To what extent the traffic restriction policies applied in Barcelona city can improve its air quality?

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Abstract

Barcelona city (Spain) is applying a series of traffic restriction measures that aim at renewing and reducing the amount of circulating vehicles to improve air quality. The measures include changes in the built environment to reduce private vehicle space in specific areas through the so-called "superblocks" and tactical urban planning actions, along with the implementation of a city-wide Low Emission Zone (LEZ) that restricts the entry of the most polluting vehicles to the city. Our study quantifies the impact of these measures in the greater area of Barcelona combining a coupled macroscopic traffic and pollutant emission model with a multi-scale air quality model. Our modelling system allows estimating the effect of different traffic restrictions upon traffic and the associated emissions and air quality levels at a very high resolution (20 m). The measures were evaluated both individually and collectively to assess both their relative and overall impact upon emissions and air quality. We show that in the absence of traffic demand reductions, the application of isolated measures that reduce private vehicle space, either through superblocks or tactical urban planning, have no overall emission impacts; only localized street-level NO_x positive and negative changes (+/-17%) are found due to traffic re-routing and the generation of new bottlenecks. It is only when these measures are combined with optimistic fleet renewal as a result of the LEZ implementation and demand reductions, that relevant global emission reductions in NO_x are obtained (-13% and -30%, respectively) with estimated NO_2 reductions of -36% and -23% at the two traffic air quality monitoring stations. Despite the potential improvements, our simulations suggest that current measures are insufficient to comply with EU air quality standards and that further traffic restriction policies to reduce traffic demand are needed.

Keywords: Multi-scale Air Quality Modelling, traffic simulation, Vehicle Emissions, Traffic Management Strategies, Barcelona

Glossary

AQD: Air Quality Directive

COPERT: Computer Program to calculate Emissions from Road Transport

CTM: Chemical Transport Model

HERMES: High-Elective Resolution Modelling Emission System

LEZ: Low Emission Zone

SPB: Superblocks

TUP: Tactical Urban Planning

VML: Virtual Mobility Lab

1. Introduction

Air pollution is a public health threat in urban areas around the world, including Barcelona (ASPB, 2019). Although over the past years the city has been reducing its NO_2 concentration levels, the traffic air quality monitoring stations still systematically exceed the annual mean NO_2 limit values established by the Air Quality Directive (AQD) 2008/50/EC (EEA, 2019). An exception has been 2020 when no exceedances were recorded due to impact of the COVID-19 lockdown upon mobility (ASPB, 2020). NO_2 limit values are typically exceeded in traffic stations, with traffic accounting for 60% of the NO_2 in the city (Ajuntament de Barcelona, 2015). Traffic pollution is of particular concern as it has been associated with increased mortality (Hoek et al., 2001) due to higher cancer risk (Beelen et al., 2008) and worsened respiratory health (Brauer et al., 2002). All in all, Barcelona recently ranked as the 6^{th} city with higher mortality risk from a total of 858 European cities (ISGlobal (2021), Khomenko et al. (2021)).

Partly due to the failed outcomes by the vehicle manufacturers in reducing NO_x from vehicle exhaust gases (i.e., excess diesel NO_x emissions, Benavides et al. (2021a)), Barcelona local authorities are focusing on mobility policies that try to reduce and renew the number of circulating vehicles within the city. These policies include, on the one hand, the implementation of traffic restriction measures aiming at reducing traffic activity in certain areas and corridors of the city and, on the other hand, the application of a Low Emission Zone (LEZ), the objective of which is to accelerate the renewal of the circulating vehicle fleet. To reduce traffic activity in particular urban areas, Barcelona is applying the Superblock system (Fig. 1 a,b), which consists on the traffic pacification of several streets within an area comprised by several blocks. The traffic pacification measures performed within the superblock comprise a reduced speed limit (10km/h), the usage of urban furniture to hassle traffic -such as urban vegetation, bollards or speed humps- and the introduction of mandatory turnings that throw out the incoming vehicles. The goal of the superblock is to provide a traffic-pacified interior

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area accessible primarily to active transport (e.g., cycling) and secondarily to residents, diverging through traffic and gaining space for leisure activities (Rueda, 2019). Along with the Superblock system, Barcelona is also applying a set of Tactical Urban Planning Actions to reduce private vehicle space of the city. These actions consist on the implementation of low-cost and scalable elements such as strips of colours, urban furniture or moveable plant beds to transform the urban space. In the case of Barcelona, the introduction of these elements allowed reducing traffic lanes dedicated to private vehicles from major urban corridors in the city, and gaining pedestrian and public transport space. The specific areas affected by SPB and TUP actions are described in Section 2.3.1 of the manuscript and in the supplementary material.

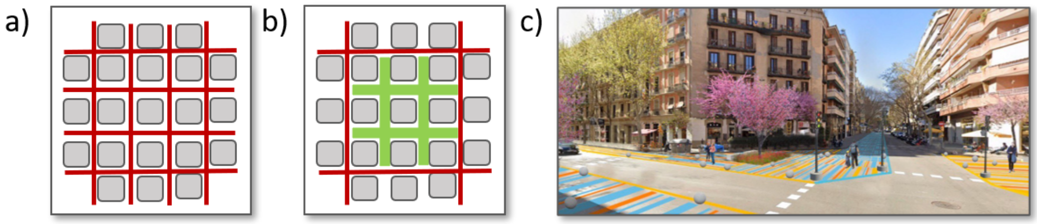

Figure 1: a) Area without the application of the superblock model and b) area with the superblock model. The grey squares represent building blocks, the green segments the streets affected by traffic pacification measures and the red segments the non-affected streets c) Image of the aplication of Tactical Urban Planning measures in a crossroad.

To quantify the impact of these measures on emission and air quality levels, the AQD encourages the use of numerical models. This is particularly relevant for Barcelona, where the monitoring network is not dense enough to properly characterise population exposure, and therefore it needs to be combined with models (Duyzer et al., 2015). Air quality models should be used for both assessment and planning; but to do so, the modelling chain has to be fit-for-purpose and properly validated and calibrated.

Mesoscale Eulerian Chemical Transport Models (CTMs), which require as input data estimated emissions and meteorological variables, are currently the most widely used when performing the evaluation of the potential emission reductions (e.g., Pisoni et al. (2019)). These air quality systems are usually combined with traffic and travel demand models (Barceló, 2011) to simulate the effect of restrictions on the traffic activity (e.g., traffic flow, speed) across the city (e.g., García et al. (2018)). The application of such an integrated modelling approach allows estimating the changes induced by the mobility action and their possible rebound effects (e.g., generation of new bottlenecks) not only in the implementation area (e.g., the LEZ), but also, more generally, in the city where it is located and its surroundings.

Despite the satisfactory performance of the CTMs, their limited resolution cannot reproduce the strong urban pollutant concentration gradients usually associated with high load traffic flows (Borge et al., 2014). In order to depict street level concentration gradients, local–scale tools are needed. The most detailed approach is the Computational Fluid Dynamics (CFD), which consists in the direct computation of the pollutant dispersion around the buildings integrating the fundamental transport governing equations. In order to deal with the turbulence in the CFD context, there are the Large Eddy Simulation (LES) techniques that explicitly solve the larger turbulent scales while modelling the smaller ones, and the Reynolds Average Navier Stokes (RANS) that compute the time average of each flow characteristic. Due to the high computational load associated with CFD solvers, simpler approaches mainly based on Gaussian dispersion models, have become very popular to assess air quality at the urban scale, specially in large computational domains (e.g., Borge et al. (2014), Jensen et al. (2017), Hood et al. (2018), Benavides et al. (2019)). Gaussian dispersion models use semi–empirical approximations to compute pollution dispersion within the urban canopy. Local-scale tools are usually coupled with regional CTMs to account for the long-range pollutant dispersion (Borge et al. (2018); Benavides et al. (2021a); Jensen et al. (2017); Hood et al. (2018); Denby et al. (2020)). Besides improving the performance of grid-based CTMs, the application of a hybrid air quality modelling approach (i.e. the combination of mesoscale and street-scale dispersion models) can also lead to more detailed results when evaluating urban mobility plans.

The coupling of such hybrid approach with traffic demand models has already been applied to estimate the impact in urban emissions and air quality levels of different structural or short term action plans. Borge et al. (2018) estimated the impact of the Madrid NO_2 protocol using a multi-scale air quality model with a mesoscale approach (1×1 km^2) for the citywide, and a street-level approach for one of the main streets in the city. Using different estimated traffic demand scenarios, their results showed that only the most restrictive measure would produce a noticeable air quality improvement (-25% in NO_x emissions). Jensen et al. (2017) estimated the NO_2 concentration values in Denmark using a multi-scale air quality modelling approach. In this case, they combined the Danish Transport Model and GPS vehicle readings to estimate traffic volume and speed, respectively. This data was used by AirGis (Jensen et al., 2001) to estimate NO_2 concentration values at different resolutions with values that ranged between -27% and +12% from observations. In Barcelona, Mueller et al. (2020) studied the health impacts of the complete implementation of the Superblock idea on the city (500 superblocks). They used the Street 5.2 air quality model (Kunz, 2005) estimating a reduction of 24% in the NO_2 concentration values assuming a 19% reduction in the private transport. They estimated 291 premature deaths due to NO_2 following a linear exposure-response function (Atkinson et al., 2018). Since the study followed a macroscopic approach obtaining the results at the city level, the most affected areas or streets as well as possible rebound effects were not identified.

Our study quantifies the air quality changes at street level of the different traffic management strategies adopted in Barcelona and for the first time their potential undesired rebound effects as a consequence of the new generated vehicle routes. To address this, we perform a multi-scale air quality modelling exercise that couples the CALIOPE-Urban, a modelling framework that combines the CALIOPE mesoscale air quality system (Baldasano et al. (2011); Pay et al. (2014b)) with the street-scale dispersion model adapted to street canyons (Benavides et al., 2019) and the traffic-emission model VML – HERMESv3 (Rodriguez-Rey et al., 2021) that allows to estimate the induced traffic emissions as a consequence of road network modifications. Additionally, we compare the mesoscale and street scale computed values to understand and quantify the differences when working at different scales.

2. Methodology

In this section we present the domain and period of study, as well as a detailed description of the model workflow. We also describe the traffic restrictions considered in the study along with their implementation in the modelling system.

2.1. Selection of the domain and period of study

The area of study is the greater area of Barcelona, which covers a surface of 101km^2 and is home to about two million inhabitants (Fig. 3a) holding one of the highest traffic densities in Europe (6000 vehicles/km^2 (Ajuntament de Barcelona, 2020a)). The study is performed from the 9th to the 25th of November of 2017. This period includes representative days of the observed NO_2 annual mean daily cycle of the city (9th - 16th) and a pollution episode with high NO_2 concentration levels (17th - 25th) to assess the impact of the traffic restriction measures in a critical air quality condition in the city. During this period, there was an exceedance of the NO_2 hourly limit value (200 µg/m^3), and six values above 160 µg/m^3 of NO_2 at the two traffic air quality monitoring stations and in a urban background site.

The NO_2 mean for the simulated study period and the NO_2 mean for the observed annual values for Eixample are of 63 (+/- 30) µg/m^3 and of 58 (+/- 26) µg/m^3, respectively. The simulated study period NO_2 mean for Gràcia is of 60 (+/- 31) µg/m^3, while the annual observed NO_2 mean is of 51 (+/- 28) µg/m^3. A detailed description of the representativeness of the selected study period with the annual mean daily cycle can be found in (Benavides et al., 2021b).

2.2. Modelling system

The emission and air quality impacts of the different traffic management strategies applied in Barcelona were analyzed using a multi-scale modelling chain based on the coupled traffic-emission model VML-HERMESv3 (Rodriguez-Rey et al., 2021), the mesoscale air quality system CALIOPE (Baldasano et al. (2011), Pay et al. (2014b)) and the street scale air quality system CALIOPE-Urban (Benavides et al., 2019) (Fig. 2).

2.2.1. Traffic and emission modelling: VML-HERMESv3

Traffic flow and speed are simulated using the Barcelona Virtual Mobility Lab (VML) model (Montero et al., 2018). The VML, which relies on the VISUM traffic simulator (PTV Group, 2019), contains information for each network link of the maximum allowed speeds, lane capacities, permitted turns, and other traffic constraints that determine the traffic assignment (e.g., vehicle flow and speed) for the study domain area. Vehicle routing is estimated according to mobility matrices (e.g., Origin-Destination matrices) derived from mobile phone data from March 2017. An Static Traffic Assignment is performed for each hour for a business-as-usual day (for a total of 24 traffic simulations). A calibration process using measured traffic counts and speed values from 138 permanent traffic stations was performed to ensure correct values of traffic flow and speed. Following the traffic simulation, the averaged link-level hourly speed, traffic flow data and the traffic network from the VML are

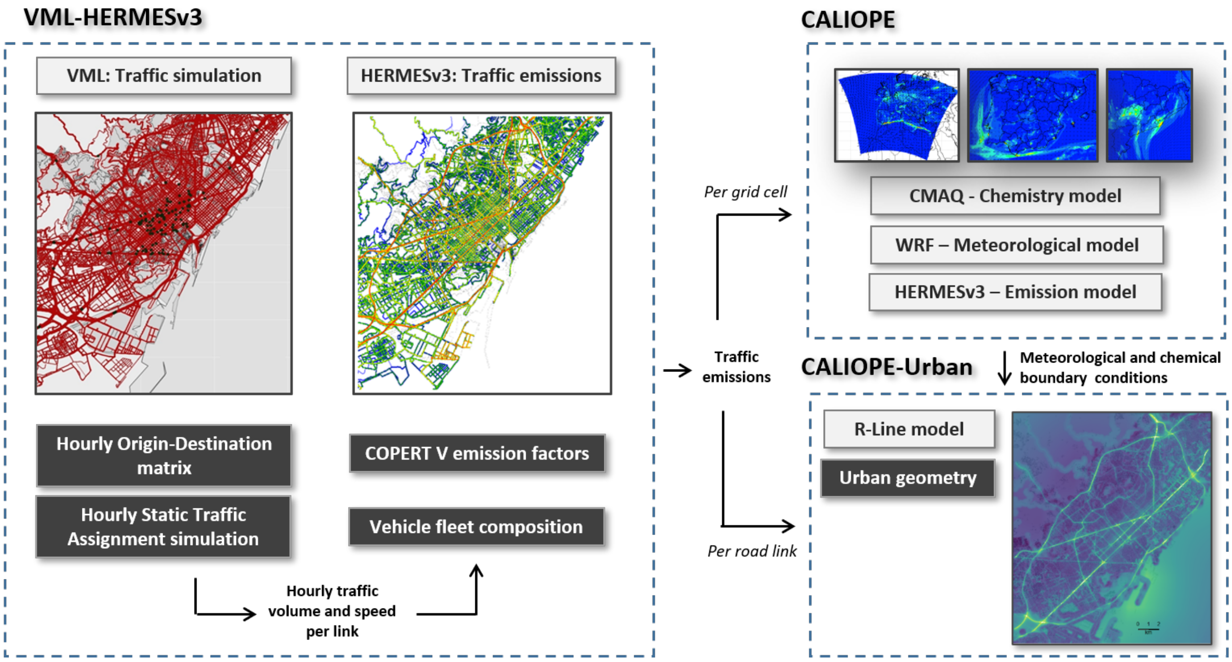

Figure 2: Schematic representation of the multi-scale modelling chain used to evaluate the impact of traffic management strategies in Barcelona. Blue dotted lines comprise the modelling systems that compose the tool (VML-HERMESv3: coupled traffic and emission model, CALIOPE: mesoscale air quality system and CALIOPE-Urban: urban scale air quality system), black boxes represent input data, grey boxes stand for the inner models, and black arrows illustrate the transfer of data between models and systems.

read by the HERMESv3_traffic emission model to compute vehicle emissions at the road link level. The coupling process is script-based and assures the correct link mapping, its assigned vehicle composition and the speed and flow temporal profiles. HERMESv3_traffic (Guevara et al., 2020) computes hourly exhaust (hot and cold-start) and non-exhaust emissions (tire, road and brake wear and resuspension) based on the Computer Program to calculate Emissions from Road Transport version V (COPERT V, which includes the corrected Diesel emission factors) (EMISIA, 2016), which are included in the tier 3 approach of the European emission inventory guidelines EMEP/EEA (EMEP/EEA, 2017). To compute vehicle emissions, HERMESv3_traffic uses the link-level average speed, traffic flow, temporal profiles and the vehicle fleet composition previously assigned to each link. A total of 5 different fleet composition profiles assigned to different regions of the city are considered. These are derived from a remote-sensing device campaign performed in 2017 (AMB and RACC, 2017), and information provided by the Barcelona's Port Authority (Port de Barcelona, 2017). A detailed description of the coupling and calibration of the VML and the HERMESv3_traffic models can be found in Rodriguez-Rey et al. (2021).

2.2.2. Mesoscale air quality modelling: CALIOPE

The mesoscale air quality modelling system CALIOPE is composed of the Weather Research and Forecasting (WRF) model version 3.5.1 with WPS (WRF Preprocessing System) version 3.9.1 (Skamarock and Klemp, 2008), combined with the HERMESv3 multi-scale atmospheric emission modelling framework (Guevara et al., 2019, 2020) and the Community Multiscale Air Quality Modelling System version 5.0.2 (CMAQ) (Byun and Schere, 2005). To obtain the adequate boundary and initial conditions, the CALIOPE system is run over Europe at a 12 km by 12 km horizontal resolution, the Iberian Peninsula at 4 km by 4 km, and the Catalonian region including Barcelona at 1 km by 1 km resolution (Fig. 2). A one-way nesting is performed to retrieve the meteorological and chemical conditions from one domain to the inner ones. An evaluation of CALIOPE results can be found in Baldasano et al. (2011), Pay et al. (2014a), and Guevara et al. (2014). CALIOPE simulations were initialised with the Global Forecast System (GFS) (NCEP, 2011), boundary conditions for chemistry come from the CAMS reanalysis of atmospheric composition (Inness et al., 2019), and anthropogenic emissions for all domains were processed using HERMESv3. For the European domain, HERMESv3 was run using the TNO-MACCIII (Kuenen et al., 2014) and the HTAPv2.2 (Janssens-Maenhout et al., 2015) inventories for European and non-European countries, respectively. For the Iberian Peninsula and Catalonia nested domains, emissions were estimated using the bottom-up module of HERMESv3, except for Barcelona domain where the estimated traffic emissions were computed by the VML-HERMESv3 coupled system previously described. The bottom-up module of HERMESv3 includes source-level emission estimation approaches mostly based on the Tier 3 calculation methodologies reported by the European EMEP/EEA air pollutant emission inventory guidebook. Further information on the methods and datasets used by HERMESv3 to compute bottom-up emissions can be found in Guevara et al. (2020). Biogenic emissions were computed for all the three domains using the MEGANv2.0.4 model (Guenther et al., 2006).

2.2.3. Street-scale air quality modelling: CALIOPE-Urban

The CALIOPE-Urban street-scale air quality model is applied over the Barcelona domain (Fig. 2) at a resolution of 20 meters. This resolution is selected to account for the strong pollutant concentration decay within tens of meters from the road edge (e.g. Black Carbon decay of more than 50% in street canyons within the initial 20 m (Amato et al., 2019)) that occur in compact cities while keeping feasible computational time and memory requirements. CALIOPE-Urban is composed of the above-mentioned CALIOPE air quality system - from where it takes the meteorology and chemical boundary conditions - and the near road dispersion model R-LINE (Snyder et al., 2013) adapted to street canyons (Benavides et al., 2019). The meteorology and chemical boundary conditions modelled by CALIOPE are downscaled to street level following the parametrisations described in Benavides et al. (2019). CALIOPE-Urban allows to estimate local traffic dispersion driven by channelled street winds and vertical mixing considering background NO_2 and O_3 concentrations, atmospheric stability, and street morphology. R-LINE applies the Generic Reaction Set (GRS) to resolve simple NO to NO_2 chemistry (Valencia et al., 2018), whose major limitation of the chemistry computations at the urban scale is the assumption of clear-sky conditions, which neglects the cloud-effects on the NO_2 photolysis rate. The street-scale dispersion model is run using the street-scale and hourly traffic emissions estimated by the VML-HERMESv3 system. These emission values are consistently used for both the street-scale (BCN-20m) and the mesoscale (CATALONIA-1km) modelling domains. Further information regarding CALIOPE-Urban can be found in Benavides et al. (2019).

2.3. Traffic restriction measures

We consider 3 different traffic restriction measures that are currently being applied or planned to be applied in the near future in Barcelona: (I) Tactical Urban Planning -TUP-, (II) Superblocks -SPB- and (III) the Low Emission Zone -LEZ-. The LEZ is applied in almost all the simulated domain, with some excluded areas and ways (Fig. 3a). It forbids the entrance of gasoline vehicles below Euro 3, diesel vehicles below Euro 4 and motorbikes/mopeds below Euro 2. Detailed descriptions of these measures can be found in Area Metropolitana de Barcelona (2020) and Ajuntament de Barcelona (2021b). Based on the set of measures presented by the Barcelona City Hall, we consider TUP actions that aim to remove vehicle lanes in major urban corridors of the city. We have reduced a total of 31.67 km from vehicle lanes, represented by the dotted blue lines in Fig. 3b. Additionally, we have implemented a total of eight superblock areas represented by the orange polygons in Fig. 3b. The considered superblocks are the ones with specific information of the planned actions made within. The specific streets modified and superblocks applied can be found in the supplementary material.

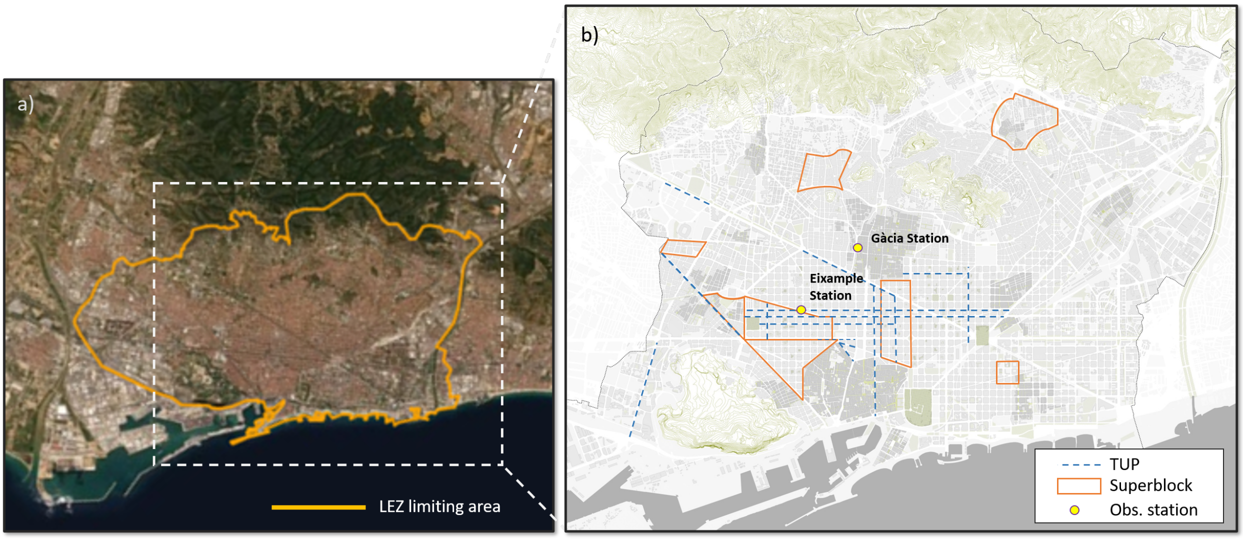

Figure 3: Barcelona study domain showing a) the area where the Low Emission Zone is applied (orange) and b) the superblocks (orange squares), the streets where tactical urban planning (TUP) actions were implemented (dashed blue lines), and the Barcelona urban traffic air quality monitoring stations (yellow dots). Adapted from Ajuntament de Barcelona (2020d). The ortogonal image from a) was obtained from Leaflet — Tiles © Esri — Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community.

In order to quantify the impact of each of these measures and differentiate their specific potential undesired rebound effects, we have simulated them individually and collectively, as specified in Table 1. On top of these scenarios, we have also modelled a Base Case (business-as-usual) scenario, which is taken as the reference for the comparison. The criteria to select the simulated scenarios was based on the ability of the traffic-emission-air quality system to estimate the new vehicle route equilibrium and the traffic associated emissions. Hence, the unique application of measures affecting vehicle emission factors (i.e., LEZ) were not considered for air quality simulations since similar studies have already been published elsewhere (Soret et al., 2014).

Table 1: List of scenarios and combination of traffic management measures considered in the study (TUP, Tactical Urban Planing; SPB, Superblocks; and LEZ, Low Emission Zone). Emissions have been modelled for all the scenarios, while we specify the scenarios where the air quality impact (AQ) has been modelled.

nº	Scenario	AQ
1	Base Case: Original 2017 network	Yes
2	Base Case + TUP	No
3	Base Case + SPB	No
4	Base Case + TUP + SPB	Yes
5	Base Case + LEZ	No
6	Base Case + TUP + SPB + LEZ	Yes
7	Base Case + TUP + SPB + LEZ + demand reduction (-25%)	Yes

One of the major difficulties in simulating the effects of traffic restrictions on vehicle fluxes is to estimate how the demand (e.g., total number of trips) will be affected due to their implementation. In this study, we assumed both the most pessimistic and optimistic scenarios, which are: (i) the number of total circulating vehicles will not change despite the measures implemented; and (ii) the traffic demand will suffer a -25% reduction once all the three different strategies are fully implemented, which is the expected reduction estimated by the Barcelona city council (Ajuntament de Barcelona, 2021b). In total, we simulated seven NO_x emission scenarios (one for each combination of traffic management strategies) and modelled the impact on NO_2 air quality levels in four of them due to the large computational load that it requires (Table 1). NO + NO_x (NO_x) and VOCs were simulated for all emission scenarios although only NO_x is represented since VOCs are used for the GRS chemical processes of CALIOPE-Urban. Even though Particular Matter (PM) is a pollutant with severe health issues, it will not be simulated in this study since the GRS module used by R-Line can only compute the dispersion of primary species (e.g., black carbon).

2.3.1. Tactical Urban Planing and Superblocks scenario

Changes on the traffic flow and speed induced by the TUP and SPB strategies were modelled following the description of measures reported in Ajuntament de Barcelona (2020b,c). To do so, we have modified target features of the original VML road network. The modifications include the removal of traffic lanes, changes in the street capacities and allowed maximum speed, and the addition of new turns to characterize SPB measures. The reduction of vehicle lanes of the TUP measures was directly applied to the VML network. The VML road capacity is calculated by the multiplication of the user-defined number of lanes and capacity of each lane, which depends on the specific road type (e.g., highway, urban corridor, etc). The number of lanes of the street links affected by the TUP measures were manually modified. Specific information of the modified links can be found in the supplementary material. For the SPB areas, in addition to the above-mentioned modifications, the construction of traffic-pacified street segments was modelled using a new segment type with a specific reduced capacity and speed. All modifications are made to prevent the circulation of modelled traffic flow as shown in Fig. 4.

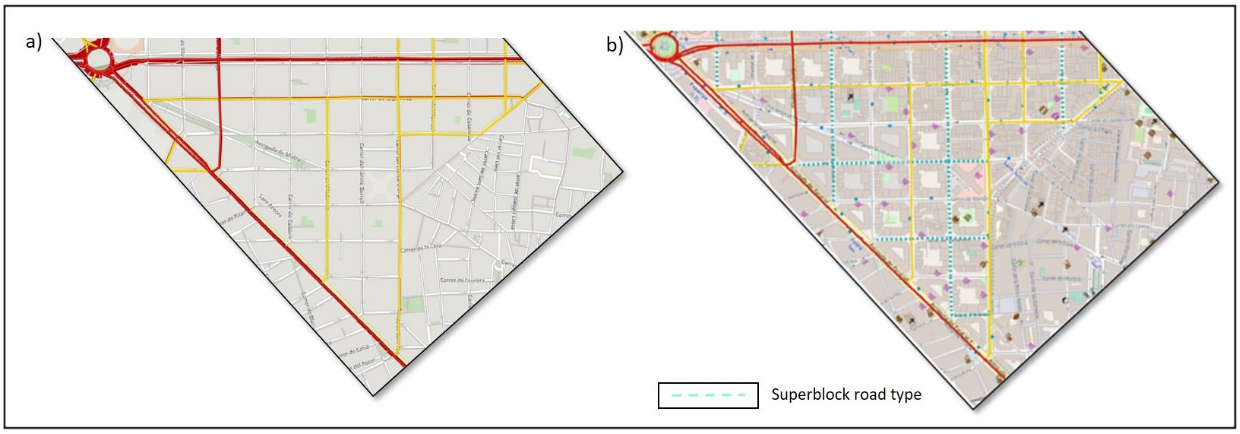

Figure 4: Screenshot of the VML traffic simulator network for (a) the Base Case scenario, and for (b) scenario SPB where a specific road type has been generated (blue dotted line) to represent the superblock restrictions. The colored segments indicate other street types with different parameters restricting vehicle movement (e.g., as a consequence of a traffic light green wave). From higher movement to lower: Red, yellow, grey, dottet blue. Detailed information about the traffic simulation can be found in Rodriguez-Rey et al. (2021).

2.3.2. Low Emission Zone scenario

The LEZ scenario, which forbids the entrance of the most polluting vehicles in the city, was simulated by adapting the description of the vehicle fleet composition profiles used in HERMESv3 to the restrictions associated to this measure. We assumed an optimistic scenario in which all banned vehicles are replaced by new Euro 6 vehicles. We wanted to reflect the tendency of drivers to switch from diesel to gasoline cars that can already be detected from the sales of gasoline-powered cars (European Automobile Manufacturers Association, 2021). To do so, we used the new registered vehicle data in Barcelona for 2019 (DGT, 2020), and applied the observed gasoline/diesel sales distribution to the new Euro 6 vehicles that appeared as a consequence of the LEZ. We did not substitute the banned vehicles by zero or low emission vehicles based on the Barcelona city hall expected vehicle fleet composition renewal for the next years, which accounts for less than 3% of zero or low emission vehicles by 2022 (Institut Cerdà, 2019).

Figure 5 compares the observed vehicle fleet composition in 2017 (AMB and RACC, 2017) and the estimated one after applying the LEZ. The share of Euro 6 diesel vehicles increases from 14% to 20%, while the share of Euro 6 gasoline vehicles increases from 6%

to 19%. The obtained LEZ fleet composition was applied to the road links within the LEZ domain represented by the green area in Fig. 3a. Due to the difficulties in assessing the LEZ impact on traffic flow (Holman et al., 2015), this scenario does not imply reductions in the simulated traffic demand.

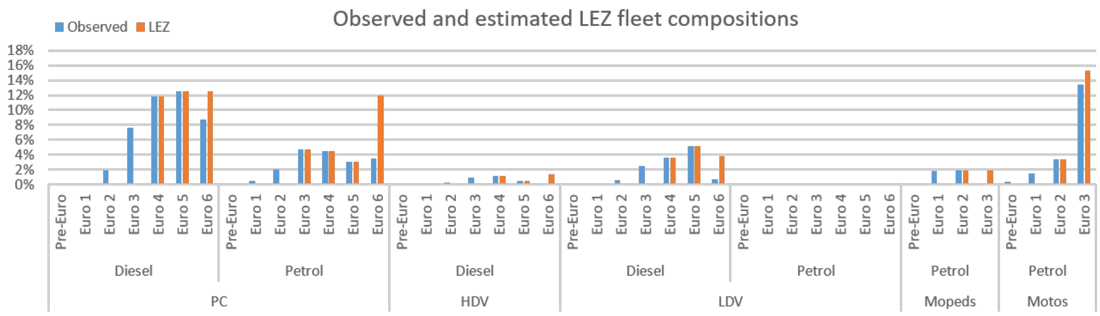

Figure 5: Observed vehicle fleet composition in 2017 (blue) and estimated Low Emission Zone (LEZ) vehicle fleet composition (orange) per vehicle type and Euro category. PC refers to Passenger Car, HDV to Heavy Duty Vehicle, and LDV to Light Duty Vehicle.

3. Results and discussion

Section 3.1 presents the NO_x emission results computed for the Base Case scenario and a comparison of the CALIOPE and CALIOPE-Urban NO_2 modelled concentrations against observations registered at the two urban traffic monitoring stations shown in Fig. 3b. The model performance at the other urban background monitoring stations can be found in the supplementary material. The emissions and air quality results for each of the traffic management scenarios are presented and discussed in Section 3.2 and 3.3 respectively.

3.1. Base Case scenario

Figures 6a and 6b show the road traffic emissions for the Base Case scenario used as input in the CALIOPE (1 km × 1 km) and CALIOPE-Urban (20 m × 20 m) systems, respectively. The VML-HERMESv3 estimated link-level vehicle emissions which are used by CALIOPE-Urban, are mapped onto the 1 × 1 km^2 gridded domain for CALIOPE in order to ensure consistency between modelling scales. Note that in Fig. 6b emission results are presented at a 50 m × 50 m resolution only for representation purposes. Both figures show that the highest NO_x values are found in the ring roads and the city center, where the main urban corridors are found. However, the street-level results allow representing the strong emission gradients that cannot be reproduced at 1 km × 1 km. Similarly, a large heterogeneity of the NO_2 distribution is observed with CALIOPE-Urban (BCN-20m), while the mesoscale CALIOPE (BCN-1km) modelling results show a rather uniform distribution of NO_2 levels across the city, the largest values found near the port area (Fig. 6c and Fig. 6d).

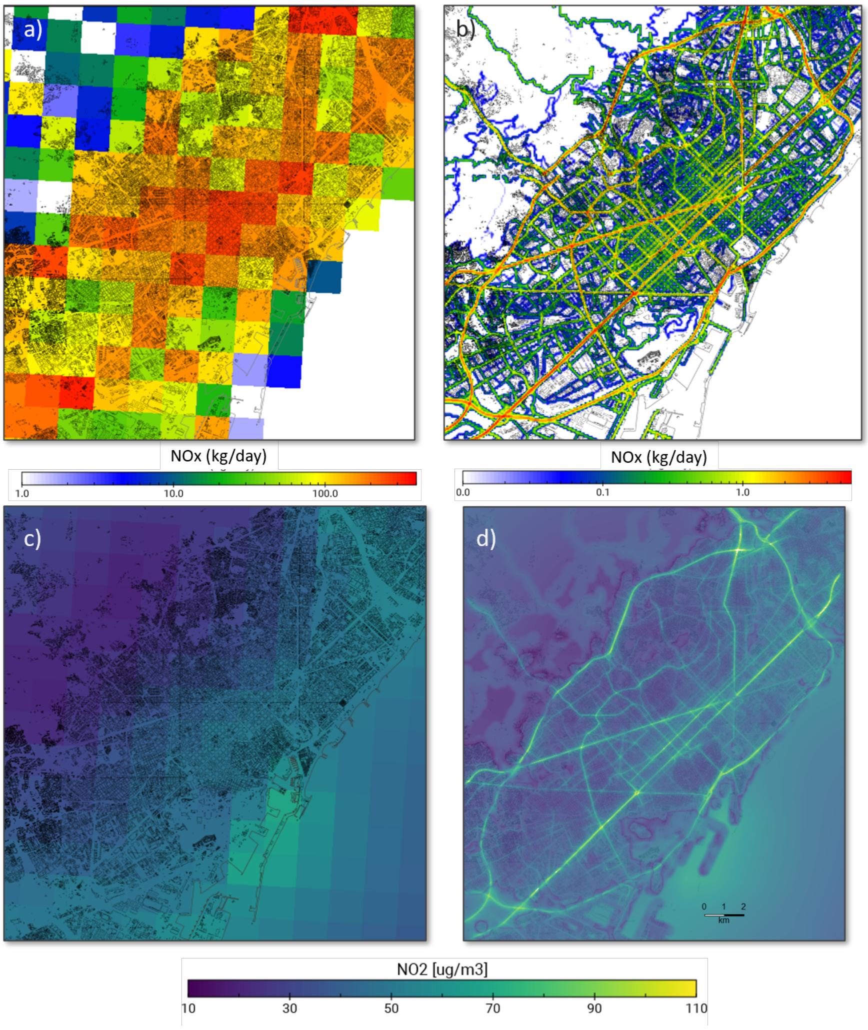

Figure 6: Average daily NO_x traffic emissions (kg/day) modelled by VML-HERMESv3 at a resolution of 1 km × 1km (a) and 50 m × 50 m (b), and average daily NO_2 concentrations ($\mu g/m^3$) modelled by CALIOPE and CALIOPE-Urban at a spatial resolution of 1 km × 1 km (c) and 20 m × 20 m (d).

Figure 7 shows the NO_2 average diurnal cycle observed at the Eixample and Gràcia stations (black dotted lines) and modelled by the CALIOPE and CALIOPE-Urban systems for the Base Case scenario (brown and pink lines, respectively). Standard statistics computed using the modelled and simulated concentrations are summarised in Table 2. CALIOPE-Urban is capable of capturing the morning and afternoon NO_2 peaks at the Eixample station, while it slightly overestimates the afternoon peak hour at Gràcia by 3% and estimates it earlier. Yet, the system is not able to properly capture the concentrations observed during the valley hours (11-16h), and it presents an underestimation of 30 µg/m^3 (-38%) in both stations. This behaviour in CALIOPE-Urban is inherited from the CALIOPE regional model, which cannot properly reproduce the vertical mixing of pollutants during daytime. Results clearly indicate that CALIOPE-Urban improves the modelling performance in capturing the NO_2 peaks with respect to the mesoscale approach (CALIOPE) while providing a more detailed information at the street-level. In both stations CALIOPE-urban reduces the mean bias observed with CALIOPE by half (-12 and -16 µg/m^3 vs -24 and -33 µg/m^3, respectively) and increases the FAC2 (fraction of predictions within a factor of two observations) by 0.21 and 0.11 in Gràcia and Eixample respectively, while maintaining a similar correlation (0.54 vs 0.58 and 0.52 vs 0.55 for Gràcia and Eixample).

Table 2: NO_2 model evaluation statistics calculated for the urban (CALIOPE-Urban) and mesoscale (CALIOPE) system at Eixample and Gràcia stations for the period of study (7 to 25 November 2017). *FAC2* refers to the fraction of modelled results within a factor of 2 of observations, *MB* refers to the mean bias, *RMSE* refers to root-mean-square Error, and r to the correlation coefficient.

Site	Model	FAC2	MB	RMSE	r
Eixample	CALIOPE	0.67	-23.99	38.01	0.52
	CALIOPE-Urban	0.77	-12.00	32.65	0.55
Gràcia	CALIOPE	0.54	-33.34	46.36	0.54
	CALIOPE-Urban	0.75	-15.88	36.00	0.58

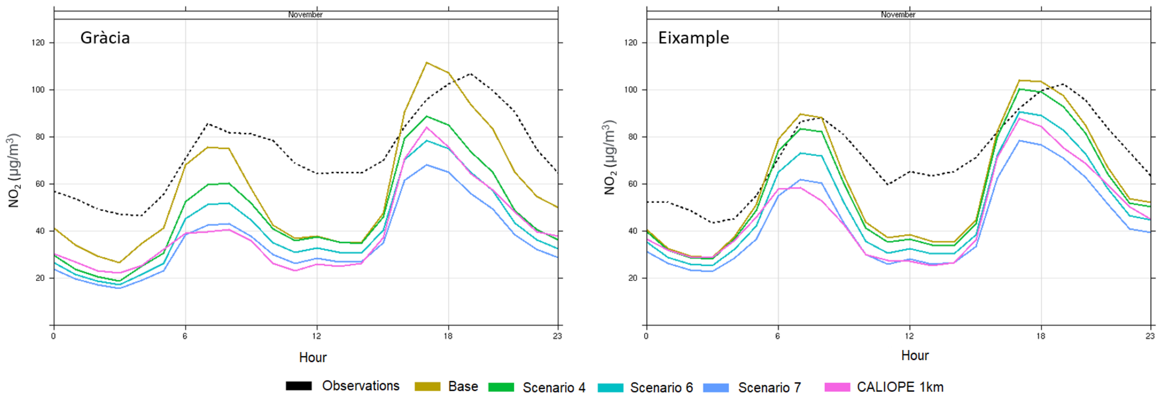

Figure 7: NO_2 average diurnal cycle observed (dotted back) and modelled with CALIOPE-Urban for the Base Case scenario (brown), scenario 4 (green), scenario 6 (sky blue) and scenario 7 (blue), and with CALIOPE for the Base Case scenario (pink) at Gràcia and Eixample urban traffic stations during the period of study (7 to 25 November 2017).

3.2. Impact of traffic strategies on NO_x emissions

Figure 8 shows the aggregated NO_x daily mean emissions for the base case scenario over the complete modelling domain, and the relative difference with the scenarios 2 to 7 for the period of study. According to these results, emissions are only reduced on those scenarios where the LEZ or the traffic demand reduction of -25% are implemented (scenarios 5 to 7). For all the other scenarios, when only TUP or SPB strategies are considered, the impact on the total NO_x emissions is negligible (+0.1%, due to the new generated congested areas).

Maximum reductions (-30%) are achieved when all the traffic management strategies are combined and a -25% reduction of the number of vehicles is assumed. The combination of all strategies without changes on the number of circulating vehicles shows overall NO_x emission reductions of -13.1%.

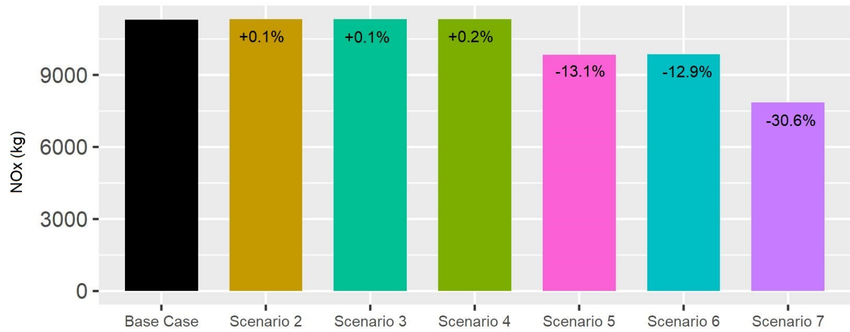

Figure 8: NO_x daily mean emissions (kg) for all scenarios and the relative differences (%) between the Base Case and the other simulated scenarios.

Despite not having any impact on the overall emissions, a significant redistribution of emissions at the street level can be observed when only implementing the TUP and SPB measures (scenarios 2 - TUP -, 3 - SPB -, and 4 - TUP+SPB -), which is caused by the re-routing of traffic assignment. To illustrate that, Fig. 9 shows the daily mean NO_x difference in an aggregated grid of 100 m × 100 m between the scenarios 2 to 7 with the Base Case scenario. Note that emissions at Fig. 9 are shown in a grid of 100m for representation purposes, but the original emission outputs are obtained and passed to CALIOPE and CALIOPE-Urban at the road link level. Since scenario 4 is the one combining TUP and SPB measures, in Fig. 10 we take a closer look into how the traffic flow (in annual average daily traffic, AADT) and associated NO_x emissions change in five representative street cells. The mentioned streets over the analysed emission cells are illustrative, since the 100 m × 100 m emission grid cell could also contain parts of other street segments. In this sense, the cell in one of the urban corridors with higher traffic load and emissions, Aragó (1) (Fig. 10), shows an average reduction of -17% (-1.3 kg $NO_x/100m^2$) in the simulated NO_x emission levels along the cell with a traffic flow reduction of -24% (-21.000 vehicles/day) (Fig. 10). On the other hand, NO_x emission increases up to +17% (+0.5 kg $NO_x/100m^2$) are observed in other adjacent street cells (e.g., Tarragona (4) or Viladomat (5)) as a consequence of a traffic flow increase of +30% (+6.000 vehicles/day) and +125% (+5.500 vehicles/day) respectively (Fig. 10). Viladomat (5) is of particular interest since the street is within a superblock area but it is still absorbing the traffic through it. In the view of these values, we have not found evidence of linearity between the absolute or relative traffic flow increment/decrement with the absolute or relative increase or decrease in NO_x emissions. This might be caused by the emission dependency in both traffic flow and speed, by the presence of other segments within the grid adding extra emissions and the difficulties of the macroscopic system in recreating vehicle emissions under congested situations.

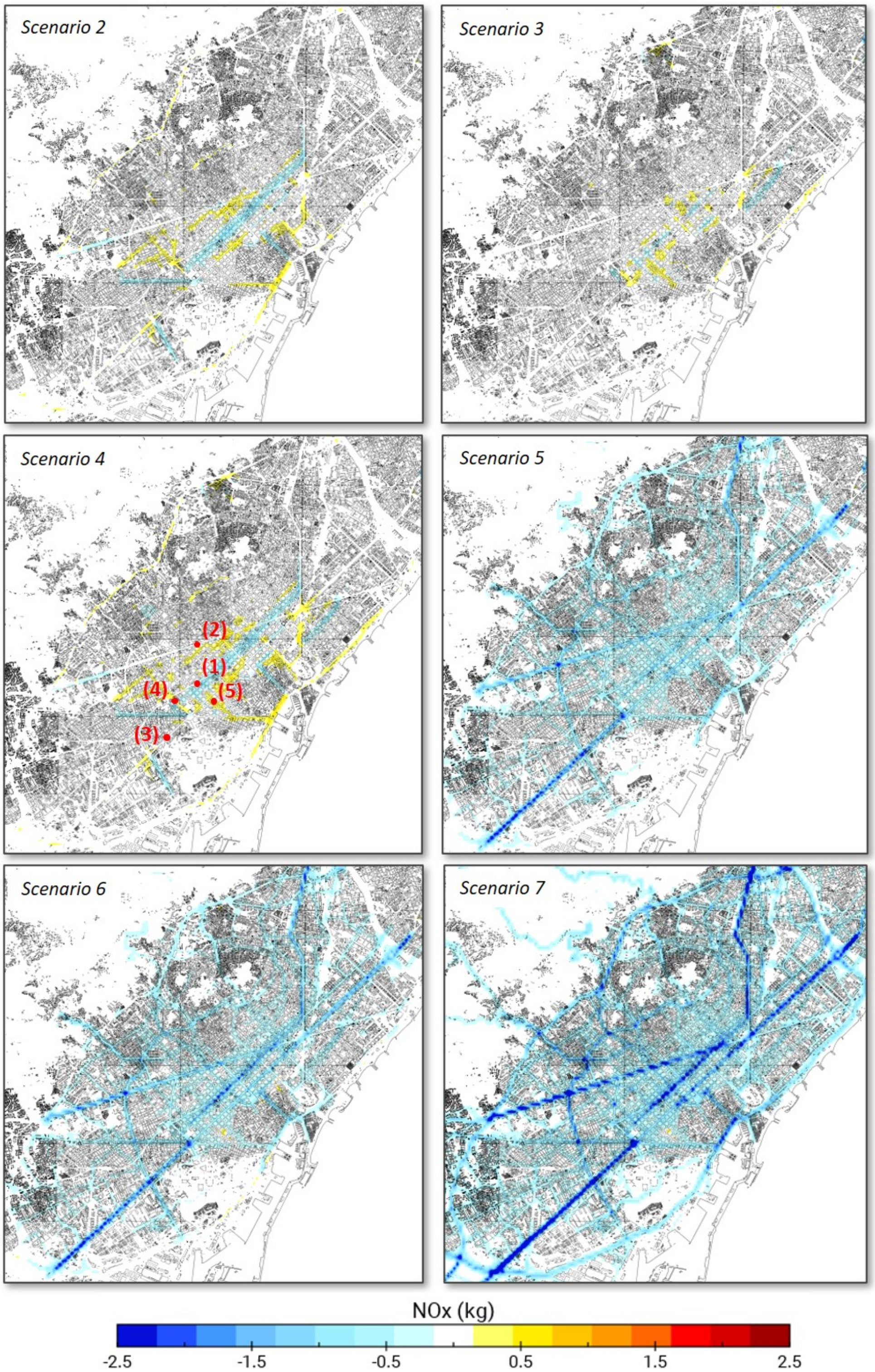

Figure 9: Daily mean NO_x emission differences (kg/100m^2) from the Base Case scenario with the scenarios 2 to 7 for the period of study. Scenario 4 also shows the location of the streets commented in Fig 10: Aragó (1), Diagonal (2), Gran Via (3), Tarragona (4) and Viladomat (5).

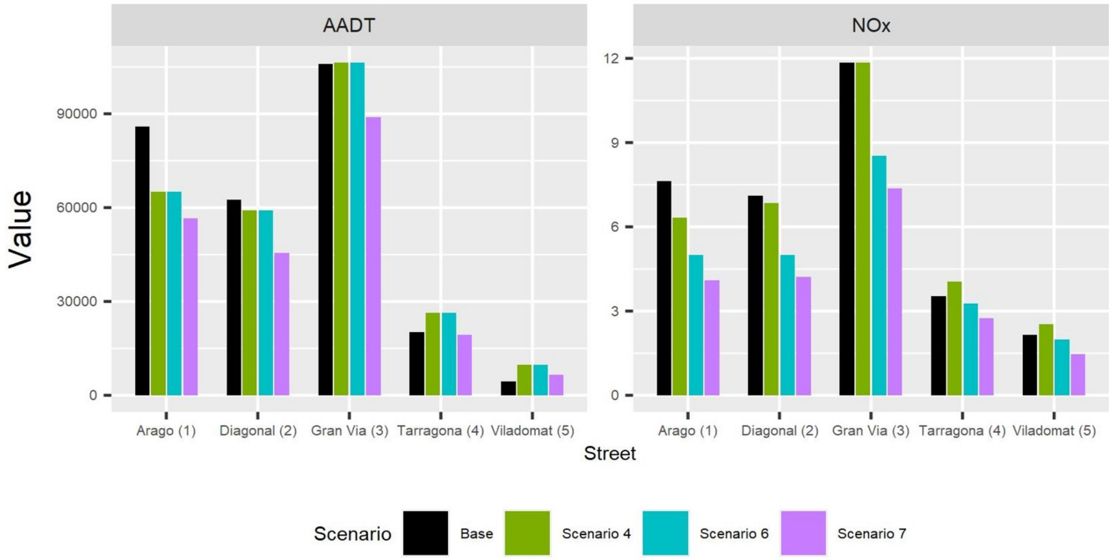

Figure 10: Annual average daily traffic (AADT) and daily mean NO_x emissons (kg) of the streets mentioned in Fig. 9 for the scenarios Base Case, 4, 6 and 7.

As described in Rodriguez-Rey et al. (2021), the macroscopic system cannot properly estimate the location of bottlenecks and the start-stop vehicle behaviour, which implies an underestimation of vehicle emissions in these situations. Our results reveal that large superblocks cannot avoid the through pass of vehicles within the designated area if traffic pacification measures are not applied in all streets within the superblock (Fig. 4). Smaller superblocks like the Poble Nou and Sarrià show NO_x emission decreases in all their streets that can reach up to -15%. This is due to the already low traffic load of such areas, that now discourage the through traffic, becoming areas used only by residents and services.

3.3. Impact of traffic strategies on NO_2 air quality levels

Figure 11 illustrates the differences between modelled NO_2 concentrations averaged over the period of study in scenarios 4, 6 and 7 and the Base Case scenarios using CALIOPE (left column) and CALIOPE-Urban (right column) systems. In line with the emission results, the impact of traffic measures on NO_2 concentrations is mainly observed when LEZ and/or the traffic demand reduction of -25% are implemented (scenarios 6 and 7). Under these two scenarios (6 and 7), NO_2 daily mean reductions of -5 to -10 µg/m^3 (-10% to -20%) and of -10 to -25 µg/m^3 (-20% to -30%) are observed in the main urban corridors, respectively, during the period of study. In both scenarios, the largest NO_2 decreases occur in the most trafficked streets due to the presence of less polluting vehicles (LEZ) and the implementation of TUP and SPB measures in such streets. When only TUP and SPB measures are considered (scenario 4), NO_2 impacts are very limited. NO_2 reductions and increases of similar intensity (+/-5 µg/m^3) are observed as a function of the street due to the traffic re-routing, as explained in section 3.2. The strong street gradients and associated NO_2 concentration changes modelled with CALIOPE-Urban cannot be reproduced with the

CALIOPE mesoscale system, which captures NO_2 reductions of only -6 to -10 µg/m^3 and between -3 to -6 µg/m^3 for the scenarios 7 and 6, respectively.

As shown in Table 3, with CALIOPE-Urban and under the most restrictive scenario with a demand reduction of -25% (scenario 7) the NO_2 averaged daily maximums would be reduced by a -36% and -22.5% in Gràcia and Eixample monitoring stations. This would represent a reduction of the observed daily maximum from 108 to 69 µg/m^3 (-39 µg/m^3) and from 101 to 78 µg/m^3 (-23 µg/m^3) of NO_2 for Gràcia and Eixample monitoring stations. If we perform the same exercise for the average daily mean, the observed NO_2 daily mean during the study period for Gràcia would be of 45.5 µg/m^3 (-38%) and of 52.4 µg/m^3 (-26.6%) for Eixample. On the other hand, the NO_2 reductions captured by the mesoscale CALIOPE system are around half (-18% and -17% for the daily average mean and daily maximum, respectively).

Table 3: Period-averaged daily mean and period-averaged daily maximum modelled NO_2 values (μg/m^3) for the Base Case scenario and the relative difference with the scenarios 4, 6 and 7 at the Gràcia and Eixample air quality station.

		CALIOPE-Urban		CALIOPE	
Scenario	Station	Daily mean average	Daily maximum	Daily mean average	Daily maximum
NO_2 base case (μg/m^3)	Gràcia	57.4	111.0	39.3	82.0
	Eixample	59.2	105.0	46.5	87.0
Scenario 4 (Diff. %)	Gràcia	-18.6%	-18.7%	0.0%	0.0%
	Eixample	-4.4%	-2.0%	0.0%	0.0%
Scenario 6 (Diff. %)	Gràcia	-28.6%	-26.2%	-10.4%	-6.1%
	Eixample	-15.0%	-11.8%	-10.8%	-8.0%
Scenario 7 (Diff. %)	Gràcia	-38.0%	-36.4%	-18.1%	-17.1%
	Eixample	-26.6%	-22.5%	-18.3%	-17.2%

Our work provides an estimate of the expected emissions and concentration levels after the application of the traffic restrictions in Barcelona. Based on the relative reductions obtained, we estimate that all the simulated scenarios would fail in reducing the annual average value below the AQD limit of $\leq$ 40 µg/m^3 of NO_2 in the two traffic stations for the considered study period. Yet, under scenarios 6 and 7, the NO_2 hourly exceedance of 216 µg/m^3 that occurred in November 2017 would very likely have been avoided.

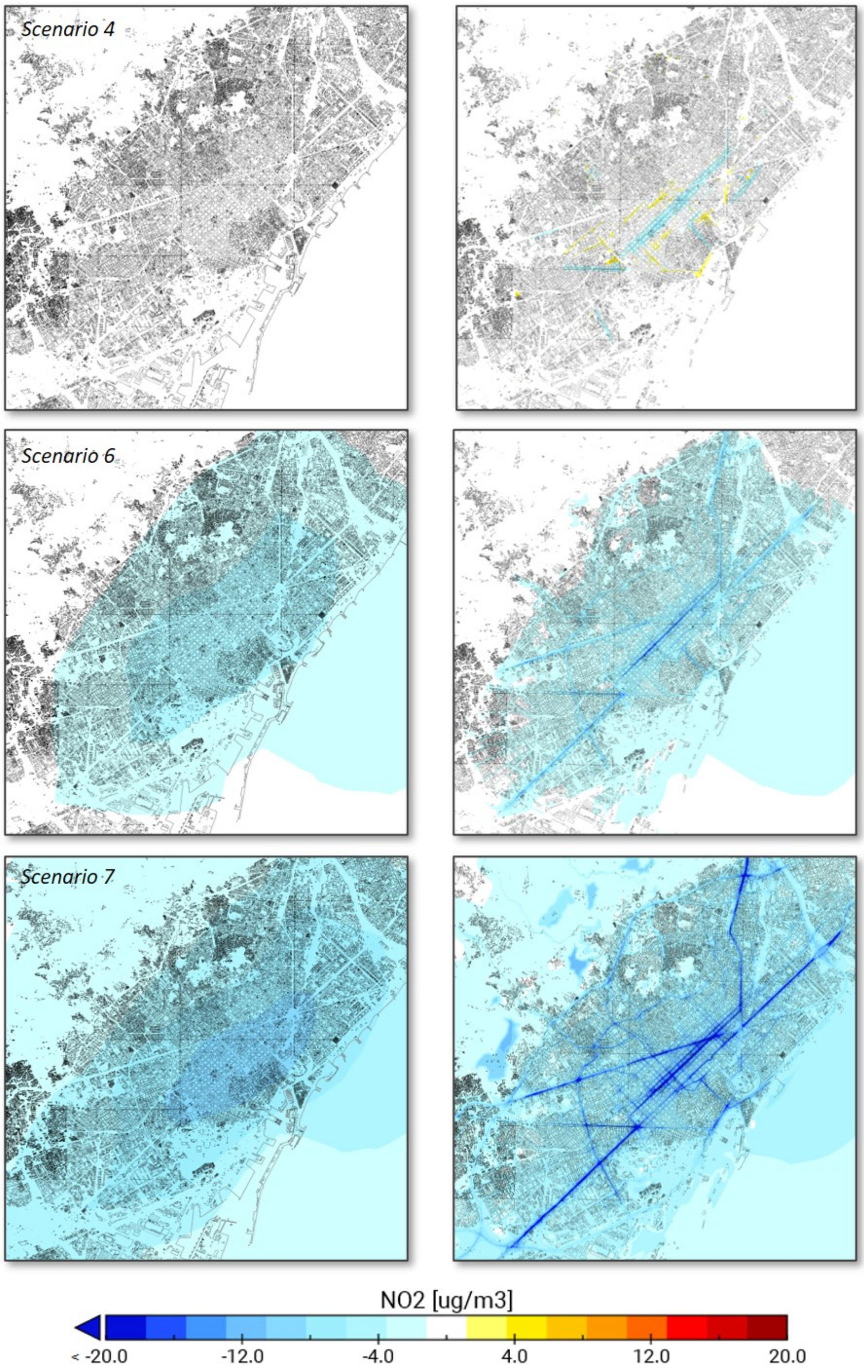

Figure 11: Daily mean NO_2 concentration difference ($\mu g/m^3$) between the base case and the scenarios 4, 6 and 7 for the November period. Left column shows the mesoscale values from CALIOPE model (1km) while right column shows the CALIOPE-Urban street scale model results (20m). Bluewish and yellowish colors indicate a decrease and increase in emissions, respectively.

4. Conclusions

We quantified the impact of different traffic management strategies on the NO_x emissions and NO_2 concentration levels in the city of Barcelona. To do so, we performed a multi-scale air quality modelling exercise that combines mesoscale (1×1 km) and street-scale (20×20 meters) air quality modelling tools, fed by a coupled macroscopic traffic and vehicle emission model. A total of 7 NO_x emission scenarios and 4 NO_2 air quality scenarios were simulated during a bi-weekly time period, which coincides with an air pollution episode that took place in November 2017. The scenarios comprise simulations of individual and varying combinations of the mobility measures currently being applied in Barcelona: a Low Emission Zone (LEZ), which aims to forbid the entrance of most polluting vehicles, Tactical Urban Planing (TUP) measures, which reduce the space that private transport has on specific streets of the city, and the Superblocks (SPB), which prevent the entrance of vehicles in a certain urban area delimited by several blocks. We additionally added a scenario where all these measures were combined with a traffic demand reduction of -25% based on the City Hall's expectations over the next years. The main findings and conclusions of this work are as follows:

- The largest road transport NO_x emission reductions in Barcelona (-30%) are obtained when combining all traffic management strategies (LEZ, TUP and SPB) together with the -25% traffic demand reduction. The computed reductions are only of -13% when traffic demand is kept constant.

- When only implementing measures related to the reduction of private transport space (TUP and SPB), overall NO_x changes are negligible (+0.1%). Nevertheless, these measures generate a traffic redistribution along the network, which shows a noticeable impact on the street-level emission distribution, with NO_x variations up to +/-17% in specific streets as a consequence of the new vehicle routing and the variation in traffic flow and speed. We have not found evidence of linearity between the traffic flow and speed variation and the increment or decrement in NO_x emissions.

- The impact on NO_2 air quality levels follows the same pattern as for emissions. Scenarios comprising all the traffic strategies with and without the -25% demand reduction show the largest NO_2 reductions at the main urban corridors (with daily mean reductions of -10 to -25 $\mu g/m^3$ and -5 to -10 $\mu g/m^3$, respectively and daily max reductions up to -70 $\mu g/m^3$ and -50 $\mu g/m^3$, respectively). When only implementing the TUP and SPB measures, limited increases and decreases of NO_2 are observed (+/-5 $\mu g/m^3$) due to traffic re-routing.

- The expected differences at the two traffic air quality monitoring stations of the city (Gràcia and Eixample) when implementing all traffic strategies and the demand reduction are of -38% and -27% for the daily mean average, and of -36% and -23% when considering the averaged daily max values for Gràcia and Eixample, respectively. These values decrease by approximately a 10% without considering the demand reduction.

- The NO_2 daily mean and peak concentration reductions modelled with the mesoscale system are almost two times lower than the ones obtained with the urban scale system. Despite presenting consistent results, the mesoscale system is not capable of modelling the strong street gradients and associated NO_2 concentration changes induced by the mobility restrictions. Considering these results, we recommend that the evaluation of urban traffic management strategies is performed applying a multi-scale modelling approach with street scale resolution for an optimal result.

- Although traffic management strategies lead to significant emissions and air quality improvements, the reductions achieved are insufficient to ensure proper air quality levels. These strategies must be accompanied by a large decrease in the total number of vehicles circulating throughout the city.

The methodology followed in this study can provide highly-detailed data for health assessment studies, like the one performed by Mueller et al. (2020). The authors are aware of the important health-related implications of Particular Matter and we are working towards including this pollutant in future works of this modelling system. On the same direction, the developed tool could be used for an ex-ante evaluation of further mobility policies applied by policy-makers, providing some insights before its application. In Barcelona, since the current measures appear to be insufficient to reduce the NO_2 levels below the EU AQD, the authors suggest the study of other proven-effective measures in reducing traffic demand like the congestion charging scheme, with successful results in Milan, London or Stockholm (Croci, 2016) combined with a more restrictive LEZ (Bigazzi and Rouleau, 2017).

This research shows that the application of a multi-scale air quality tool, combining traffic, emission and street dispersion models is essential to properly capture the induced NO_x and NO_2 variations generated by the application of different traffic management strategies. We acknowledge the limitations of the macroscopic traffic model to properly recreate the start-stop vehicle behaviour under congested situations, which implies an underestimation in vehicle emissions, as shown in Rodriguez-Rey et al. (2021). The macroscopic tool is however appropriate to estimate the impact of the analysed strategies at urban scale. The usage of a microscopic tool able to properly estimate traffic flow and vehicle emissions at the studied domain it is currently not a viable option due to the data and computational load needed. We also acknowledge the limitations of the study related to traffic demand modelling. It was assumed constant over the different scenarios studied, with the exception of scenario 7 which had a demand reduction of -25%. In reality, a modal transfer could occur between the private and public transport, or to other active ways of mobility (e.g., cycling) due to the private transport restrictions. In future works we plan to keep with the analysis of possible new TMS such as the application of green corridors (Ajuntament de Barcelona, 2021a) or to study the impact of additional measures that are currently not being considered by the city council such as the implementation of a congestion charge.

Author contributions. DRR, MG, MPL, JC and AS designed the research. JB and JMA participated in the building and calibration of the CALIOPE-Urban model. DRR performed the model coupling process and ran the experiments assisted by MG, JMA, OJ, JB and CT. MG, CP and OJ supervised the work. DRR prepared the paper with contributions from all co-authors.

Interests statement. The authors declare that they have no conflict of interest

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