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Modelling of Air Pollution Dispersion Coupled with Traffic Flow Simulation, as a Digital Twin, for the Correct Implementation of Low Emission Zones: An Innovative Approach for Smart Cities

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Abstract

The growing urbanization, combined with increasingly strict air quality regulations, requires innovative approaches to manage air pollution, particularly from vehicular emissions. One of the most widely used methods to regulate air pollution in cities is the implementation of the called low emission zones (LEZs), areas of a city in which certain vehicles are restricted or their use is discouraged through economic fees. This paper proposes a comprehensive methodology for the implementation and management of low emission zones, integrating advanced air pollution dispersion models and traffic flow simulations. The proposed approach uses the SUMO model for traffic simulation and the GRAL model for high-resolution pollutant dispersion, supported by meteorological data from the WRF and GRAMM models. The method ensures accurate delimitation of LEZs and enables effective monitoring of air quality both before and after its implementation. The methodology was successfully applied in several European cities, demonstrating its adaptability and effectiveness. The results showed significant improvements in air quality predictions, thereby validating the proposed LEZs and contributing to the broader goals of urban air quality management.

Keywords: Low Emission Zones (LEZS); Modelling; Pollution; Digital Twin; Traffic Flow Simulation

Introduction

The ongoing process of migration from rural to urban areas, with an estimation of 68% of the global population living in cities by 2050, is expected to significantly worsen air quality in the upcoming decades. The European Environmental Agency (2020) estimates that the transport sector accounts for over 40% of emissions related to air pollution, which in fact is the largest environmental health risk (e.g., Anderson, 2020; Simeonova et al., 2019) and contributed to around 7 million premature deaths worldwide in 2012 according to the World Health Organization (WHO, 2013). In order to improve public health, governments are taking measures to regulate ambient air quality, including fuel taxes or congestion tolls.

General

In this context, low emission zones (LEZs) are one of the most widely used mechanisms to regulate air pollution coming from the transport sector. LEZs are designated areas in a city where certain vehicles are restricted, or their use is discouraged through financial charges. These zones can be stablished in various ways, often combining fees and other limiting strategies to regulate vehicle access based on emissions, size, weight, type, or time of day (e.g., Zhai and Wolff, 2021). LEZs are particularly common in Western and Northern Europe, with a total number of LEZs of 320 in 2022. This number is expected to increase in the upcoming years due to the new national laws in countries such as Spain and France (Azdad et al., 2022). In Spain, for example, the Law 7/2021, dated May 20, concerning Climate Change and Energy Transition, mandates that Spanish cities with populations exceeding 50,000 inhabitants, as well as insular territories and municipalities with populations greater than 20,000 inhabitants, must have adopted sustainable urban mobility plans by 2023. These plans are required to implement mitigation measures aimed at reducing emissions associated with mobility. Among other provisions, this includes the establishment of low emission zones when regulated pollutant limits set forth in Royal Decree 102/2011 are exceeded. Other countries that have implemented similar solutions to LEZs include Beijing (Zhang et al., 2018), Hong Kong (Ai et al., 2016) and New York (Baguestani et al., 2020).

Although low emission zones are generally seen as a suitable measure to reduce air pollution, the evidence regarding their effectiveness is slightly controversial, with a number of LEZs having failed to meet European air quality standards (Boogard et al., 2012; Ellison et al., 2013). The issue arises prior to the implementation of LEZs, as there is a lack of high-quality and comprehensive tools necessary for accurately quantifying urban air quality. Such tools would allow not only to delimit LEZs based on air quality data, but also to estimate the reduction of emissions and air quality impacts after the implementation of the LEZs.

In this paper, we address this issue by proposing an innovative method through the use of dispersion models combined with traffic flow simulation to ensure the correct implementation of LEZs. Modelling the air quality and road traffic before the LEZ helps to delimit the LEZs based on the model results and serves to quantify the impact of the LEZ after its implementation.

This paper is structured as follows. In Section 2 we review existing research related to the field of low emission zones. Then, Section 3 presents a detailed description of the proposed approach. In Section 4 we present some success stories from Spain where our solution has been implemented and finally, Section 5 provides a discussion of the employed methodology.

Related work

The concept of low emission zones is relatively recent, with the first LEZs introduced in Sweden in 1996. At that time, LEZs only targeted older, large diesel-powered vehicles such as buses and heavy goods vehicles. It has been only in recent years that LEZs have begun to address private cars. For that reason, the research about LEZs is still scarce and most of the studies have been conducted after the implementation of LEZs to evaluate its effectiveness (e.g., Boogaard et al., 2012; Ellison et al., 2013; Lebrusán and Toutouh, 2020).

These studies show significant differences with respect to the success of LEZ implementation in reducing air pollution. For example, Panteliadis et al. (2014) showed a decreased in PM10 and NOx concentrations after the implementation of the LEZ in Amsterdam, while the study of Boogaard et al. (2012) showed no significant improvements in the same area. Additionally, an evaluation of the success of the LEZ in London conducted by Ellison et al. (2013) just showed marginal improvements in London's air quality. Another issue identified in the literature is the lack of attention to air quality outside of low-emission zones (e.g., Da Silva et al., 2014).

These problems underscore the need for a comprehensive tool that allows not only to assess the air quality impacts of an LEZ in a correct way, but also to carry out a study prior to the implementation of LEZs. In this context, and with the drastic increase of computational resources in recent years, the use of numerical models has become increasingly popular (e.g., Ceccato et al., 2024; Cesaroni et al., 2012). Yet, just a few studies have tried to use numerical models to perform both ex-post evaluation of LEZs, i.e. after the implementation of LEZs (e.g., Keuken et al., 2012), and ex-ante evaluation, i.e. prior to LEZs (e.g., Carslaw and Beevers, 2002; Cesaroni et al., 2012). However, these models were often just applied to major roads exceeding a certain number of vehicles per day, which resulted

in air pollution levels not being adequately addressed in the entire city.

The approach we propose in this paper aims to contribute to the field of low emission zones by combining a numerical modelling with traffic flow simulation to create a powerful tool, as a digital twin, for effectively assessing and planning low emission zones.

Proposed approach

The approach proposed in this paper consists of two components: modelling of air pollution dispersion and the implementation of a traffic flow simulation, as a digital twin, both of which will be explained in this section.

Modelling of air pollution dispersion and traffic flow

For the drafting of the low emission zones project under Royal Decree 1052/2022, of December 27, which regulates low emission zones, an appropriate methodology is required in order to comply with the Law on climate change and energy transition and Royal Decree 102/2011 on the improvement of air quality and subsequent developments. In order to achieve the air quality improvement objectives, the Royal Decree recommends the use of mathematical models.

In this context, we propose the combined use of traffic flow models, meteorological models and microscale flow models of pollutants to solve, reproduce and predict the dispersion of pollutants in urban environments. This system allows to have permanently updated data on air quality throughout the city with their current and predicted pollution levels and helps in the successful implementation of low emission zones.

Methodology

The whole modelling process for the implementation of LEZs is illustrated in Fig 1. The process starts with a regional scale meteorological and air quality simulation/prediction (1), with a further increase in spatial resolution (2). Additionally, the system incorporates a high-resolution traffic flow model, based on real traffic data, whose objective will be to calculate road traffic on all roads in the city and thereby calculate all emissions derived from it (3). Finally, these emissions combined with those from other sources such as industry, together with data from the geometry of the city's buildings and the meteorological forecast, will be introduced into a high-resolution pollutant dispersion model with the dual purpose of performing scenario simulations and short- term predictions (4). Each of these modellings are explained in the following sections:

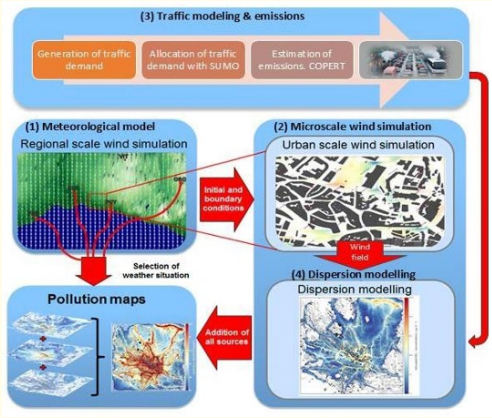

Figure 1: Schematic diagram of the numerical modelling system.

Traffic modelling

We use the SUMO (short for Simulation of Urban Mobility) model to simulate the road traffic and then calculate all emissions derived from it following the COPERT methodology. The model outputs provide information related to road transport (number of vehicles, average speed, etc.), as well as emissions associated with traffic. As inputs, the model requires at least a road network and traffic demand. The quality of the road network must be high, as the SUMO model requires detailed characterization when run with microscopic and mesoscopic approaches (each vehicle and its dynamics are modelled individually). The model can be run through an user interface (Fig. 2).

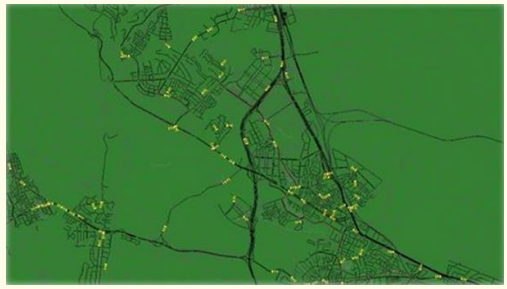

Figure 2: SUMO simulation through a graphic user interface.

The road network can be built from Open Street Map (OSM) data to obtain an overview of the study area. Importing the road network from an OSM map offers many advantages, as these maps contain valuable information about the roads, such as allowed road speed, number of lanes, direction, etc. Although OSM offers a great amount of information, it is always important to review the network in order to fix errors in the input data or any problems that may arise when importing the road network. For this purpose, SUMO includes the Netedit tool which contains a user interface that allows to modify the road network manually. In the case of simple networks with little branching and for which there is no data record in OSM, it is possible to generate the network manually from data provided by the client, e.g. from vector files with the network and its corresponding characterization.

In the absence of real traffic data, traffic demand is generated by applying the "randomTrips.py" script, which allows traffic demand to be generated when the flow of vehicles on the network roads is unknown. For this purpose, the tool selects pairs of origin-destination roads in a uniform and random manner, or with a defined distribution. During the execution of the script itself, another SUMO tool called "duarouter" can be called if desired. The purpose of "duarouter" is to determine the vehicles and routes for the trips (origin-destination) generated by "randomTrips.py", i.e. to define all the intermediate roads between the origin and destination of each trip. For routing, "duarouter" has 4 algorithms to determine the shortest route between origin and destination: Dijkstra (default), Astar, CH and CHWrapper. Dijkstras, for instance, facilitates the identification of the shortest/fastest route (based on the weights assigned to the connections between nodes, distance, or travel time) from a source node to a destination node. The algorithm commences at a source node, calculates the travel cost to potential adjacent nodes, and selects the one with the lowest cost. This process is repeated until the shortest/fastest path between the source node and the remaining nodes in the network is ascertained. The SUMO model is then run to determine travel times, with these results being taken into account in the next iteration.

In each iteration, the weights of the connections between nodes are updated, resulting in new routes, and creating a set of alternative routes. The Gawron algorithm is then used to select routes from among the possible alternative routes. The Gawron method is used to calculate the probability of route selection by drivers in a transportation network. The Gawron method is based on the iterative updating of travel times and the probabilistic assignment of alternative routes. The following factors are considered by the algorithm to determine the probability of a driver choosing a particular route:

- The travel time recorded in the previous iteration.
- The sum of the travel times on a set of alternative routes.
- The prior probability of selecting each route.

Travel time updates follow an iterative process. In the event that a driver d opts for route r in iteration i, the travel time T_d (r, i + 1) is calculated from the aggregated average travel time in the previous iteration, as expressed in the following equation:

$$T_d(r, i + 1) = \tau_d(r, i) \qquad (1)$$

For alternative routes within the driver's choice set, the travel time is adjusted by a memory parameter β, which serves to smooth out the influence of previous iterations:

$$T_d(s, i + 1) = \beta \times \tau_d(s, i) + (1 - \beta) \times \tau_d(s, i - 1) \qquad (2)$$

Where s represents the routes not selected in iteration i and β has a default value of 0,3. This avoids the need for drivers to accurately recall previous travel times and encourages a progressive adaptation process.

This method allows for a realistic modelling of driver decision making, taking into account traffic variability and the evolution of travel times on the network. By using SUMO's capabilities, a more realistic estimate of urban transport emissions can be obtained and different scenarios can be simulated.

Dispersion modelling

The dispersion model (step 4 in Fig. 1) uses a Lagrangian model called GRAL, designed to reproduce 3D concentration fields of (passive) contaminants at very high resolution (up to 2-3 m), under complex topographic and building configurations. The code is parallelized to reduce the computational time. The model is able to simulate the following situations: Dispersion of chemically non-reactive contaminants, Dry and wet deposition and sedimentation, Dispersion in road tunnels, Dispersion over the entire wind speed range without any lower threshold, and for all stability conditions, Dispersion in built-up areas, including downwashing in building elements, Dispersion of ducted emissions, taking into account temperature and exit velocity, Dispersion in complex terrain, allowing for building effects, Decay rates, and Flow and dispersion within vegetation layers.

The effect of buildings and vegetation on dispersion will be addressed using a microscale flow field model, which is fully integrated into the model code.

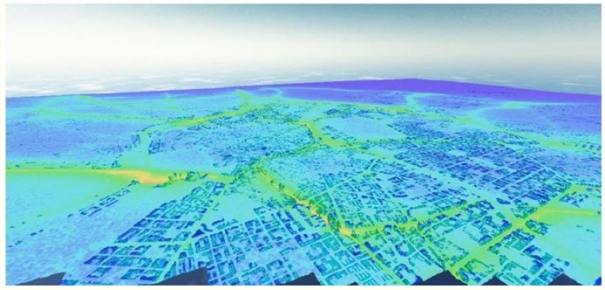

Figure 3: Example of GRAL output in city NOx modelling.

Meteorological modelling

Regarding meteorological modelling, the meteorological data required for the GRAL simulation is obtained from simulations with the WRF (Weather Research and Forecasting) mesoscale meteorological model (step 1 in Fig. 1), which in turn will feed the GRAMM microscale meteorological model (step 2 in Fig. 1), which will increase the spatial resolution to 300 m.

The WRF model is a state-of-the-art meteorological model that allows obtaining wind, pressure, temperature and humidity fields, among others, with high spatio-temporal resolution, which are of utmost importance as input data for air quality models. The WRF model has the particularity of being able to be locally configured to represent spatial domains at different scales (from hundreds of meters to thousands of kilometers.) depending on the study to be carried out. On the other hand, the GRAMM model, through WRF and using a finer resolution of topography, provides a higher resolution of the meteorology of the area, by calculating flow fields in complex terrain (Fig. 4).

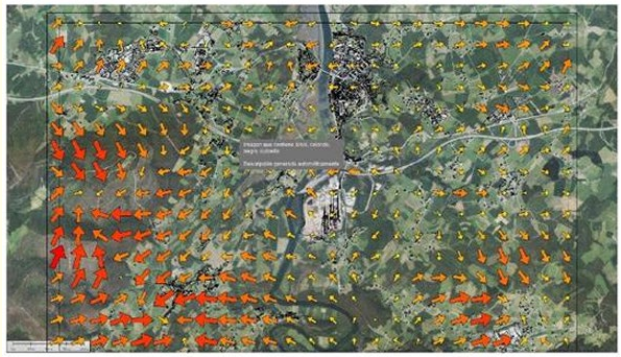

Figure 4: Wind field at 10 m height generated by GRAMM for a case study.

Modelling of air pollution dispersion and traffic flow

The modelling services are integrated into a platform, named AIRADVANCED, in a SaaS (software as a service) format. AIRADVANCED will display all the information related to the LEZ (noise levels, incidents detected, pollution levels, proposed penalties, etc.) (Fig. 5).

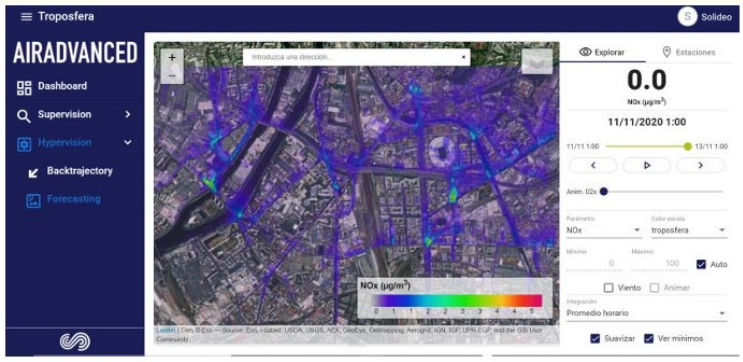

Figure 5: AIRADVANCED, platform for the management of LEZs.

The platform will also be able to integrate other technological solutions deployed in the city, such as IoT sensors or information systems. For that reason, the platform is structure in several key vertical to address each aspect of city management. These verticals can include transportation and mobility (where the control of LEZs would be included), environment, tourism and energy management.

Evaluation and results

The methodology described in section "Proposed approach" was developed during the TRAFAIR Project: Understanding Traffic Flows to Improve Air Quality, a project cofounded by the European Union (Po et al., 2019). The objectives of this project were, among others, the definition of a standard set of metadata capable of representing urban air quality maps and the development of a service for the prediction of urban air quality based on meteorological forecasts and traffic flows. The modelling, using HPC (High Performance Computing) resources, was successfully applied to reach these goals, and the service was successfully implemented in Zaragoza (600,000 inhabitants), Florence (382,000), Modena (185,000), Livorno (160,000), Santiago de Compostela (95,000) and Pisa (9,000). These datasets (including metadata) are now published in catalogs compiled by the European Data Portal.

After the TRAFAIR project, our modelling has been executed in a number of cities. For example, the low emission zone of A Coruña, Spain, was implemented using that approach. In that project, each of the steps described in Section "Proposed approach" were applied. After modelling atmospheric dispersion with the GRAL model, bias correction or adjustment techniques were applied and a statistical spatial downscaling from the observed values at the stations was tested. In this way, the model values were corrected from the observed values, thus adjusting the model to the real data from the stations.

To evaluate compliance with the uncertainty and to perform a graphic analysis of the degree of adjustment of the model to the data observed or measured at the air quality stations, the set of statistical indicators recommended by the Forum for Air quality Modeling (FAIRMODE) working groups was used. Through statistics such as correlation, bias and standard deviation, it was observed that all stations were within the acceptance range.

With the validated model system, as a digital twin of the city, pollutant concentration maps were generated before the implementation of measures, and pollutant concentration maps were generated after implementing restrictions and modifications in the mobility of the city. With the results obtained, the measures to be implemented were validated, as well as the proposed low emission zones, and realistic and achievable improvement objectives could be set.

Discussions

Integrating high-resolution dispersion models with traffic flow modelling integrating real-time traffic data significantly enhances the precision of air quality predictions within urban environments. Notably, previous studies have shown that static or outdated traffic data can lead to inaccuracies in emission estimations and subsequent air quality predictions (Vardou-lakis et al., 2003; Beevers and Carslaw, 2005). We need to use real- time high-quality data to ensure the best result. On the other hand, the application of the modelling in cities like A Coruña, Valencia and Sevilla show its adaptability and robustness across different urban settings, showing the potential of such models in the global effort to mitigate urban air pollution.

The approach presented in this paper contributes to the growing field of research emphasizing the need for sophisticated, data-driven techniques to improve urban quality management. Indeed, air quality modelling is expected to become more and more important in the upcoming years due to the air quality legislation of the European Green Deal (EC, 2019).

Despite the strengths of the current approach, some limitations must be acknowledged. Firstly, the lack of accuracy of the emissions estimated by traffic data due to the presence of poorly characterized sources (e.g., construction activities and road dust resuspension processes) could lead to residual biases (e.g., Sokhi et al., 2022). Secondly, the computational demands of the models, especially the GRAL model, despite its capability to produce high-resolution outputs, may restrict its practical use in real-time applications.

Future research should focus on enhancing the efficiency and scalability of the models, including new technologies and data analysis techniques such as machine learning or artificial neural network models (e.g., Just et al., 2020; Sokhi et al., 2022; Zhan et al., 2017). Moreover, future studies should consider the socio- economic impacts of LEZs, addressing gaps identified in recent literature, to provide a more comprehensive assessment of their effectiveness (Andriolli and Silva, 2024; Sarmiento et al., 2023).

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