAL project, the performed research was carried out as a preliminary ex-ante assessment of the impacts of the new LEZ on pollutant emissions generated by vehicle flows. Nevertheless, in this paper a detailed analysis focused on the relationship between travel behavioral changes after the measure and pollutant emissions implementation was performed.

2.2. Data collection

In order to reach the objectives of the paper, four types of data sources were used. The former was a mobility survey, aiming to understand the possible changes in mobility behavior of future stakeholders of the new LEZ after its introduction. The latter were existing origin–destination matrices, representing travels of various vehicle classes within the area. The third one were traffic counts, adopted to estimate the trips of motorized vehicles entering the area. The last one were existing permits to enter the current LTZ. All these datasets were collected or directly provided within the scope of the ReVeAL project. In addition, data at the census area level, obtained from the Italian National Institute of Statistics (ISTAT), were used.

2.2.1. Mobility survey

The survey was made up of three sections: “Status quo”, “Future LEZ implementation” and “Socio-demographic characteristics”. In the first section, travel habits of respondents, as well as their opinions concerning the current LTZ were investigated. In particular, they were asked to report the travel modes, the frequency, and purpose of the most frequent trip performed to enter the area. Furthermore, questions were asked about the ease of traveling in the zone and the effectiveness of the current LTZ in reaching specific social and environmental goals. The second section focused on the future mobility behavior of respondents after the implementation of the new regulation. To increase the reliability of their answers, a detailed description of the new measure was provided, based on the drafted regulatory framework proposed by the Municipality of Padova within the scope of the ReVeAL project (Lewald, 2022). In particular, a figure depicting the boundaries of the LEZ was shown. Moreover, details about characteristics of allowed vehicles and users, as well as the time periods when the LEZ is enforced were given. After this introduction, respondents had to rate their propensity toward the new measure. Furthermore, they were asked to state their willingness to replace their car or to adopt an alternative mode to access the area rather than private vehicles. Besides, respondents had to answer questions regarding the potential impacts of the new measure; this set of questions was the same proposed in previous works investigating similar topics (Beck et al., 2013; Eriksson et al., 2008; Jagers et al., 2017; Oltra et al., 2021; Tarrino-Ortiz et al., 2023). In the last section, information about socio-demographic characteristics of respondents was collected. Some of the questions included in the mobility survey and used for the subsequent analysis are reported in Table 2 and Table 3.

Table 1

Description of the vehicle engine type requirement to enter the new LEZ.

Vehicle type	Allowed engine type
Public transport vehicles	Full Electric
Taxi vehicles	Full Electric
Rideshare car rental vehicles	Full Electric
Public service vehicles	Full Electric
Public administration vehicles	Full Electric, Petrol Hybrid, CNG/LPG Bi-fuel, CNG/LPG, Petrol (Euro standard 2 or higher)
Vehicles of non-resident people owing a parking space in the area	Full Electric
Motorbikes	4-stroke engine

The survey was administered through an online questionnaire, which potential stakeholders were invited to fill out, by sending them an In particular, in order to ensure that respondents were actually those affected by the new LEZ (Gonzalez et al., 2022), a list of stakeholders was provided directly by the Municipality of Padova. This list included identified people who live and/or work in the area, such as representatives of residents, and many social, economic, and service activities, such as schools, local administration, university, shops, taxi service, hospitals, and medical centers. To increase the number of potential respondents, recipients of invitation letters were asked to share the link to the survey with their employees and colleagues. In this way, the targeted people were real stakeholders of the new LEZ, who could be actually affected by its implementation. Specifically, since no preliminary information about the universe of stakeholders of the new LEZ were available, a simple random sampling technique was adopted. However, an ex-post stratification based on the following stakeholder categories was carried out: residents, people working in the area and those entering the zone for other purposes (such as study and leisure). The adopted approach contributes to provide sound data as input for the subsequent analysis. The survey was administered from March to June 2022.

2.2.2. Traffic counts

In order to estimate the travel demand of vehicles entering the current LTZ and to quantify the trips potentially accessing the new LEZ, traffic count data were used. In particular, they were obtained from the current automatic access control system, the existing continuous traffic counters in the city, and a specific on-site short-term traffic monitoring activity. The former monitoring system records vehicles 24 h a day; data are provided with a one-hour time interval. With the second monitoring system, data were gathered from existing traffic counters located on the main road network within the administrative boundaries of the Municipality. With reference to the third data collection program, cameras were installed on road sections crossed by vehicles entering the zone. This field activity was needed to cover all gates toward the study area, since not all the entries are monitored by the current control system. Videos were recorded from 7:30 to 19:30 on a working day in May 2022. The time period was selected based on the analysis of trips obtained from the operating control system, and was considered representative of the daily peak period.

Data from the three sources were processed to temporally align the three datasets. Fig. 1 shows the 47 considered road sections, 18 of which were located in the current LTZ, so that detailed and accurate information about the trips circulating in the study area could be obtained.

2.2.3. Access permits

As described in Section 2.1, access to the current LTZ is regulated by permits released by the Police Department. In particular, in order to enter the area, a vehicle owner has to buy a permit, that is associated with the number plate of a single vehicle. In this way, non-compliant vehicles can be detected by the existing automatic number plate recognition system and fines can be sent directly to the vehicle owner. The database of access permits was a list of plate numbers allowed to access the LEZ. This data source was used to define the distribution of vehicle technologies, thus identifying vehicles that can be impacted by the new drafted regulation and understand the zone of residence of vehicle owners.

2.3. Methodology

The following methodological framework was specifically designed to estimate impacts on vehicle pollutant emissions after the introduction of the new LEZ, explicitly considering potential mobility behavioral changes induced by this new policy and uncertainty associated with these modifications. Fig. 3 shows the steps of the adopted workflow.

In particular, for the Base scenario, current travel patterns were used as input to a traffic simulation model to obtain flows and travel speeds on the road network. After that, pollutant emissions generated by vehicles circulating in the area were estimated, considering vehicle characteristics and output of the traffic simulation model. For future scenarios corresponding to the introduction of the new LEZ, data from the mobility survey were used to estimate a model that predicts the probability of adopting specific mobility behaviors after LEZ implementation. Then, the model was applied to estimate the future travel patterns of users in the study area and their modal share. A series of future scenarios were generated considering the stochastic nature of mobility behavioral changes, producing different trips in the area. This information was used as input to a traffic simulation model, developed to represent traffic conditions on the road network and to estimate new traffic flows after the introduction of the new measure. After that, the pollutant emissions generated by vehicles were estimated for the defined scenarios, considering the results of the traffic simulations and the forecasted characteristics of future circulating vehicles as input. Lastly, the results of the Base (LTZ) and Future (LEZ) scenarios were

Table 2
Exogenous variables used in the ICLV model.

Name	Description	Type	Scale
Acceptability	Extent of acceptability of the new Low Emission Zone	Ordinal	From 1 = "Strongly disagree" to 5 = "Strongly agree"
Age	Age of the respondent	Metric	Years
Car availability	Available car to enter the area	Categorical	Yes, No
Driving license	Owned driving license	Categorical	Yes, No
Frequency	Frequency of access the area	Metric	Times per week
Gender	Gender of the respondent	Categorical	Female, Male
Purpose	Purpose to access the area	Categorical	Work, Shopping, Leisure
Travel mode	Travel mode currently adopted to enter the area	Categorical	Private car, Motorbike, Public transportation, Private bike, Walking

Table 3
List of indicators used in the ICLV model.

Question	Statement
Q1	To what extent do you consider that the current Limited Traffic Zone can address the following needs? [From 1 = "Very ineffective" to 5 = "Very effective"]
Q1_01	Air quality improvement
Q1_02	Reduction of circulating vehicles (independently of emitted pollutants)
Q1_03	Reduction of circulating vehicles (first considering the most pollutants vehicles)
Q1_04	Reduction of parked vehicles on streets
Q1_05	Extending pedestrian areas
Q2	Considering the area of intervention, to what extent do you agree with the following statements? [From 1 = "Strongly disagree" to 5 = "Strongly agree"]
Q2_01	Currently, traveling by car/motorbike in the area is easy
Q2_02	Currently, walking in the area is safe and pleasant
Q2_03	Currently, riding a bike in the area is safe and pleasant
Q2_04	The area of intervention is easily accessible by people with reduced mobility
Q2_05	There are many alternative travel modes to access the area beyond private car/motorbike
Q12	To what extent do you agree with the following statements regarding the potential new regulation (new Low Emission Zone) in the area? [From 1 = "Strongly disagree" to 5 = "Strongly agree"]
Q12_01	The implementation of the new regulation could impact my travel habits
Q12_04	The implementation of the new regulation could improve the quality of my life
Q12_05	The implementation of the new regulation could improve citizens' quality of life
Q12_06	The new regulation can effectively reduce air pollutants
Q12_07	The implementation of the new regulation could have a negative impact on the economic activities in the area
Q12_08	The implementation of the new regulation could increase traffic flows on the surrounding streets
Q12_09	The new measure is equitable
Q12_10	The new measure could support many people and disadvantage few others
Q12_11	The new measure could make the area more accessible by walking/bike
Q12_12	The new measure could make the area more accessible by car
Q12_13	The new measure could improve road safety of walking and bike trips in the area

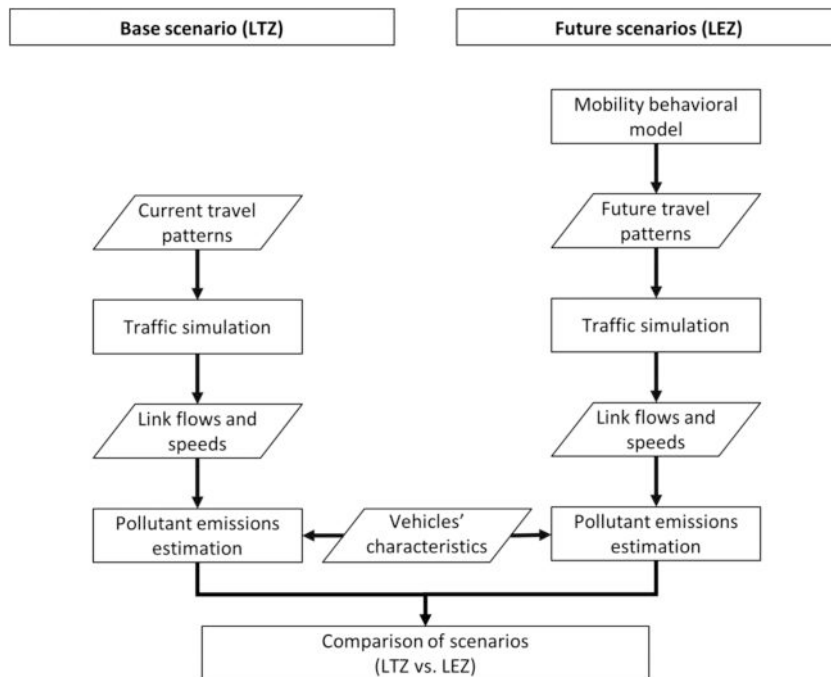


Fig. 3. Steps of the adopted methodological framework.

compared to quantify the impacts of the drafted regulation on vehicle pollutant emissions, taking into account the uncertainties associated with behavioral changes. Each of the modeling steps is described hereinafter.

2.3.1. Data integration

As reported in Section 2.2, several datasets were provided within the scope of the ReVeAL project. Each of them was used in the next

methodological steps as input of the adopted models. However, each single set of data could not be individually used to obtain a comprehensive analysis of the characteristics of all vehicles impacted by the planned measure. In particular, the mobility survey gave information to forecast the behavioral changes induced by the LEZ on the sampled stakeholders. The existing origin–destination matrices and the recorded traffic counts respectively referred to the entire number of vehicles travelling in the area and those actually entering the future LEZ, independently from the vehicle technology. Access permits provided information about the distribution of vehicle types and technologies for the whole universe of vehicles that could potentially enter the area. To overcome the limitations of each dataset and to obtain coherent and reliable information about the universe of vehicles entering the regulated area, all the datasets were integrated and aligned. In particular, by applying an Iterative Proportional Fitting approach (Ortuzar and Willumsen, 2011), the information from the provided datasets were combined to obtain a synthetic population of motorized vehicles currently accessing the future LEZ area and their characteristics, in terms of vehicle type and technology.

2.3.2. Mobility behavioral model

To model the complex decision process that leads to a potential adaptation of users' behavior after the introduction of the new LEZ, an Integrated Choice and Latent Variable (ICLV) model was implemented (Vij and Walker, 2016). Psychological factors, such as opinions, perceptions, and attitudes, were found to play a significant role in traveler's choices (Jagers et al., 2017; Morton et al., 2021; Oltra et al., 2021; Sun et al., 2016). In particular, previous authors highlighted some latent factors that could influence individual behaviors toward a vehicle access restriction measure, such as policy beliefs, like the perceived effectiveness of the new regulation in reaching sustainable goals (Eriksson et al., 2008), the awareness of current environmental issues (Jia et al., 2017), and negative attitudes toward the new intervention (Jiménez-Espada et al., 2023). In addition, unobserved psychological factors were found to impact travel habits, such as mode choice (Kamargianni et al., 2015; Kim and Lee, 2023). Therefore, neglecting the potential effect of latent variables on mobility behavior can lead to a poor analysis of mobility behaviors, particularly when observable variables cannot completely explain complex travel decisions or the impact of these variables can be overridden by the influence of latent constructs (Vij and Walker, 2016). Compared to traditional discrete choice models, the ICLV allows to explicitly include the effect of psychometric latent variables to better understand user's behaviors (Kamargianni et al., 2015). By including these latent constructs as soft covariates, ICLV models allow to obtain a deeper understanding of the decision process, thus improving predictive ability of traditional models (Abou-Zeid and Ben-Akiva, 2011; Bhat and Dubey, 2014). Lastly, unlike Structural Equation Models, the ICLV model combines the factor analytic technique, used to highlight potential latent variables, with classical econometric approach (Vij and Walker, 2016).

Specifically, A ICLV model consists of two elements: a discrete choice sub-model and a latent variable sub-model. The former is based on the Random Utility Theory framework (McFadden, 1974), in which a decision maker n is assumed to choose the alternative i that maximizes their perceived utility. Latent variables, representing any unobservable aspects of the individuals, cannot be directly measured, therefore, they are defined as a function of other observable variables. In particular, in the latent variable sub-model, structural equations define the relationship between observed characteristics of the individuals and latent variables, which, at the same time, explain a set of indicators, obtained from the individuals, through measurement equations (Bahamonde-Birke et al., 2017b).

Specifically, for a decision maker n , a generic (l) latent variable X_{lin}^* depends on k explanatory variables X_{kin} , following the structural equation:

$$X_{lin}^* = \lambda_0 + \sum_k \lambda_{lki} X_{kin} + \varpi_{lin} \quad (1)$$

where λ_0 is a constant, λ_{lki} are coefficients associated with X_{kin} and ϖ_{lin} is a random error term.

Latent variables cannot be observed by the analyst; therefore, their indirect measurement is performed by collecting a set of q indicators, whose value is directly provided by individuals in surveys. For this reason, measurement equations are used to measure latent variables through indicators (Atasoy et al., 2013). In particular, a generic continuous indicator I_{qin}^* is defined by the measurement equation:

$$I_{qin}^* = \alpha_0 + \sum_t \alpha_{lqi} X_{lin}^* + \xi_{qin} \quad (2)$$

where α_0 is a constant, α_{lqi} are coefficients associate with latent variable X_{lin}^* and ξ_{qin} is a normally distributed random error component (Bahamonde-Birke et al., 2017b). For identification purposes, the constant and coefficient values of one of the indicators associated with each latent variable have to be normalized to 0 and +/- 1, respectively (Ben-Akiva et al., 2002).

In this work, observed indicators I_{qin} are gathered from individuals using a Likert scale with 5 levels. Therefore, 4 parameters τ_s are defined, so that:

$$I_{qin} = \begin{cases} 1 & \text{if } I_{qin}^* \leq \tau_1 \\ 2 & \text{if } \tau_1 < I_{qin}^* \leq \tau_2 \\ 3 & \text{if } \tau_2 < I_{qin}^* \leq \tau_3 \\ 4 & \text{if } \tau_3 < I_{qin}^* \leq \tau_4 \\ 5 & \text{if } I_{qin}^* > \tau_4 \end{cases} \quad (3)$$

And

$$\tau_1 \leq \tau_2 \leq \tau_3 \leq \tau_4 \quad (4)$$

The probability that observed indicator I_{qin} takes the value z in the Likert scale is given by:

$$P(I_{qin} = z) = P(\tau_{z-1} < I_{qin}^* \leq \tau_z) \quad (5)$$

As in previous works applying ICLV models (Abou-Zeid and Ben-Akiva, 2011; Bouscasse, 2018; Kavta and Goswami, 2022), latent variables are assumed to be normally distributed, therefore the probability of obtaining a given response for a generic indicator is obtained from an ordered probit model.

In addition, in order to consider the symmetry of the observed indicators, two parameters to be estimated (Δ_1 and Δ_2) are defined, so that:

$$\begin{cases} \tau_1 = -\Delta_1 - \Delta_2 \\ \tau_2 = -\Delta_1 \\ \tau_3 = +\Delta_1 \\ \tau_4 = +\Delta_1 + \Delta_2 \end{cases} \quad (6)$$

In the discrete choice sub-model, taking the form of a multinomial choice mode (Bahamonde-Birke et al., 2017a; Vij and Walker, 2016), the utility function is expressed as a function of explanatory observed variables X_{kin} and latent variables X_{lin}^* :

$$U_{in} = \beta_0 + \sum_k \beta_{ki} X_{kin} + \sum_l \beta_{li} X_{lin}^* + \varepsilon_{in} \quad (7)$$

where β_0 is a constant, β_{ki} are coefficients associated with X_{kin} , β_{li} are coefficients associated to X_{lin}^* and ε_{in} is an independently and identically Gumbel-distributed error term. The stochastic components ω_{lin} , ξ_{qin} and ε_{in} are assumed to be independent (Vij and Walker, 2016).

In this work, the potential behavioral choices of a generic stakeholder after the LEZ implementation were evaluated. In particular, as regards those directly impacted by the new measure, i.e. stakeholders currently using a private motorized mode that is no longer allowed to enter the area by the drafted regulation, the following three alternative short-term options were considered:

- Vehicle substitution: replacing the currently adopted private motorized vehicle to enter the area with a less polluting one.
- Modal shift: switching from the currently used motorized means toward a sustainable mode, such as public transportation, bike, or walking.
- Destination change: maintaining the currently adopted travel mode and avoiding to enter the new regulated area.

The considered explanatory variables include socio-demographic characteristics and travel habits of respondents and are reported in Table 2. Indicators were gathered from respondents' answers to specific questions listed in Table 3. These items were derived from previous studies investigating users' opinions concerning the introduction of urban vehicle access restrictions, in general, and a LEZ, in particular (Beck et al., 2013; Eriksson et al., 2008; Jagers et al., 2017; Oltra et al., 2021; Tarrino-Ortiz et al., 2023). In order to validate the model, the following out-of-sample validation approach was adopted (Glerum et al., 2014). First, the original dataset was randomly divided into two portions, containing the 80 % and 20 % of the observations respectively. Then, the model was re-estimated on the first subset (80 % of the observations) and applied to the second subset to test its prediction capabilities.

The estimation, validation, and application of the ICLV model was performed using Biogeme software (Bierlaire, 2023).

2.3.3. Traffic simulation model

A traffic simulation model was implemented to represent traffic flows on the network, for both the Base and Future scenarios. On the supply side, the entire territory of the Municipality was considered, to evaluate the impacts on all the trips in the study area (Rodriguez-Rey et al., 2022; Sánchez et al., 2021), that is depicted in Fig. 1. In particular, the area was partitioned into 504 Traffic Analysis Zones (458 internal zones and 46 external zones). The road network consisted of 16,765 nodes and 22,456 links. On the demand side, existing origin–destination matrices were updated with traffic counts registered in the 47 road sections reported in Section 2.2.2, thus obtaining the current travel demand for the Base scenario. These matrices represent motorized vehicle trips in the area (cars, motorbikes, public transport vehicles and freight vehicles) and were derived from the provided Sustainable Urban Plan of Padova. In line with the procedure adopted in that plan (Comune di Padova, 2019), the traffic simulation model was implemented to obtain flows that might occur on a working day. Therefore, the model was calibrated considering traffic volumes observed during the on-site activities carried out in a working day in May 2021, within the scope of the ReVeAL project. The analysis of data from the existing access monitoring system of the current LTZ pointed out that the number of vehicles entering the area in that day was similar to those recorded in other working days. Furthermore, the selected period overlapped the one corresponding to the administration of the mobility survey to stakeholders (Section 2.2.1), thus aligning the two data sources. As far as the future scenarios are concerned, the sub-matrix representing trips entering the area was modified by applying the mobility behavioral model to generate travel demand after the implementation of the LEZ. Specifically, the following travel patterns were assigned to the predicted behavioral changes of individuals currently using a motorized travel mode, whose access is no longer allowed by the drafted regulation:

- The trips of those who decided to replace the adopted private vehicles with less polluting ones were maintained.
- The trips of those who decided to shift to a less polluting travel mode were diverted to active modes and public transportation.
- The trips of those who decided not to enter the area were assumed to stop at the TAZ closest to the boundary of the regulated area, thus simulating that the private vehicle is used to reach the nearest parking space, from where the traveler can walk to the LEZ (Dias et al., 2016; Gonzalez et al., 2023).

In this way, a coherent procedure was adopted. In particular, in order to predict the potential changes on travel behavior of those actually impacted by the new regulation, the behavioral model was applied to the synthetic population of stakeholders currently entering the area of the future LEZ, using private motorized vehicles (car and motorbike). Specifically, the obtained distribution of travel behaviors was assigned to the flows of vehicles currently accessing the future LEZ, corresponding to vehicles that could be affected by the measure. These volumes were derived from the traffic simulation model representing the current situation (Base scenario).

Simulation runs were carried out considering the AM peak period (7:00–8:00), when approximately 15 % of vehicles were observed to enter the regulated area, so that the worst conditions on the road network are modeled (Host et al., 2020; Sánchez et al., 2021). The procedure was implemented using CUBE Voyager (Bentley Systems, 2020).

2.3.4. Emission estimates

For Base and future scenarios, pollutant emissions were quantified, with the aim of assessing the impacts of the introduction of a LEZ on those emissions in the area. Specifically, only emissions generated by motorized private vehicles were considered, since the evaluation is based on relative terms respect to the Base scenario and public transportation means usually circulate independently on the number of passengers (Sánchez et al., 2021). Moreover, active modes, such as bicycle and walking, were assumed to generate zero pollutant emissions (Poulhès and Proulhac, 2021). Furthermore, a tank-to-wheel analysis was carried out, thus focusing on pollutants generated by tailpipe emissions, without considering the contribution of energy production (Krause et al., 2020).

The estimation was performed using the COPERT model, developed by the European Environment Agency (EMISIA, 2023). This model has been widely adopted by several authors for independent research activities (Burón et al., 2004; Ceccato et al., 2022; Chicco and Diana, 2021; Host et al., 2020; Jiang et al., 2020; Rodriguez-Rey et al., 2022; Sánchez et al., 2021) and European member states to build official national emission inventories for road transportation (Davison et al., 2021). The implemented approach is based on the formulas of the Tier 3 emission calculation method, reported in the “EMEP/EEA Air Pollutant Emission Inventory Guidebook” (Ntziachristos et al., 2019). The methodology allows to obtain emission factors describing the emission performance of various vehicle types. These factors are derived from well-defined driving cycles, representing standard traffic conditions for different engine technologies. In each cycle and for each pollutant, the relationship between the mean emission level per unit distance and the average driving speed is obtained (Fontaras et al., 2014).

In particular, the following input data were used to estimate the amount of CO, CO₂, NO_x, and PM generated by vehicles traveling on the road network in the study area:

- Length, congested speed, and traffic volume for each link, derived from the traffic simulation model.
- Characteristics of the circulating vehicles: vehicle types, fuel types and EURO emission standards. This information was obtained:
 - o For the Base scenario, by analyzing the database of the current fleet circulating in the area (ACI, 2023).
 - o For future scenarios, by considering the proposed regulation for the new LEZ and the characteristics of the new vehicles registered in the area (ACI, 2023), which were assumed to be purchased by those deciding to replace their current motorized vehicle (Peters et al., 2021; Rodriguez-Rey et al., 2022). In particular, in this scenario, vehicles impacted by the measure were selected by combining the planned access restrictions and the characteristics of vehicles currently entering the regulated area, obtained from the database of circulation permits, as described in Section 2.3.1.

Following this procedure, the pollutant emissions generated by vehicles circulating in the entire road network were calculated for each scenario, considering, for the future ones, the new restrictions applied in the new LEZ and the behavioral changes induced by its implementation. The total emissions of the future scenarios were compared with those obtained for the base one to quantify impacts on pollutants generated by vehicles.

2.3.5. Uncertainty in future scenarios

In order to evaluate the impacts of the LEZ introduction on vehicle pollutant emissions in the study area considering uncertainties associated with potential changes in stakeholders' behavior, several future scenarios were generated. In particular, the application of the behavioral model allowed to obtain the probabilities that an individual entering the LEZ with motorized means no longer authorized to access the area could decide to replace the vehicle, shift to a sustainable mode, and avoid entering the regulated area. The model also provided an estimation of the potential variabilities associated with these choices, thus implicitly quantifying the stochastic nature of these outcomes. In particular, as in any Random Utility Model (Train, 2003), the choice probabilities were obtained through a simulation approach, in which utility of each alternative is calculated for many draws of the random terms; in this way, a set of choice probabilities is estimated for each choice option. The resulting probability ranges were combined to obtain several potential future scenarios, each of which implementing the effect of possible changes in mobility behaviors induced by the new LEZ.

3. Results

3.1. Characteristics of the sample

The survey link sent to potential stakeholders of the new LEZ was accessed by 509 individuals and 236 of them completed the entire questionnaire. Due to the spatial configuration of the analyzed area, gathering the characteristics of the universe of the population entering the zone to assess the representativeness of the sample was challenging. Nevertheless, to achieve this aim, a detailed review of existing official data sources was carried out. Results are presented hereinafter, in addition to practical considerations about the spatial and temporal alignment between the sample and available information related to the whole population of potential stakeholders of the LEZ. Data about permits to enter the area, issued by the Police Department, and traffic counts, performed during on-site activities, are referred to the analyzed period, however they are related only to vehicles, and, therefore, they do not contain information about people using different travel modes to access the LEZ. Furthermore, official statistical data provided by the Municipality of Padova included information only about residents in the central area of the city, that does not match the planned boundaries of the new LEZ (Comune di Padova, 2021). A better spatial alignment was observed for official data provided by the Italian National Institute of Statistics (ISTAT). The dataset included information about residents and people working in census areas, however the former were retrieved in 2021 (ISTAT, 2021) and the latter in 2011 (ISTAT, 2011). These data were considered to carry out a tentative analysis on the minimum sample size and the related potential margin of error, since they provided the best spatial alignment and the best temporal alignment for residents; furthermore, this dataset is the only one reporting information about employees in the area. Based on this analysis, the universe of residents and stakeholders is about 7.500 people. Following the approach adopted by Hensher et al. (Hensher et al., 2005), the sample size was found to be appropriate, considering the propensity toward a more sustainable behavior as the discriminant choice outcome, for a margin of error of 10 % at 90 % confidence level.

The basic characteristics of the collected sample and the travel habits related to the regulated area are reported in Table 4. Considering the previously described limitations of the datasets about the universe of stakeholders of the LEZ, the mean age (49.5) and the gender distribution (54 % of female respondents) of the sample are similar to those of residents in the central part of the city (average age of 49.4 and 55 % of female residents) (Comune di Padova, 2021; ISTAT, 2021). By observing the table one can note that about 40 % of the users frequently access the area and no respondents stated that they never entered the zone, thus confirming that the survey properly targeted those that could be impacted by the drafted regulation. The modal share of trips toward the area shows that the majority of participants uses active modes (about 60 %); while around one fifth of travels is carried out on motorized means (private car and motorbike), public transportation is adopted by 11 % of respondents. The distribution of the main purposes to enter the area is quite balanced among work, shopping, and leisure. The results shown in Table 4 highlight that most of the interviewed stakeholders supports the adoption of the LEZ (about 67 %), indicating a future potential willingness to comply with the drafted regulation and, therefore, possible consequent behavioral changes.

Table 5 reports the percentage distribution of the stated changes in travel habits to enter the area after the introduction of the new LEZ. The shown data are obtained from the mobility survey, by analyzing the collected responses of stakeholders directly impacted by the drafted regulation. The results indicate that a significant portion of people (around 67 %) could decide to travel by using the current motorized mode to reach an area closest to the boundary of the regulated zone. Furthermore, 16 % of stakeholders are willing

Table 4
Characteristics and travel habits of the collected sample of stakeholders.

		N	Percentage
Frequency of entering the area	Never	0	0.0 %
	Less than once a week	85	36.0 %
	From 1 to 3 times a week	60	25.4 %
	More than 3 times a week	91	38.6 %
Travel mode to access the area	Car	43	18.2 %
	Motorbike	13	5.5 %
	Public transportation	27	11.4 %
	Private bike	67	28.4 %
Purpose	Walking	86	36.4 %
	Work	91	38.6 %
	Shopping	69	29.2 %
Acceptability of the LEZ	Leisure	76	32.2 %
	Strongly disagree	10	4.2 %
	Disagree	37	15.7 %
	Neutral	30	12.7 %
Gender	Agree	91	38.6 %
	Strongly agree	68	28.8 %
	Female	142	60.2 %
Age	Male	94	39.8 %
	20–35	23	9.7 %
	36–50	81	34.3 %
	51–65	127	53.8 %
	More than 65	5	2.1 %

to replace their current means with a less polluting one, allowing them to enter the LEZ. Lastly, a modal shift toward a sustainable mode, such as public transportation, could occur for 16 % of the individuals. The analyzed distribution pointed out that different behavioral choices could occur after the introduction of the new LEZ, entailing complex consequences on the transportation system. For this reason, unlike previous works, these impacts should not be neglected in the estimation of effects of the drafted regulation on pollutant emissions generated by vehicles in the area.

3.2. Mobility behavioral model estimation

In order to ensure a proper specification of the latent variables, an Exploratory Factor Analysis was performed (Atasoy et al., 2013). This technique allows to understand what observed indicators reveal most of the information about the latent variables and it was adopted since the relationship between these two elements was unknown (Simpson et al., 2022). In particular, this approach is used to identify significant relationships between indicators and latent variables, which are modeled through measurement equations described in Section 2.3.1. Table 6 shows the factor loadings obtained by using a promax rotation method and considering a threshold value of 0.4 (Hair et al., 2018). Three factors (corresponding to latent variables) were identified, respectively explaining 17 %, 16 % and 10 % of the total variance. The internal consistency of these constructs was assessed by estimating Chronbach's alphas, that were all greater than 0.6 (Kavta and Goswami, 2022). Based on this analysis, three latent variables can be used for the ICLV model. In particular, the first latent variable (Factor 1) includes indicators associated with potential positive impacts of the new LEZ, such as improving citizens' quality of life, reducing air pollutants, and increasing safety. The second latent variable (Factor 2) groups statements concerning the perceived effectiveness of the current LTZ (e.g., the reduction of circulating and parked vehicles, safety of biking and walking trips). The third latent variable (Factor 3) is useful to understand negative attitudes toward the new regulation and includes items related to the absence of travel modes alternative to private motorized means to enter the area, negative impacts on commercial activities within the area, and new traffic generated on the roads surrounding the LEZ. By analyzing the three constructs, the associate latent variables were respectively named "Perception of benefits of the new LEZ", "Perceived effectiveness of the current LTZ" and "Negative attitude toward the new LEZ".

The results of the latent variable sub-model are reported in Table 7 and Table 8. In particular, the former shows the structural equations, and the latter shows the measurement equations. Results in Table 7 indicate that the two latent variables related to the new LEZ are explained by the same variables but with opposite signs of coefficients. Specifically, being aged less than 40 years increases the perception of benefits of the new measure and decreases the negative attitude toward the LEZ. This could be due to the higher awareness toward environmental issues that younger people tend to have, compared to older people; for this reason, they are likely to perceive the current LTZ regulation as not so effective in reaching sustainable goals; therefore, they probably consider that the new LEZ could have a more significant positive impact on environment. Moreover, using a private car to enter the area was found to increase the negative attitude toward the new LEZ, and, symmetrically, decrease the perception of benefits of the new measure. This highlights that car drivers tend to be against the introduction of LEZ. Regarding the latent variable related to the current LTZ, being under 40 years was observed to decrease the perceived effectiveness of the measure, while an opposite effect was found for infrequent accesses to the area. The signs of the coefficients of the measurement equations reported in Table 8 are in line with expectations. In particular, they are all positive, except that of indicator Q2_05, corresponding to the availability of means alternative to private car to enter the regulated area. As reported in Section 2.3.1, for each measurement equation associated with a latent variable, the intercept and the coefficient of each indicator were respectively fixed at zero and unitary value (one or minus one, depending on the results of the factor analysis).

As described in Section 2.3.1, the discrete choice sub-model is used to predict the likelihood to change travel behavior after LEZ implementation for those affected by the drafted regulation (i.e., vehicle substitution, mode shift, and destination change). Several model specifications were tested, and the results of the best model are reported in Table 9, which shows the obtained significant variables. As one can note, the signs of the constants of mode shift and destination change options are respectively negative and positive. This indicates that, compared to vehicle replacement, mode shift decisions are less likely to be adopted, and destination changes are more likely to occur, all other things being equal. Furthermore, the acceptability of the drafted regulation was found to play a significant role in future behaviors. Specifically, those against the LEZ tend not to replace their vehicles, while those supporting the measure are more willing to shift to a sustainable travel mode. Regarding the vehicle substitution decision, older people working in the future LEZ are more likely to replace their vehicle, probably because they could have a higher income than young people. Furthermore, the frequency of accessing the area decreases the likelihood to substitute the current travel mode. Lastly, concerning the decision to adopt a more sustainable travel mode, the perception of potential benefits of the new LEZ increases the likelihood to perform the shift. The goodness-of-fit indicators for the estimated ICLV model are reported in Table 10.

The results of the out-of-sample validation of the estimated ICLV model are reported in Table 11. The table shows the observed market share of the three behavioral choice options, as well as the predicted market share with the average value and the corresponding 90 % confidence interval bounds, which were generated by simulation (Piras et al., 2021). As one can note, the observed and

Table 5
Distribution of behavioral changes after the LEZ introduction.

Behavioral choice	Percentage value
Vehicle substitution	16.3 %
Mode shift	16.3 %
Destination change	67.4 %

Table 6
Results of the Exploratory Factor Analysis.

Statement*	Factor 1	Factor 2	Factor 3
Q1_01			
Q1_02		0.629	
Q1_03		0.589	
Q1_04		0.616	
Q1_05		0.649	
Q2_01			
Q2_02		0.800	
Q2_03		0.672	
Q2_04		0.561	
Q2_05			-0.485
Q12_01			0.410
Q12_04	0.710		
Q12_05	0.729		
Q12_06	0.791		
Q12_07			0.670
Q12_08			0.445
Q12_09	0.706		
Q12_10			
Q12_11	0.624		
Q12_12			
Q12_13	0.579		

* Statement details are reported in Table 3.

Table 7
Results of the structural equations of the ICLV model.

Name	Perception of benefits of the new LEZ		Perceived effectiveness of the current LTZ		Negative attitude towards the new LEZ	
	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
Age less than 40	0.240	1.920	-0.394	-2.210	-0.337	-2.160
Car mode	-0.433	-3.120	-	-	0.714	3.990
Frequency less than once a week	-	-	0.326	1.870	-	-
Intercept	0.655	8.670	0.437	4.090	-0.192	-2.470

predicted choice probabilities are quite similar, highlighting the good prediction capability of the developed model.

Behavioral changes and pollutant emissions

The following tables report the results of the scenarios obtained by applying the model predicting future behavioral changes after the introduction of the new LEZ and performing traffic simulations. Specifically, in order to synthesize the potential range of the impacts of the new measure considering uncertainty associated with variations in mobility habits, the outcomes are provided for three scenarios: an average scenario and two scenarios (Minimum and Maximum scenario), respectively minimizing and maximizing the positive effects of the drafted regulation. Furthermore, in order to provide a holistic view of these impacts, the results were analyzed considering future potential modal share, as well as the pollutant emissions.

In particular, Table 12 shows the modal share of people accessing the LEZ for the current and future scenarios, where travel modes are grouped into motorized means and other means (public transportation and active modes). The results highlight that the measure could reduce the current modal share of motorized means (about 23 %); specifically, the percentage reduction is 4.1 % on average and it ranges from 1.8 % to 7.7 %.

To quantify the impacts of the new LEZ on vehicle pollutant emissions both within and outside the regulated area, pollutant emissions were calculated by distinguishing vehicles circulating in the two zones. In particular, for each pollutant, for each vehicle technology and for each link of the network, emission factors were estimated as a function of the congested speed on that link, obtained from the traffic simulation model. Then, for each pollutant, for each vehicle technology and for each link, emission factors were multiplied by the length of that link to calculate the emissions generated by that vehicle technology. Following the COPERT approach, for each pollutant and for each link, the total emissions produced by all vehicles on that link were estimated as the weighted average of different vehicle technologies traveling on that link, where traffic volumes on that link were provided by the simulation model. The same procedure was applied for the Base and Future scenarios. However, in the former, the current distribution of vehicle technologies was considered. Whereas, in the latter, forecasted behavioral changes caused new traffic flows on the links and a new distribution of vehicle technologies for those entering the LEZ.

Table 13 reports the estimated absolute values of CO, CO₂, NO_x, and PM₁₀ produced by vehicles for the Base scenario, whereas Table 14 shows the percentage variations estimated for future scenarios with respect to the current one, considering all the vehicles circulating in the study area (the one regulated by the new measure and the zone outside the LEZ). The results indicate that the measure could significantly decrease the amounts of pollutant emissions within the regulated area. Specifically, different reduction

Table 8

Results of the measurement equations of the ICLV model.

Latent variable	Indicator		Value	Rob. Std err	Rob. t-test	Rob. p-value
Perception of benefits of the new LEZ	Q12_04	Const.	-0.733	0.367	-2.000	0.046
		Coeff.	1.500	0.548	2.740	0.006
	Q12_05	Const.	-0.299	0.289	-1.040	0.300
		Coeff.	1.370	0.431	3.170	0.002
	Q12_06	Const.	-0.480	0.301	-1.590	0.111
		Coeff.	1.300	0.448	2.900	0.004
	Q12_09	Const.	-0.594	0.281	-2.110	0.035
		Coeff.	1.110	0.419	2.640	0.008
	Q12_11	Const.	0.104	0.151	0.688	0.491
		Coeff.	0.975	0.244	4.000	0.000
	Q12_13	Const.	0.000	-	-	-
		Coeff.	1.000	-	-	-
Perceived effectiveness of the current LTZ	Q1_02	Const.	0.198	0.157	1.260	0.207
		Coeff.	0.761	0.294	2.590	0.010
	Q1_03	Const.	0.000	-	-	-
		Coeff.	1.000	-	-	-
	Q1_05	Const.	0.348	0.189	1.840	0.065
		Coeff.	0.577	0.349	1.650	0.098
Negative attitude toward the new LEZ	Q2_05	Const.	0.000	-	-	-
		Coeff.	-1.000	-	-	-
	Q12_01	Const.	0.214	0.090	2.380	0.017
		Coeff.	0.867	0.285	3.040	0.002
	Q12_07	Const.	0.118	0.100	1.190	0.235
		Coeff.	1.200	0.311	3.860	0.000
Parameter						
Delta1			0.335	0.020	16.800	0.000
Delta2			0.889	0.042	21.200	0.000

Table 9

Results of the discrete choice sub-model of the ICLV model.

Name	Vehicle substitution		Mode shift		Destination change	
	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
Constant	-	-	-4.810	-3.620	6.980	4.060
Acceptability – Strongly disagree [ref.Neutral]	-7.010	-9.770	-	-	-	-
Acceptability – Agree [ref. Neutral]	-	-	2.040	2.530	-	-
Age	0.120	3.610	-	-	-	-
Frequency	-0.427	-1.645	-	-	-	-
LV – Perception of benefits of the new LEZ	-	-	13.200	7.510	-	-
Purpose – Work	1.170	1.790	-	-	-	-

Table 10

Indicators of the goodness-of-fit of the ICLV model.

Goodness-of-fit indicator	Value
Null log likelihood	-6332.43
Final log likelihood	-3745.89
Likelihood ratio test	5173.09
Rho-square-bar	0.401
AIC (Akaike criterion)	7589.78
Bayesian Information Criterion:	7759.51

Table 11

Results of ICLV validation.

Behavioral choice	Observed market share	Predicted market share		
	Value	Average value	90 % C.I. lower bound	90 % C.I. upper bound
Vehicle substitution	2.1 %	3.5 %	1.3 %	8.3 %
Mode shift	70.2 %	72.9 %	67.6 %	78.1 %
Destination change	27.7 %	23.6 %	16.8 %	29.4 %

Table 12
Current and future modal share after the LEZ introduction.

Scenario	Current modal share	Future modal share		
	Base	Average	Minimum	Maximum
Motorized means	23.7 %	19.6 %	21.9 %	16.0 %
Other means	76.3 %	80.4 %	78.1 %	84.0 %

ranges are obtained, depending on the considered pollutants: from 90.6 % to 98.1 % for CO, from 76.6 % to 95.4 % for CO₂, from 97.5 % to 99.5 % for NO_x and from 96.5 % to 99.3 % for PM₁₀. These benefits are due to the adoption of less polluting vehicles and modal shift toward more sustainable modes, both induced by the introduction of the drafted regulation. However, these positive effects are strongly reduced if the area outside the LEZ is considered. Specifically, percentage change of CO ranges from 1.2 % to −1.1 %, that of CO₂ from 0.0 % to −1.0 %, that of NO_x from 0.1 % to −1.4 % and that of PM₁₀ from −0.3 % to −1.4 %. As one can note, even if the magnitude of such variations is quite limited due to the extension of the study area, the analysis points out that, in some cases, pollutant emissions could increase outside the regulated zone. This could be due to the longer trips that some travelers have to carry out, in order to avoid entering the LEZ and park the vehicle in areas close to the boundary of the regulated zone.

4. Discussion of results

The implemented analysis framework was used to quantify impacts on vehicle pollutant emissions after the introduction of a LEZ, considering potential behavioral changes and their uncertainty induced by the new regulation. The mobility behavioral model allowed to understand the factors affecting new travel habits of potential users of the LEZ. In particular, as described in Section 3.2, the results of the ICLV model indicated that younger people tend to be more inclined to this kind of innovative and sustainable regulation (Hansla et al., 2017; Morton et al., 2021), showing a positive perception of the benefits of such a measure. Furthermore, as highlighted in previous studies (Oltra et al., 2021; Sun et al., 2016), car drivers tend to be against the introduction of LEZ and other vehicle access restrictions, since these interventions directly impact their travel habits. This suggests that a proper strategy to gather their support should be designed, for instance, by progressively implementing the planned restrictions (Ellison et al., 2013). In addition, people occasionally entering the area were found to consider the current LTZ as an effective measure to tackle congestion and pollution problems in the city center, probably because these individuals are only partially impacted by the LTZ restrictions and therefore more inclined to consider the positive aspects of such a measure (Tarrío-Ortiz et al., 2023). Regarding potential changes in travel behaviors after the LEZ implementation, a general unwillingness to change travel mode was pointed out, indicating that people tend to maintain their private vehicle and simply avoid entering the area or substitute it with a less polluting one. This suggests that the LEZ could fail in inducing sustainable travel habits and a potential spillover effect could arise due to the increasing traffic and parking demand in the surrounding areas generated by those who decided to keep their vehicle (Lurkin et al., 2021; Rodriguez-Rey et al., 2022). For this reason, this rebound effect should be considered in the framework to estimate the impacts of a LEZ on vehicle pollutant emissions (Gonzalez et al., 2023). In addition, preferences for vehicle replacement could prevent the measure to reduce traffic and the use of public space within the LEZ, caused by motorized means allowed to enter the area (Gonzalez et al., 2023; Peters et al., 2021). Like in previous works (Jia et al., 2017), the acceptance of the new measure was found to directly impact potential changes in travel behavior toward sustainable habits. This finding indicates that public acceptability is a key element to ensure the effectiveness of the measure in reaching its sustainability targets (Morton et al., 2021; Oltra et al., 2021; Zheng et al., 2014). Moreover, the ICLV model showed that old people are more willing to replace their current pollutant vehicle, probably because they tend to have a high income (Tarrío-Ortiz et al., 2022). In addition, as observed by previous authors, people accessing the area by car for working purposes are likely to maintain their mode, and, therefore, they are more inclined to buy a new vehicle to meet the requirements of the LEZ (Gonzalez et al., 2022). Lastly, the analysis pointed out that awareness of potential positive effects of the new regulation plays a non-negligible role toward the shift to sustainable travel modes (Jia et al., 2017; Nikitas, 2018). This suggests that proper information campaigns about the benefits of the LEZ could be an effective strategy to promote sustainable travel habits among travelers.

The results of the application of the mobility behavioral model allowed to quantify to what extent the measure could induce changes in travel habits of people accessing the regulated area. In particular, the outcomes reported in Section 3.3 pointed out that the measure could lower the modal share of motorized modes. However, the magnitude of the impact is limited (2–8 %), compared to the value obtained by previous authors in Madrid (around 30 %) (Tarrío-Ortiz et al., 2022). The comparison points out that these values

Table 13
Pollutant emissions generated by vehicles circulating within and outside the LEZ for the Base scenario.

Pollutant	Area	
	Within the LEZ	Outside the LEZ
CO [g]	348.5	308'185.2
CO ₂ [kg]	125.8	97'692.8
NO _x [g]	218.6	163'237.5
PM [g]	5.5	4'210.4

Table 14
Percentage reductions of pollutant emissions generated by vehicles circulating within and outside the LEZ for the future scenarios.

Pollutant	Within the LEZ			Outside the LEZ		
	Average scenario	Minimum scenario	Maximum scenario	Average scenario	Minimum scenario	Maximum scenario
CO	-95.3 %	-90.6 %	-98.1 %	0.2 %	1.2 %	-1.1 %
CO ₂	-88.5 %	-76.6 %	-95.4 %	-0.5 %	0.0 %	-1.0 %
NO _x	-98.8 %	-97.5 %	-99.5 %	-0.5 %	0.1 %	-1.4 %
PM	-98.3 %	-96.5 %	-99.3 %	-0.8 %	-0.3 %	-1.4 %

are site-specific, highlighting that the use of data collected on-field is of paramount importance to properly quantify the impacts of a LEZ in a specific region.

The results of the traffic simulation model and the pollutant emission estimation model were used to assess the effects of the new measure on generated pollutants. It is worth mentioning that, although the traffic simulation model allowed to obtain the traffic flows of motorized private vehicles (cars and motorbikes), public transport vehicles and freight vehicles, the output of the model was used to evaluate changes in the traffic patterns of those actually impacted by the proposed regulation. For this reason, flows of motorcycles and private cars were considered for estimating pollutant emissions. In particular, since the objective of the work is to evaluate the effects of the new measure in relative terms, i.e. in relation to the current situation, the trips of public transportation and freight vehicles were not included in the quantification of emissions. The former were assumed to travel independently from the number of passengers. Moreover, based on the specific characteristics of the site and the considered time period, the latter are vehicles used for the local market and those adopted by the existing Urban Consolidation Center. The drafted regulatory framework allows the access of both types of vehicles. Therefore, changes in pollutant emissions could not be due to these vehicle categories. The outcomes of the traffic simulation model highlighted that, in line with the specific targets of a LEZ, the pollutant emissions in the regulated area were reduced. This result is confirmed by previous studies on LEZs, highlighting that significant decreases occur only within the zone (Ellison et al., 2013; Ferreira et al., 2015). For these reasons, the environmental benefits of such a measure could be increased by expanding the regulated area (Host et al., 2020; Poulhès and Proulhac, 2021). The reduction in pollutant emissions in the area was due to the mobility changes induced by the new measure (that is, fleet renewal, shift toward sustainable vehicles and destination change). This confirms that a holistic assessment of behavioral changes should be performed, in order to obtain a sound basis for LEZ planning (Lurkin et al., 2021). With regard to variations in pollutant emissions outside the zone, the percentage values depend on the spatial extension of the considered area. However, the analysis of these results highlighted that the level of emissions increased in some scenarios. This is due to the long detours that drivers who are not willing to replace their vehicles and shift to a sustainable mode could take to park their vehicles outside the regulated area. This confirms that the adopted modeling framework allowed to evaluate a spillover effect that was induced by such behavioral changes after the LEZ and should not be neglected in the estimation of impacts of the measure on vehicle pollutant emissions (Dias et al., 2016; Gonzalez et al., 2023; Host et al., 2020; Lurkin et al., 2021; Rodríguez-Rey et al., 2022). It is worth noting that, for the specific case study, the entity of these effects is dampened by the wide extension of the study area, highlighting that the size of the intervention zone considered in the analysis plays a non-negligible role on the results of impact assessment. Lastly, the magnitude of the estimated negative effects outside the LEZ is limited, indicating that the drafted regulation could not generate a significant impact outside the regulated area, for the case study. However, to avoid any potential negative rebound effects in external zones, the measure should be combined with other policies (Gonzalez et al., 2022; Sánchez et al., 2021; Tarrío-Ortiz et al., 2022). These interventions should promote the shift toward sustainable vehicles, rather than inducing vehicle substitution. Specifically, replaced vehicles, even if they are less polluting than the previous ones, could continue producing traffic flows and occupy public space within the LEZ. On the contrary, shifts from private motorized vehicles toward public transportation or active modes could effectively contribute to reduce congestion and parking problems, both within and outside the LEZ. In addition, those who decide to park their vehicles close to the LEZ boundary use their means for part of the trips toward the area; in this way, pollutant emissions are avoided only for the last portion of these travels. Conversely, modal switches could allow emission reductions for the entire trip toward the LEZ. However, such policies should be designed in order to guarantee proper accessibility to the regulated area. These interventions include the promotion of public transportation and sharing mobility, the creation of bike paths, and park and ride areas.

It is worth mentioning that, beyond the quantification of changes in pollutant emissions generated by vehicles impacted by a LEZ, the analysis of the combined effects of the measure on air quality inside and outside the regulated area is a challenging task. As highlighted by previous authors, results from past assessments of the environmental impact of a LEZ, in terms of concentrations of pollutants in the air, were often conflicting and site-specific (Holman et al., 2015), due to the presence of confounding factors (Boogaard et al., 2012; Holman et al., 2015). Specifically, the extension of the regulated area compared to the whole city can play a non-negligible role on the comprehensive evaluation of the intervention (Dablanc and Montonen, 2015). For the specific case study, the extension of the evaluated LEZ is about 0.3 square kilometer, corresponding to about 0.3 % of the administrative area of the Municipality of Padova. In Europe the size of existing LEZ is quite variable: 5 square kilometer in Madrid (Spain), corresponding to 0.8 % of the city (Tarrío-Ortiz et al., 2021), 8 square kilometer in Rome (Italy), corresponding to 0.6 % of the city (Ku et al., 2020), 88 square kilometer in Berlin (Germany), corresponding to 10 % of the city (Lurkin et al., 2021), 26 square kilometer in Lisbon (Portugal), corresponding to 33 % of the city (Silva et al., 2014); in London, the LEZ covers the whole city, and an Ultra Low Emission Zone was gradually extended from 21 to 380 square kilometer, corresponding to 1.3 and 24 % of the Greater London (Transport for London, 2021). For the analyzed area, the percentage of the city covered by the planned LEZ is limited, therefore the combined impact of new traffic patterns on air quality inside and outside the regulated zone is expected to be small. In addition, the general procedure to

estimate concentrations of pollutants in the air from pollutant emissions requires assumptions about meteorological conditions, pollutant emission sources in the area and geometrical characteristics of the site (Sánchez et al., 2021; Smith et al., 2021). For these reasons, an ex-ante assessment of the impacts on air quality could lead to uncertain and variable outcomes and is out of the scope of the presented study.

5. Conclusions

In this paper, the future impacts of a Low Emission Zone (LEZ) on vehicle pollutant emissions were quantified, considering changes in travel habits induced by the drafted regulation (i.e., vehicle replacement, modal shift and destination change). In particular, a three-fold evaluation framework was developed, composed of a behavioral model, a traffic simulation model and an emission model. The approach was applied to a case study in Padova (Italy) where a LEZ is likely to be enforced. Data from a mobility survey administered to future stakeholders, traffic counts, and characteristics of vehicles were used to calibrate the implemented models. In order to take into account the stochastic nature of potential variations in user travel behaviors, several future scenarios were generated. For each of them, the pollutant emissions generated by vehicles circulating in the area were estimated and compared with those obtained for the current situation.

The results of the model forecasting future behavior of travelers accessing the LEZ highlighted that a strong opposition could come from car drivers, suggesting that specific attention should be paid in targeting these stakeholders, for instance, by gradually applying access restrictions. In addition, a general unwillingness to adopt more sustainable travel behavior was highlighted. Specifically, people are more willing either to maintain their vehicle, parking it outside the LEZ to avoid entering the area, or to replace it with a less polluting one, rather than shifting to a sustainable travel mode. This indicates that an increase in traffic flows and parking demand outside the LEZ could generate a spillover effect and the access of renewed vehicles could prevent a congestion and land use reduction within the LEZ. Moreover, the results confirmed that the support of the measure could effectively help in reaching sustainability targets of the LEZ. Furthermore, the shift toward travel modes alternative to private motorized vehicle could be encouraged if the awareness of the benefits of the LEZ is increased.

The analysis of the future modal share of individuals entering the regulated area pointed out that the measure could contribute to reduce the use of motorized private modes up to 8 %. A significant decrease in pollutant emissions was observed within the LEZ, generated by fleet renewal, modal shift, and destination changes, highlighting the effectiveness of the measure. Limited variations were obtained outside the area (around 1 %), and some scenarios exhibited a slight increase in pollutant emissions due to a spillover effect produced by long detours to avoid entering the zone.

The research can provide useful insights for policy makers and transportation planners to design a proper strategy for implementing a Low Emission Zone. Specifically, the findings of the analysis contribute to the understating of the complex behavioral impacts induced by the regulation. Furthermore, the work highlighted that a holistic modeling framework should be adopted to obtain a comprehensive and solid prediction of the impacts of the measure on vehicle pollutant emissions.

The present work has some limitations that can be overcome in future research steps. First, in this work, a macroscopic traffic simulation model was adopted. Even if this technique cannot properly reproduce vehicle behavior, thus potentially biasing emission estimates (Rodríguez-Rey et al., 2021), the approach is usually implemented for simulations at a large urban scale (Rodríguez-Rey et al., 2022). Second, the considered behavioral changes induced by the drafted regulation are related to a short-term period; however, other impacts might occur even in a long-term period, such as variations in workplaces or frequency of systematic trips toward the LEZ (Lurkin et al., 2021; Tarrío-Ortiz et al., 2022). Third, the analysis was focused on a specific time period on a working day, when most of the trips entering the regulated area were observed; in a future research step, a 24-hour analysis can be carried out, considering different time periods, thus evaluating the daily impacts of the LEZ on vehicle pollutant emissions with different traffic conditions (Poulhès and Proulhac, 2021; Tarrío-Ortiz et al., 2022). In addition, within the scope of the ReVeAL project, the survey administration managed by the Municipality of Padova resulted in a limited sample size. Nevertheless, although potential stakeholders of the new LEZ were effectively targeted, the quantification of the whole universe of people entering the area was a challenging task. In future phases of the work, a new mobility and behavioral surveys can be administered, to obtain a greater number of responses. Furthermore, based on the characteristics of the area and the considered regulatory framework, flows of public transportation and freight vehicles were not considered in the pollutant emissions estimation, since they are not impacted by the drafted regulation. However, the implemented procedure can be easily tailored to other case studies, where environmental effects of a LEZ could depend on travel patterns of these vehicle categories. The results of the proposed evaluation framework should be referred to the specific temporal and spatial boundaries considered in the present research work, that were defined by the analyzed regulation. However, the adopted method is scalable and flexible, therefore it can be transferred and applied to different time periods and study areas. Lastly, due to privacy issues imposed within the scope of the ReVeAL project, the mobility survey does not include some socio-economic questions, such as the specific place of residence, income and household composition. Although the residence location can be useful to understand the origins of travels toward the area, performed by the sampled interviewees, respondents were asked to declare whether they live inside or outside the future LEZ. However, the distribution of the zones of residence of vehicle owners could be obtained from the analysis of access permits to the current LTZ. Furthermore, the mobility patterns of the universe of trips accessing the regulated area were directly derived from the origin–destination matrix, used as input of the traffic simulation model. As regards household income and composition, these variables could affect mobility behaviors. For instance, the distribution of stakeholders' income should be considered when the local authority assesses the equity of the implemented measure (Di Ciommo and Shiftan, 2017). Moreover, the number of children in stakeholders' household can influence both long-term and short-term choices related to private car, such as vehicle ownership (Haque et al., 2019) and car adoption (McCarthy et al., 2017). Even though these socio-economic variables were not included in the presented

work, the proposed methodology allows to consider a wide range of factors that can affect mobility behavioral changes after the LEZ implementation.

CRedit authorship contribution statement

Riccardo Ceccato: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. **Riccardo Rossi:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft. **Massimiliano Gastaldi:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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