Environ Sci Pollut Res (2017) 24:12026–12037
DOI 10.1007/s11356-015-5556-6

BIOMONITORING OF ATMOSPHERIC POLLUTION: POSSIBILITIES AND FUTURE CHALLENGES

Scenario-based analysis of traffic-related $PM_{2.5}$ concentration: Lisbon case study

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Received: 26 June 2015 / Accepted: 5 October 2015 / Published online: 21 October 2015

Abstract Air quality in urban centers constitutes a challenge ahead for most cities. For this reason, the objective of this research work was to evaluate the impacts of changing traffic-related parameters on particulate matter (PM) concentration for several hierarchical street levels using real-world data for the city of Lisbon, Portugal. For that purpose, 2014 data regarding meteorological conditions, traffic volumes, typical vehicle speed, and a vehicle representative of the fleet was used in an air quality dispersion model (CALINE4). The available data allowed building a baseline case for several streets that are representative of the traffic circulation conditions in Lisbon, which was compared with different scenarios: hypothetical introduction of a cordon toll (S1.1 to S1.4) and the implementation of a low emission zone (S2.1 and 2.2). The results indicate that reductions on $PM_{2.5}$ concentrations from 5 to 42 % may be obtained from the implementation of the scenarios. Overall, this study demonstrates that modeling tools based on real-world data can provide a good approach to study urban policies regarding traffic-related PM exposure. Additionally, implementation of such measures requires an integrated strategy that enables proper enforcement and monitoring, as well as an adequate management of traffic flows between the implementation boundaries.

Responsible editor: Constantini Samara

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Keywords $PM_{2.5}$ concentration · Scenarios · Urban policies · Modeling · LEZ · Cordon toll

Introduction

Road transportation has become a major contributor to air pollution, and, since more than 50 % of world population lives in cities (UN 2009), this is an issue that causes approximately two million deaths per year (WHO 2008). OECD (2012) estimates that, regarding environmental issues, exposure to particulate pollutants will be the main cause of premature deaths in 2050.

Particulate matter (PM) (particles smaller than 10 μm (PM_{10}) and smaller than 2.5 μm ($PM_{2.5}$)) can have different sources, including the burning of liquid fuels, coal, or wood, but also natural sources, such as windblown dust and chemical reactions. In most European urban environments, the primary source of PM_{10} emission is road transport (WHO 2005).

Epidemiological studies have consistently documented adverse health effects of air pollution (Brunekreef and Holgate 2002; Cohen et al. 2005; Dockery et al. 1993; Pope and Dockery 2006), and traffic-related air pollution is considered to be of particular importance due to its proximity to population in urban centers and to its volumes of emission (Jerrett et al. 2009; Zuurbier et al. 2011). Regarding the impacts of air pollution, PM exposure can be related to diverse cancers (Brunekreef and Holgate 2002), chronic respiratory diseases, cardiovascular diseases, and higher probability of allergies and birth defects (Miller et al. 2007; Pandya et al. 2002; Sørensen et al. 2003).

In order to reduce the pollutants emissions from road transport, and consequently reduce their atmospheric and health impacts, increasingly stringent European regulations (EURO standards) on tailpipe emissions of new vehicles sold have been introduced to regulate CO, HC, NO_X, and PM (EC 2007) during the last decades. The first regulatory step was EURO 1 which was implemented in 1992, EURO 2 came into force in 1996, EURO 3 in 2000, EURO 4 in 2005, and EURO 5 in 2009 (Dieselnet 2015), imposing lower admissible level of emissions on light-duty vehicles along time. Furthermore, the European Union has also set air quality standards for PM_{10}, regulating a 24-h limit value of 50 μg/m^3, which may not be exceeded more than 35 times per year. A second limit value, an annual average value, was set at 40 μg/m^3. These limit values had to be accomplished by January 1, 2005 (Council of the European Union 1996, 1999a, b). Additional targets exist for $PM_{2.5}$ (for individual monitoring stations as well as for average population exposure). For example, the deadline for meeting the 25 μg/m^3 annual target was January 1, 2010, while the exposure concentration obligation (ECO) of 20 μg/m^3 will enter into force in 2015. Nevertheless, these limits are still exceeded quite often.

On a local level, several policy measures have also been adopted in an attempt to tackle this emission problem. In more detail, air quality action plans are being applied. These plans include measures such as stimulation of public transportation usage, ring road utilization, traffic flow improvement, speed limit reduction, congestion charging, and implementation of low emissions zones (LEZs). LEZs are areas where only vehicles with pollutant emission levels lower than a certain limit are allowed to enter.

In Europe, around 200 LEZs have already been implemented mostly in the last decade (Wolff and Perry 2010) (http://urbanaccessregulations.eu/). LEZs constitute a considerably harsh option because they require adaptations in driving habits and can lead to fleet renewal. Moreover, until now, there have not been clear evidences of their effectiveness in really reducing air pollution and ultimately improving public health. This makes their application debatable, namely in a cost-effectiveness standpoint, as questions arise whether they are worth pursuing (van Erp et al. 2012).

Previous studies have evaluated the effectiveness of local traffic policy measures using both modeled and/or measured air pollution concentrations. Johansson et al. (2009) evaluated the implementation of a charging zone in Stockholm based on measured and modeled changes in road traffic. The authors estimated that the annual average NO_x concentrations would be up to 12 % lower along the most congested streets, while PM_{10} concentrations would decrease by up to 7 %, comparing to a baseline scenario without the charging zone. The reductions on traffic emissions were expected to be mainly due to decreased traffic flow, while lower congestion had small effect.

Cesaroni et al. (2012) evaluated the impact of two LEZs established in Rome. Due to the policy implementation, reductions of 33 and 58 % for PM_{10} and NO_2 emissions were estimated for the passenger cars in the intervention area. The authors concluded that the study provided evidence that policies aimed at reducing traffic-related air pollution have beneficial effects: a decrease of emissions, of concentrations, of population exposure, and health gains.

Boogaard et al. (2012) investigated air pollution at street level before and after the implementation of local traffic policies including LEZs directed at heavy-duty vehicles in five Dutch cities. Measurements were made at several locations allowing to conclude that, apart from one urban street where traffic flows were significantly reduced, the local traffic policies were too modest to produce considerable decreases in traffic-related air pollution concentrations.

Qadir et al. (2013) analyzed the concentrations and source contributions of particulate organic matter before and after implementation of a low emission zone in Munich, Germany. The contribution of traffic particulate organic matter emission was found to decrease by about 60 % after the implementation of the LEZ.

Ellison et al. (2013) studied the impacts of the LEZ implementation in vehicle fleet composition and air quality in the city of London. The authors concluded that the LEZ had a substantial effect on the composition of the vehicle fleet in London with its influence in increasing the replacement rate for older vehicles being sustained in the years since. They also found that even though the number of heavy-duty vehicles had increased within the LEZ, London's air quality has improved marginally with reductions in concentrations of PM_{10} and NO_X.

However, so far, there are very few papers with such real-world detailed data using a scenario-based analysis that allows quantifying the effects of implementing several policy measures. Considering this, in order to better understand the variables influencing PM emissions, a low-level analysis is required, by performing an evaluation based on hierarchical street levels, considering their real-world data on traffic volumes and vehicle speeds. This work aims at evaluating impacts on PM concentration of different policies (in this case, the implementation of cordon tolls and LEZs) with influence on traffic-related parameters applied to several hierarchical street levels[1] (from arterial to local roads) using real-world data for the city of Lisbon, Portugal.

LEZ in Lisbon, Portugal

The case study for this research work is the city of Lisbon. The city of Lisbon is an interesting case of analysis because it presents several areas with considerable problems regarding exposure to local pollutants. With few industrial sources in Lisbon, road vehicles are the main cause of air pollution in

[1] Level 1—arterial roads; level 2—collector and distributor roads; levels 3 and 4—local roads.

Fig. 1 Spatial location of the LEZ (adapted from Câmara Municipal de Lisboa (2015))

the city which is particularly relevant near major roads (Ferreira et al. 2000). Lisbon road network is composed by 32 % of arterial and collector roads, which comprehend 72 % of the city's traffic volumes, and by 68 % of local roads gathering 28 % of the traffic (Câmara Municipal de Lisboa 2005). In 2011, 49 % of the trips in Lisbon were performed by private transport (including cars and motorcycles), while pedestrian/cyclist and public transport shared 51 % (17 and 34 %, respectively) of the total mobility (INE 2014).

High PM levels are frequently registered in the local air quality monitoring stations, not complying with the legislated limits (Ferreira et al. 2002). Therefore, the LEZ concept has been introduced in Lisbon in 2011 and, since then, the geographical coverage of the measure has been increasing. The third stage of LEZ took effect in January 2015, and, thereafter, all vehicles registered before January 1, 2000 were prohibited to circulate in the city center, which affects approximately 30 to 40 % of the Lisbon fleet (Câmara Municipal de Lisboa 2014). The overall goal of the policy was to reduce the concentration of pollutants, namely PM and NO_2, in order to protect the population health and ultimately to accomplish the limit values imposed by the European legislation.

Lisbon is divided in two distinct LEZ: zone 1, which comprehends the downtown center and a major avenue, which often exceeds the PM emission limits (Ferreira et al. 2006); and zone 2, which comprehends a larger area of up to 25 km^2 and is delimited by major avenues. Figure 1 presents a schematic representation of the spatial location of zones 1 and 2.

Table 1 Zones 1 and 2 characterization regarding the percentage of streets and the number of lanes per hierarchical level

Level	Percentage of streets		Average number of lanes	
	Zone 1 (%)	Zone 2 (%)	Zone 1	Zone 2
1	0	0.3	–	–
2	0	2.2	–	4
3	25	7.0	3	3
4	75	90.5	1	2

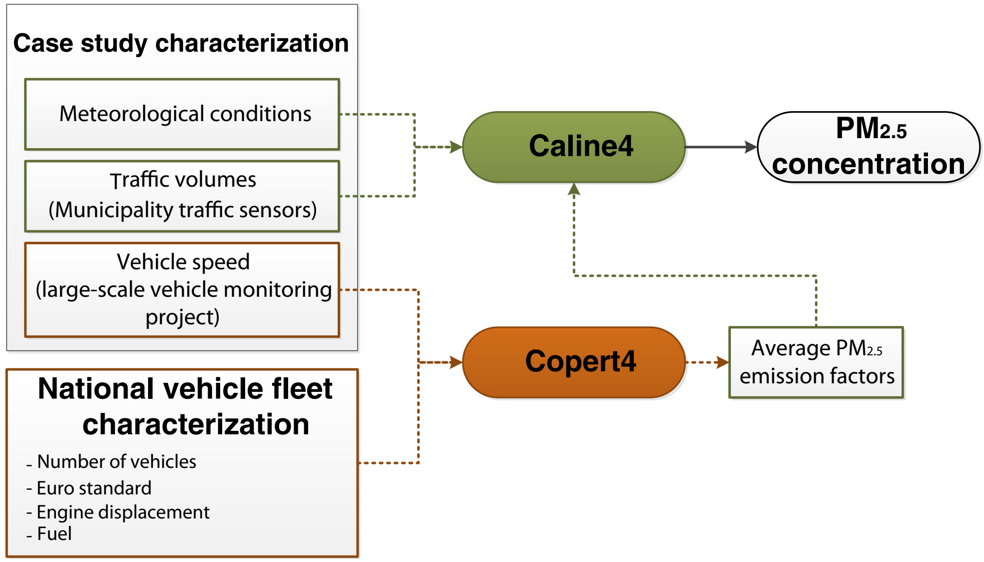

Fig. 2 Overview of the applied methodology

Both zones are mainly composed by local roads (levels 3 and 4) but zone 2 presents a small percentage of level 2 roads (collector and distributor roads), while zone 1 only has level 3 (25 %) and level 4 (75 %) streets, as is presented in Table 1. Even though zone 2 presents 0.3 % of level 1 streets (arterial), these streets were not considered in this study due to their low representativeness when compared with the other levels. Besides this, all level 1 streets are part of the boundary that delimitates zone 2. The average number of lanes characterization was also computed based on the street by street analysis.

In order to perform a general analysis on the impacts of possible scenarios in the city of Lisbon, a weighted average based on Table 1 streets distribution was considered.

Methodology

A general overview of the applied methodology to estimate traffic-related $PM_{2.5}$ concentration is presented in Fig. 2. The performed analysis included a monthly and seasonal comparison of PM exposure for different hierarchical street levels. This methodology is based on real-world data from multiple sources and it is intended to be as generic as possible, in order to be replicated elsewhere. The tools and numerical models were selected accordingly to perform a consistent low-level analysis that can be built into a city level.

The methodology was tested in six scenarios, where the baseline case (BAU) was compared with different scenarios consisting on hypothetical introduction of a cordon toll (drivers could be charged when crossing the boundary of a predefined tolling area, with consequences in terms of traffic volumes, S1.1 to S1.4) and the implementation of a low-emission zone by restricting the access of older (and more polluting) vehicles to the city center (S2.1 and 2.2).

Going into more detail into the methodology, in order to estimate traffic-related $PM_{2.5}$ concentration, an air quality dispersion model was used. The model chosen was CALINE4 (Benson 1989), which is based on the Gaussian diffusion

Table 2 Overview of the information used, its description, and data sources

Data	Description	Time period	Source	Data-processing
Meteorological conditions	Temperature and wind speed in a 30 min basis	7 years average	University of Lisbon[a]	N/A
Traffic volumes	Traffic volume (in number of vehicles) in a 15 min basis for three different hierarchical street levels	1 year (2014)	Municipality	N/A
Typical vehicle speed	Average vehicle circulation speed in each street obtained from large-scale vehicle monitoring project for three different hierarchical street levels	June to October 2014	i2D project (ITDS and IDMEC-IST 2011)	N/A
Vehicle fleet characterization	Vehicle fleet characterization (number of vehicles, engine displacement, fuel) based on the average national fleet composition to obtain average fleet $PM_{2.5}$ emission factors	2012	ACAP (Autoinforma and ACAP 2000 to 2013)	Copert4 (a European reference vehicle emission model)

[a] Meteorological data was provided by the investigation group MARETEC/LARSYS, Grupo de Previsão Numérica do Tempo, Instituto Superior Técnico, Universidade de Lisboa

Table 3 Average meteorological conditions (temperature and wind speed)

Level	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Temperature (°C)	11.6	11.7	13.8	15.6	18.0	20.9	22.2	22.9	21.6	19.0	14.0	11.5
Wind speed (m/s)	3.7	4.0	4.1	4.2	4.4	4.6	5.1	4.9	4.1	3.7	3.7	3.7

equation and employs a mixing zone concept to characterize pollutant dispersion over the roadway. It allows assessing air quality impacts (air concentration of CO, NO_2, and suspended particles), on a microscale level, estimating pollutants concentrations up to 500 m away from the roadway. According to Chen et al. (2009), from the USEPA Gaussian dispersion models (CALINE4, CAL3QHC, and AERMOD), CALINE4 and CAL3QHC are more adequate when detailed meteorological data is not available, even though AERMOD may simulate atmospheric processes more precisely. Other authors (Majumdar et al. 2010) state that CALINE4 offers several advantages when compared to other models, such as the technical refinements (the mixing zone residence time, the initial vertical dispersion parameter, reduced sensitivity to stability class, augmented rate of vertical dispersion, and the usage of the directional variability) that better describe the dispersion process near roadways. Also, the user-friendliness and the easiness to operate with a WINDOWS-based system are presented as CALINE4's advantages (Majumdar et al. 2010). Finally, the lower input data requirements of CALINE4 to assess at a microscale level PM dispersion was observed as a potential advantage to replicate the developed approach in this work to other locations.

CALINE4 presents a simple approach, however, considering that there are several other uncertainties in the used methodology, it was considered that using a more complex air quality model would not considerably improve the quality of the results, with consequent disadvantages in terms of input requirements and simulation complexity, as well as replicability of methodology to other locations where much more detailed information will most likely not be available. Regarding the models inputs, whenever possible, real-world data with high temporal resolution was used.

This study aims at estimating the impact of different scenarios by considering streets that are representative of the typical conditions in Lisbon. For that purpose, the simplifications made by using CALINE4 were considered acceptable. CALINE4 requires a characterization of the street environment, which includes meteorological conditions, traffic volumes, typical vehicle speed, and vehicle fleet average emission factor. Other input parameters were also incorporated, including link coordinates, receptor coordinates, link height (set as zero), mixing zone width (is the width of the roadway plus 3 m on either side and was considered to be variable according to the number of lanes), aerodynamic roughness coefficient (400 cm, typical value for a central business district (Benson 1989)), and ambient pollutant concentration (considered to be zero). Table 2 presents an overview of the type of information used, its description and data sources.

Regarding the meteorological conditions, average values were obtained from half an hour basis data, for a 7-year period (2008–2014). Table 3 presents the average meteorological conditions (temperature and wind speed) along the year.

Traffic volumes were provided by the municipality in a 15 min basis for the year of 2014 (source: CML, traffic and urban mobility department). These values are measured by traffic sensors installed on streets considered to be representative of the typical traffic conditions of the city. Average annual daily traffic (AADT) for each hierarchical street level, along the year, is presented in Table 4. This information is particularly useful not only for road characterization but also for testing cordon toll scenarios with consequent traffic reductions.

Regarding vehicle emissions, Copert4 (a reference vehicle emission model developed for the European Environmental Agency) (Gkatzoflias et al. 2007) was used to estimate the PM emission factor (in grams per kilometer) for the existing

Table 4 Average annual daily traffic (AADT) for each hierarchical level

Level	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2	57,372	59,532	59,756	58,480	61,438	58,104	58,870	49,366	58,510	59,484	58,258	55,656
3	24,146	25,288	24,918	24,270	24,892	23,816	23,676	19,002	21,958	22,586	22,146	29,046
4	11,216	11,392	11,586	12,370	12,964	11,788	12,094	10,846	12,164	12,374	11,966	16,584

Table 5 Characterization of the national fleet in 2012 (percent) considering buses (a) and passenger cars/light commercial vehicles (b)

Emission standard	(a) Urban buses			Emission standard	(b) Passenger cars and light commercial vehicles			
	Midi (%)	Standard (%)	Coaches (%)		Gasoline (%)	Diesel (%)	Hybrid (%)	LPG (%)
Conventional	5.8	5.8	11.6	Pre-Euro	4.6	2.3	0	0
Euro I[a]	2.2	2.2	4.4	Euro 1	6.7	3.7	0	0
Euro II[a]	3.9	3.9	7.9	Euro 2	11.5	7.0	0	0
Euro III[a]	5.7	5.7	11.3	Euro 3	13.2	14.6	0	0
Euro IV[a]	5.2	5.2	10.4	Euro 4	6.5	18.6	0.2	0.01
Euro V[a]	2.2	2.2	4.4	Euro 5	2.8	8.2	0	0.05

[a] The standard for heavy-duty vehicles is identified by roman numerals while the equivalent standard for light vehicles is identified by Arabic numerals

average national vehicle fleet and for the LEZ scenarios. Copert4 was used for the baseline scenario characterization using as assumptions 100 % urban driving conditions and variable speeds (from 15.6 to 40.5 km/h). Since it was not possible to accurately identify which vehicles typically travel in a certain road at a given day, an average representative vehicle for the case study was considered. This vehicle represents the average Portuguese vehicle for 2012. Table 5 presents the Portuguese fleet characterization (for 2012) in terms of fuel distribution, emission standard, and type of vehicle distribution (Autoinforma and ACAP 2000 to 2013).

For characterizing the average speed in the city of Lisbon, on-board data loggers were used to collect on a large-scale driving speeds over Lisbon streets under real-world conditions. A sample of 40 drivers, driving in Lisbon over 6 months with an on-board data logger connected to the vehicle OBD port, allowed to build an extensive database of 1 Hz georeferenced driving data (ITDS and IDMEC-IST 2011). This data allowed establishing a correlation between hierarchical street levels and average driving speeds. Maximum and minimum average speeds used for each hierarchical street level are shown in Table 6.

The next step was to evaluate the influence of specific policies on traffic reductions and the implementation of LEZ, so six scenarios were developed. The detailed definition of the scenarios is presented in Table 7.

The average $PM_{2.5}$ emission factors, estimated with Copert4, for the fleet of light commercial vehicles, public buses, and passenger cars are shown in Table 8. LEZ restrictions are not applicable to motorcycles and there is practically no circulation of heavy-duty vehicles in the city center (Brás 2012), therefore they were not considered in this analysis.

In scenario 1, there are no differences in the emission factors when comparing to the baseline case (BAU). As for scenario 2.1, the emission factors decreased 16 and 14 % for zones 1 and 2, respectively. Under scenario 2.2, a lower reduction of the emission factors was obtained (zone 1: 13 %; zone 2: 10 %).

This data sample applied in CALINE4 allowed building a baseline case for streets that are representative of the traffic circulation conditions in Lisbon.

The influence of scenario 1 in the traffic volumes is calculated directly in CALINE4 inputs. However, for the LEZ scenarios (S2.1 and S2.2), another $PM_{2.5}$ average emission factor was computed due to vehicle fleet modifications. For that purpose, it was considered that, in scenario 2.1, a fleet renewal would occur so vehicles older than Euro 2 standard (before January 2000) (Dieselnet 2015) were replaced by newer vehicles (Euro 3, 4, and 5) maintaining the current fleet distribution. A 16 and 14 % average reduction in the average fleet PM emission factor for zones 1 and 2, respectively, would be observed in this scenario. Regarding the traffic volume, for zone 2, the traffic volume was kept equal to the baseline case. However, for zone 1, since Euro 2 vehicles are not allowed to enter this zone, a traffic reduction of 23.3 % (corresponding to all Euro 2 vehicles) was considered.

In scenario 2.2, only newer vehicles are entitled to enter the LEZ leading to different emission factors (13 % average reduction in the fleet PM emission factor in zone 1 and 10 % average reduction in zone 2) and to traffic reductions on both zones. For zone 1, a traffic reduction of 35.7 % (all vehicles

Table 6 Maximum and minimum average speed (km/h) for each hierarchical street level

Level	Average speed (km/h)	
	Min	Max
2	23.6	40.5
3	17.2	34.0
4	15.6	22.6

Table 7 Scenarios definition and characterization

Scenarios		Scenario definition	Meteorological data	Traffic volume
Baseline case (BAU)		Current situation (baseline year: 2014)	Average conditions for the city of Lisbon (7 years)	Current situation
Scenario 1	S1.1	Implementation of cordon tolls. The fleet remains equal to the BAU.		5 % traffic reduction
	S1.2			10 % traffic reduction
	S1.3			15 % traffic reduction
	S1.4			20 % traffic reduction
Scenario 2	S2.1	Implementation of a LEZ. Fleet renewal. All vehicles older than Euro 2 standard are replaced by newer vehicles.		Equal to BAU for zone 2. Traffic reductions of 23.3 % on zone 1 due to the LEZ restrictions.
	S2.2	Implementation of a LEZ. Considering only the newer vehicles of the fleet. Older vehicles will not enter the LEZ.		Traffic reductions due to the LEZ restrictions (zone 1: 35.7 % and zone 2: 17.3 %)

registered before January 2000) was considered, while for zone 2, traffic volume was assumed to decrease by 17.3 % (corresponding to the vehicles registered before January 1996).

Other important assumption for these scenarios was that a full compliance of the restrictions was assumed and that the LEZ operates 24 h per day. Even though the authors are aware of the fact that LEZ entry restrictions will lead to an increase on vehicles kilometers traveled outside the LEZ, the impacts in terms of $PM_{2.5}$ concentrations were only analyzed within the LEZ where traffic reductions are expected to occur.

Additionally to the impacts in terms of $PM_{2.5}$ concentrations, a simplified economic analysis was also performed. A valuation of both PM emissions and energy consumption was performed based on the external costs and avoided fuel consumption. External costs valuation is mainly due to the health costs which include both morbidity (especially respiratory and cardiovascular diseases) and premature mortality. Global warming impacts are also accounted. As for fuel consumption, average sale prices were considered to assess the avoided fuel consumption. Table 9 presents the costs considered for PM emission and energy consumption.

Results

In order to evaluate the impacts of different policies on traffic-related PM concentration, the developed scenarios were tested and analyzed. Figure 3 presents the $PM_{2.5}$ concentration results obtained for the baseline (BAU) and the alternative scenarios for zones 1 and 2. In both zones, the impacts of seasonal effects are observed, particularly on July, August, September, and December where the traffic volumes and meteorological conditions affect both the magnitude and the shape of the PM concentration profile. As expected, the average $PM_{2.5}$ concentration decreases along the six scenarios (from 5 to 42 % for both zones).

Due to the tighter restrictions imposed in zone 1 (only vehicles complying with Euro 3 standard or higher can circulate within this area), the fleet renewal scenarios S2.1 and S2.2 are most effective on this area, presenting an improvement of 34.6±1.5 and 43.2±1.6 % in traffic-related PM concentration, respectively. In zone 2, the reductions presented by S2.1 and S2.2 are 15.2±1.7 and 25.1±1.7 %, respectively. Table 10 summarizes the average $PM_{2.5}$ concentration for each

Table 8 Average $PM_{2.5}$ emission factors (in g/km) for the baseline case and for the developed scenarios

Level	Scenario											
	BAU		S1 - zones 1 and 2		S2.1 - zone 1		S2.1 - zone 2		S2.2 - zone 1		S2.2 - zone 2	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
2	0.038	0.045	0.038	0.045	0.032	0.037	0.032	0.038	0.033	0.039	0.034	0.040
3	0.040	0.049	0.040	0.049	0.034	0.041	0.034	0.042	0.035	0.042	0.036	0.044
4	0.045	0.050	0.045	0.050	0.038	0.041	0.039	0.043	0.039	0.043	0.041	0.045

Table 9 Costs considered for PM emission (€/g) and energy consumption (€/l)

	Costs
PM	0.087 €/g (European Parliament and the Council of the European Union 2009)
Energy consumption	Diesel—1.377 €/l
	Gasoline—1.541 €/l (Eurostat 2014)

month and scenario. On average, traffic reduction scenarios present an almost linear correlation with $PM_{2.5}$ average concentration (CALINE4 only estimates traffic-related $PM_{2.5}$ concentrations). In zone 1, S1.1, S1.2, S1.3, and S1.4 indicate reductions of 5.1±1.6, 10.6±1.8, 15.1±1.5, and 19.1±1.6 %, respectively. For zone 2, these scenarios present reductions of 5.8±1.7, 10.8±2.3, 15.2±1.7, and 19.6±1.5 %, respectively.

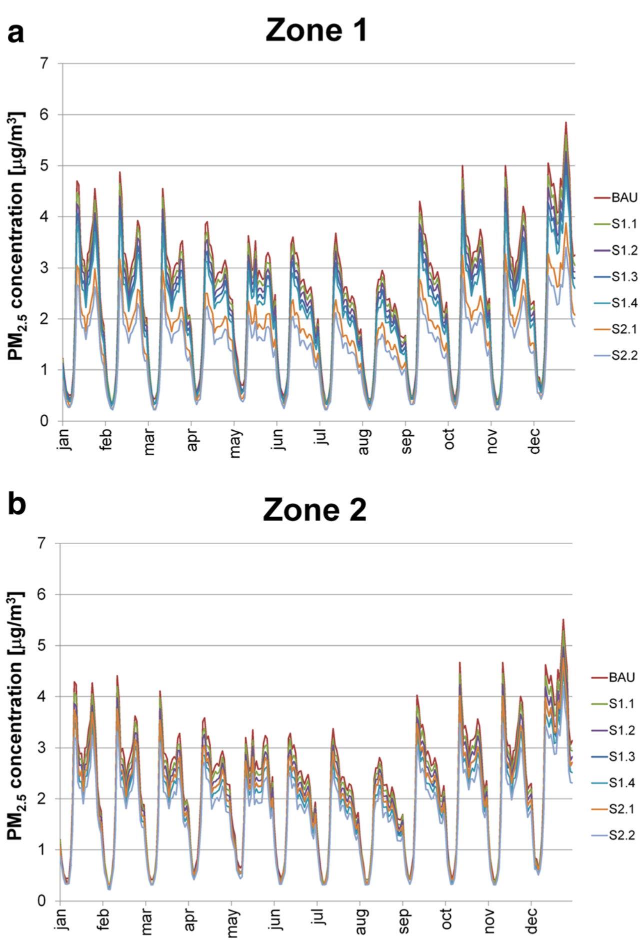

Fig. 3 Estimated traffic-related $PM_{2.5}$ concentrations for **a** zone 1 and **b** zone 2

Figure 4 presents the hourly average traffic-related $PM_{2.5}$ concentration over a typical day. It can be observed that for all tested scenarios, the morning peak starts at 7 h, the highest traffic-related $PM_{2.5}$ concentration occurs at 8 h and reduces gradually until lunch hour (13 h). The afternoon peak starts at 17 h and finishes by 20 h. Future emission control strategies should include vehicle volume hourly shift and specific measures according to the time of the day. For instance, imposing scenario 2 (S2.1 or S2.2) on higher $PM_{2.5}$ concentration periods (also correspondent to higher traffic volume periods) and limitations on traffic volumes (S1.1 to S1.4) on off-peak periods.

Figure 5 presents the mass emission of traffic-related $PM_{2.5}$ for each of the scenarios considered, with different fleet emission factors and traffic volumes for zones 1 and 2. It can be observed that small traffic reductions (S1.1 and S1.2) present savings of ~0.3 and 0.5 t for zone 1 and 8.3 and 16.6 t for zone 2, respectively. More extreme scenarios of traffic reduction lead, as expected, to higher $PM_{2.5}$ reductions (15 and 20 % for both zones 1 and 2 for S1.3 and S1.4). However, it can be observed that S2.1 and S2.2 (considering fleet renewal) are more effective scenarios (36 and 44 % for zone 1 and 14 and 26 % for zone 2 for S2.1 and S2.2, respectively) than traffic volume reduction, with the benefit of not reducing mobility patterns.

Comparing scenarios 2.1 and 2.2 allow to conclude that the main impact on concentration contributions resulted from the removal of older vehicles (S2.2) (previous to Euro 2 and Euro 1 for zones 1 and 2, respectively) from the roads. The fleet renewal (S2.1) was of lesser importance.

In order to validate the model results, the authors compared the BAU results with the measured values (from a nearby air quality monitoring station, Entrecampos, which is the closest to the study area measuring $PM_{2.5}$) (Agência Portuguesa do Ambiente 2015). Since this study considers only traffic-related $PM_{2.5}$ concentrations, data regarding source apportionment from a previous study was considered. Almeida et al. (2005) found that, for Lisbon, vehicle exhaust contributes to 22 % of the total mass of $PM_{2.5}$. Assuming this, it was possible to conclude that the maximum deviations between measured and simulated values ranged from −38 to 35 % (by comparing the monthly averages). The modeling quality objectives (defined as the maximum deviation of the measured and calculated concentration levels) established by the European Directive 1999/30/EC (Council of the European Union 1999a, b) define a minimum accuracy of 50 % which allowed to consider the model results acceptable.

When analyzing the traffic-related $PM_{2.5}$ emissions savings, valuing avoided health costs, cost reductions of 1 to 6 k€ are observed, as presented in Table 11. When

Table 10 Average traffic-related $PM_{2.5}$ concentration ($\mu g/m^3$) for the BAU and for the scenarios along the year

Zone	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Zone 1	BAU	2.6	2.4	2.4	2.4	2.4	2.1	2.0	1.8	2.4	2.6	2.6	3.5
	S1.1	2.5	2.3	2.2	2.3	2.2	2.0	1.9	1.7	2.3	2.5	2.5	3.3
	S1.2	2.3	2.2	2.1	2.2	2.1	1.9	1.8	1.6	2.1	2.4	2.3	3.1
	S1.3	2.2	2.1	2.0	2.1	2.0	1.8	1.7	1.5	2.0	2.2	2.2	3.0
	S1.4	2.1	2.0	1.9	2.0	1.9	1.7	1.6	1.5	1.9	2.1	2.1	2.8
	S2.1	1.7	1.6	1.5	1.6	1.5	1.4	1.3	1.2	1.6	1.7	1.7	2.3
	S2.2	1.5	1.4	1.3	1.4	1.3	1.2	1.1	1.0	1.4	1.5	1.5	2.0
Zone 2	BAU	2.4	2.2	2.2	2.3	2.2	2.0	1.9	1.7	2.3	2.5	2.5	3.3
	S1.1	2.3	2.1	2.1	2.1	2.1	1.9	1.8	1.6	2.1	2.4	2.3	3.1
	S1.2	2.1	2.0	1.9	2.0	2.0	1.8	1.7	1.6	2.0	2.2	2.2	3.0
	S1.3	2.0	1.9	1.9	1.9	1.9	1.7	1.6	1.5	1.9	2.1	2.1	2.8
	S1.4	1.9	1.8	1.8	1.8	1.8	1.6	1.5	1.4	1.8	2.0	2.0	2.7
	S2.1	2.0	1.9	1.9	1.9	1.9	1.7	1.6	1.5	1.9	2.1	2.1	2.8
	S2.2	1.8	1.7	1.6	1.7	1.7	1.5	1.4	1.3	1.7	1.9	1.8	2.5

valuing the fuel not consumed, cost reductions of −11 to 175 k€ are observed. Both cases present significant cost reduction potentials. Specifically in scenario 2.1, energy consumption increases when compared to BAU, due to the higher fuel consumption factor attributed by COPERT to the newer vehicles (EURO 2 onwards) (a shift toward larger or more powerful cars increased the specific consumption despite the increase in efficiency) (Enerdata 2012).

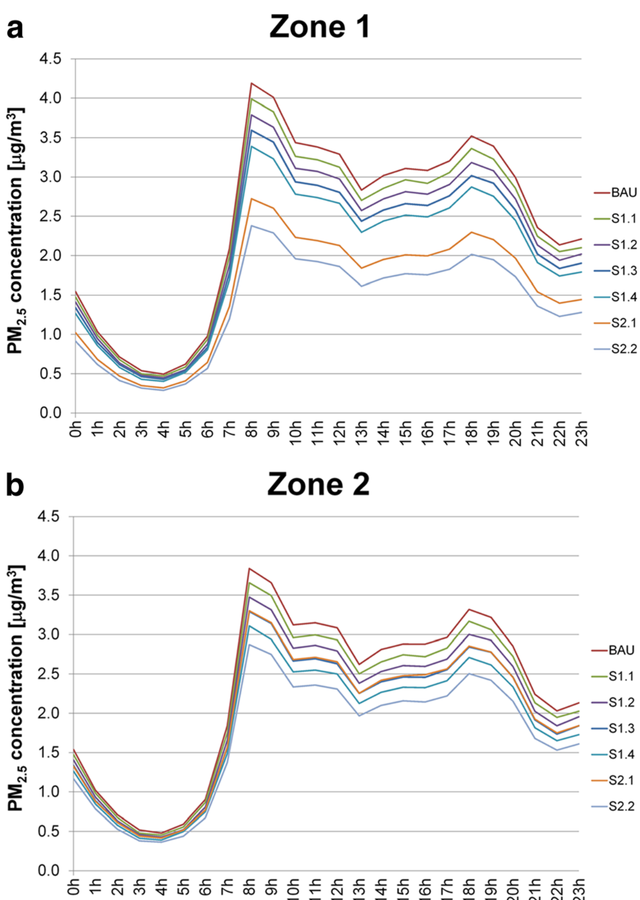

Fig. 4 Average traffic-related $PM_{2.5}$ concentration ($\mu g/m^3$) for the BAU and for the scenarios along the day for **a** zone 1 and **b** zone 2

Conclusions

The problem of air quality in urban centers remains an issue in a large number of cities, resulting in the implementation of policies to overturn that fact. The analysis performed in this work provides evidence that urban policies, such as cordon tolls and LEZ, are effective in reducing traffic-related $PM_{2.5}$ concentrations and, consequently, have beneficial health effects. Overall, reductions on traffic-related $PM_{2.5}$ concentrations from 5 to 42 % may be obtained from the implementation of scenarios. Furthermore, the results allow concluding that the most effective measure to implement is the cordon toll since the traffic restriction imposition leads to significant results, while the fleet renewal effects are more variable. However, the implementation of such measures requires an integrated strategy that enables proper enforcement and an adequate management of traffic flows between the implementation boundaries. The real-world monitoring of the implementation of these measures should also be promoted, in order to verify its impacts and help the design of future urban air quality and transport policies.

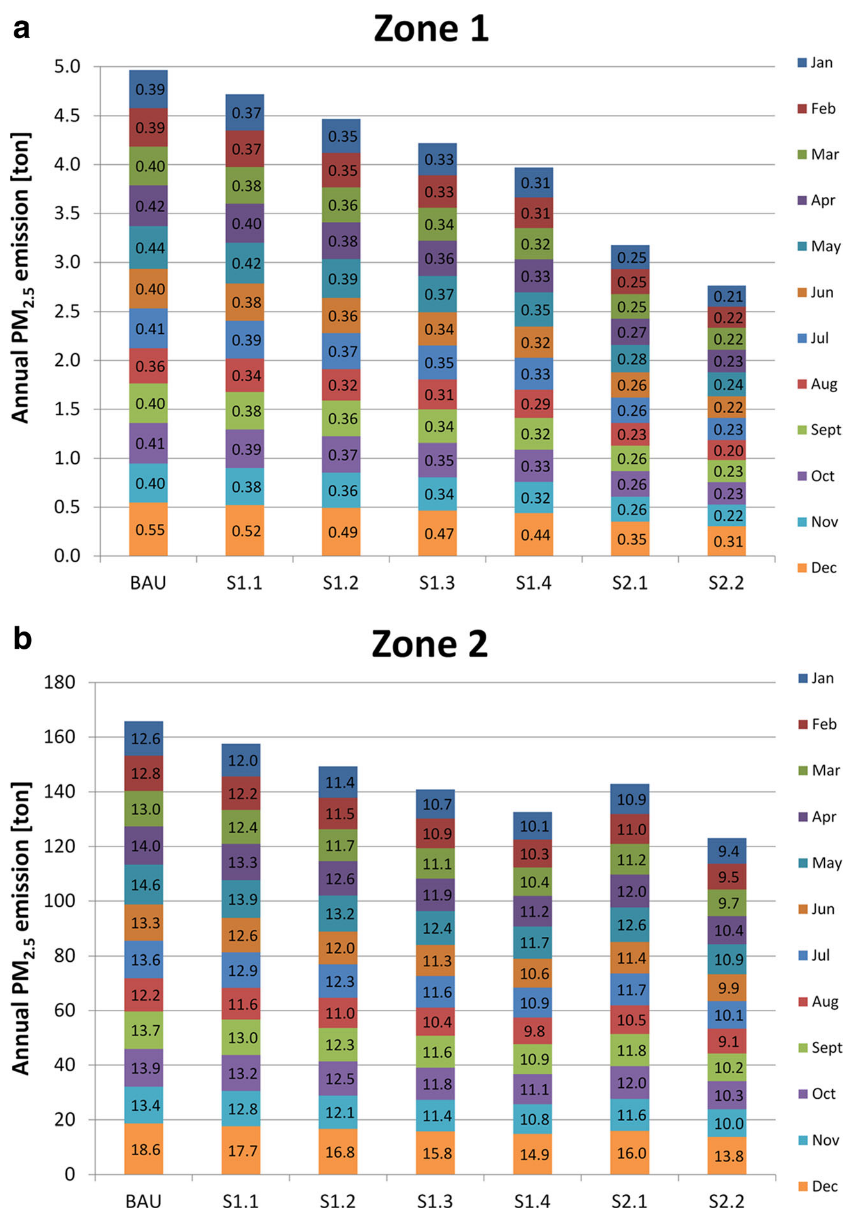

Fig. 5 Total traffic-related $PM_{2.5}$ emitted (in ton) for the BAU and for the scenarios for **a** zone 1 and **b** zone 2

Table 11 Traffic-related $PM_{2.5}$ emissions and energy consumption savings for each scenario and for each hierarchical level

Zone	Savings	Level	S1.1 (€)	S1.2 (€)	S1.3 (€)	S1.4 (€)	S2.1 (€)	S2.2 (€)
Zone 1	$PM_{2.5}$ emission	3	1172	2347	3519	4694	8432	10,383
		4	555	1111	1665	2221	4000	4921
		Average	709	1420	2129	2659	5108	6287
	Energy consumption	3	42,077	84,221	126,293	168,444	179,632	284,922
		4	20,349	40,742	61,094	81,470	87,510	138,426
		Average	25,781	51,612	77,394	96,484	110,540	175,050
Zone 2	$PM_{2.5}$ emission	2	3580	7165	10,745	14,331	10,106	18,631
		3	1172	2347	3519	4694	3268	6062
		4	555	1111	1665	2221	1539	2862
		Average	664	1330	1994	2659	1849	3432
	Energy consumption	2	122,195	244,546	366,756	489,129	−50,444	367,955
		3	42,077	84,221	126,293	168,444	−19,925	125,822
		4	20,349	40,742	61,094	81,470	−9735	60,973
		Average	24,100	48,248	72,351	96,484	−11,335	72,235

Acknowledgments The authors acknowledge Fundação para a Ciência e Tecnologia for the Doctoral (PD/BD/105714/2014) and Post-Doctoral (SFRH/BPD/79684/2011) financial support, as well as a project grant (SusCity Project, MITP-TB/C S/0026/2013). This work was also supported by Fundação para a Ciência e Tecnologia, through IDMEC, under LAETA, project UID/EMS/50022/2013. Thanks are also due to Project SoMoMUT—Soft Mode Modeling in Urban Trips (PTDC/ECMURB/1407/2012). The authors would also like to acknowledge Direcção de Mobilidade e Transportes Terrestres of Câmara Municipal de Lisboa for providing the traffic count data and the investigation group MARETEC/LARSYS, Grupo de Previsão Numérica do Tempo (Instituto Superior Técnico, Universidade de Lisboa) for providing the meteorological data.

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