

THE ROLE OF ELECTRIC VEHICLE IN LOW EMISSION ZONES: POTENCIAL IMPACTS FOR THE CITY OF LISBON, PORTUGAL

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Abstract

The objective of this work was to evaluate the role of EVs in low emission zones on reducing PM and CO concentrations using real-world data for Lisbon, Portugal. A baseline case for representative streets of Lisbon traffic circulation conditions was built and compared with different scenarios: implementation of a LEZ (S1) and EVs introduction (S2 and S3). The results indicate that reductions from 14 to 81% on PM_{2.5} and from 62 to 99% on CO concentrations may be obtained. Overall, this study demonstrates that modeling tools based on real-world data can provide a good approach to study pollutants exposure urban policies.

Keywords: *EV (electric vehicle), emissions, pollution, policy*

1 INTRODUCTION

The transportation sector is a major contributor to energy consumption and to air pollution. This sector was responsible for 32% of the EU-28 energy consumption in 2013 and for 22% of greenhouse gases (GHG) emissions [1]. Furthermore, since more than 50% of world population lives in cities, it is estimated that air pollution causes approximately two million deaths per year [2]. Epidemiological studies have consistently documented adverse health effects of air pollution [3-6], 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 [7, 8]. Regarding the impacts of air pollution, particulate matter (PM) exposure can be related to diverse cancers [3], chronic respiratory diseases, cardiovascular diseases and higher probability of allergies and birth defects [9-11]. As for carbon monoxide (CO), several epidemiological literature references have linked short-term exposure to ambient CO with increased risks of all-cause and cardiovascular outcomes (such as hospitalization and mortality) [12-14].

As a way to reduce pollutants emissions from road transport, increasingly stringent European regulations (EURO standards) on tailpipe emissions of new vehicles sold have been introduced to regulate CO, HC, NO_x and PM [15] 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, EURO 5 in 2009 and finally, EURO 6 in 2014 [16], imposing lower admissible levels of emissions on passenger cars and light-duty vehicles along time. Furthermore, the European Union (EU) has also set air quality standards regulating several pollutants. The Air quality standards as given in the EU Ambient Air Quality Directive are presented in Table 1. Nevertheless, these limits are still exceeded quite often.

Table 1: Air quality standards as given in the EU Air Quality Directive [17, 18]

Pollutant	Averaging period	Value	Entered in force in	Permitted exceedances each year
PM ₁₀ , limit value	24 hours	50 µg/m ³	1 January 2005	35
PM ₁₀ , limit value	Calendar year	40 µg/m ³	1 January 2005	n/a
PM _{2.5} , limit value	Calendar year	25 µg/m ³	1 January 2015	n/a
PM _{2.5} , limit value	Calendar year	20 µg/m ³	To be met by 1 January 2020	n/a
PM _{2.5} , exposure concentration obligation (ECO)	–	20 µg/m ³	Legally binding in 2015 (years 2013, 2014, 2015)	n/a
CO, limit value	Maximum daily 8-hour mean	10 mg/m ³	1 January 2005	n/a

On a city level, several policy measures may be considered in the attempt to tackle this energy consumption and emission problem. When considering a technological solution, electric mobility is regarded as an opportunity for significantly reducing the amount of CO₂ emitted by the transportation sector, increase renewable energy penetration, as well as to mitigate the emissions of local pollutants. The shift to electric mobility would therefore have substantial impacts for urban systems due to their zero local emissions and noise reduction potentials [19, 20]. However, such technologies still have significant weaknesses that prevent them from being true alternatives, such as purchase cost, performance, autonomy and recharging limitations [21-24].

When addressing the air quality problem in urban areas from an operational point of view, the implementation of low emission zones (LEZ) has been performed worldwide as a way of reducing emissions while promoting fleet renewal. LEZs are areas where only vehicles with pollutant emission levels lower than a certain limit are allowed to enter. Consequently, LEZs constitute a great opportunity to promote zero emission solutions in particular electric vehicles (EVs). In Europe around 200 LEZs have already been implemented mostly in the last decade [25] (<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 [26]. Other studies have tried to address the possible impacts of LEZ [27-31], suggesting reductions of up to 60% in particulate organic matter emission due to the introduction of a LEZ. As for the impacts of EVs, several studies have quantified the potential gains of their introduction, which can typically reach up to 70 to 80% on a life-cycle perspective [32-34].

However, so far, little focus has been given on real world detailed data quantifying the impacts of both technological and operational options, in this case of the introduction of electric vehicles combined with LEZ. Considering this, in order to better understand the variables influencing air pollutants emissions, a low-level analysis is required, by performing an evaluation based on hierarchical street levels¹, combining real-world data on traffic volumes and vehicle speeds. This work aims at evaluating the impacts on PM and CO of an integrated strategy of implementation of LEZ and of electric vehicles using real-world data for the city of Lisbon, Portugal.

2 METHODOLOGY

The case study for this research work was the city of Lisbon, Portugal. The 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 [35]. In 2011, 49% of the trips in Lisbon were performed by private transport (including cars and motorcycles), while pedestrian/cyclist and public transport were responsible for 51% (17% and 34%, respectively) of the total mobility [36].

High PM levels are frequently registered in Lisbon by the local air quality monitoring stations, not complying with the legislated limits [37]. Therefore, the LEZ concept has been introduced in Lisbon in 2011 and, since then, the geographical coverage of the measure has been increasing. Currently, Lisbon is

¹ Level 1 – Arterial roads; Level 2 – Minor arterial streets; Level 3 – Distributor and collector streets; and Level 4 – Local streets.

divided in two distinct LEZ: Zone 1, which comprehends the downtown center and a major avenue, which often exceeds the PM emission limits [38]; and Zone 2, which comprehends a larger area of up to 25 km² and is delimited by major avenues. Figure 1 presents a schematic representation of the spatial location of Zone 1 and 2.

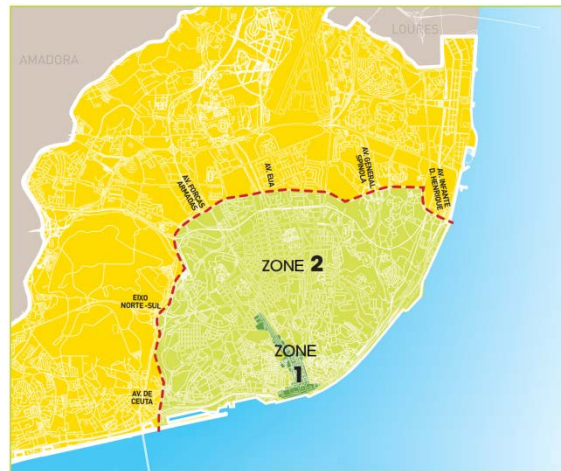


Figure 1: Spatial location of the LEZ (Adapted from Câmara Municipal de Lisboa [39], [40])

Both Zones are mainly composed by Level 3 and 4 streets but Zone 2 presents a small percentage of Level 2 roads, while Zone 1 only has Level 3 (25%) and Level 4 (75%) streets, as is presented in Table 2. Even though Zone 2 presents 0.3% of Level 1 roads, these were not considered in this study due to their low representativeness when compared with the other levels. Besides this, all Level 1 roads 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 2 streets distribution was considered.

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

Level	Description	Percentage of streets		Average number of lanes	
		Zone 1	Zone 2	Zone 1	Zone 2
1	Arterial roads	0%	0.3%	-	-
2	Minor arterial streets	0%	2.2%	-	4
3	Distributor and collector streets	25%	7.0%	3	3
4	Local streets	75%	90.5%	1	2

A general overview of the applied methodology to estimate traffic-related PM_{2.5} and CO concentration is presented in Figure 2. The performed analysis included a monthly and seasonal comparison of PM and CO 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 in other cities. The tools and numerical models were selected accordingly to perform a consistent low-level analysis that can be built into a city level.

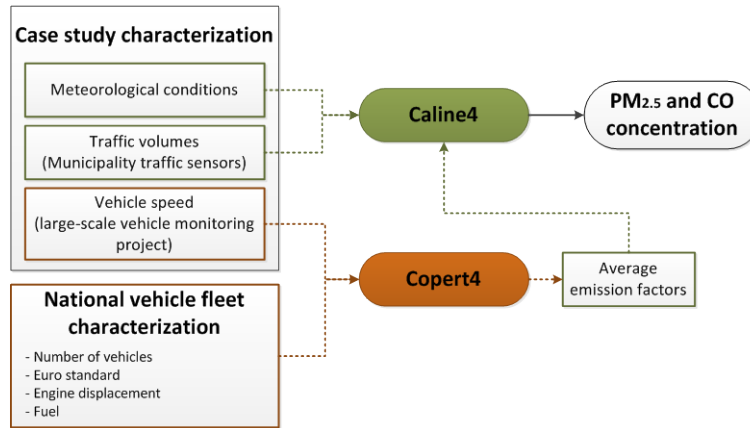


Figure 2: Overview of the applied methodology (adapted from Faria, Duarte [40])

The methodology was tested in four scenarios, for assessing the impacts of introducing a LEZ combined with the introduction of electric mobility. The detailed definition of the scenarios is presented in Table 3.

Table 3: 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)	Based on the current experiences of LEZ: - 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.
Scenario 2 (S2)	Based on the possibility to promote fleet renewal to electric vehicles: - Implementation of a LEZ. - Fleet renewal: All vehicles older than Euro 2 standard are replaced by electric vehicles.		Equal to BAU for Zone 2. Traffic reductions of 18.4% on Zone 1 due to the LEZ restrictions.
Scenario 3 (S3)	Based on the EU vision for the transportation sector in 2030 (stated on the White Paper for Transports [41]): - Implementation of a LEZ. - Fleet renewal: 50% of all passenger cars are replaced by electric vehicles. All light-duty vehicles are replaced by electric vehicles.		Traffic reductions due to the LEZ restrictions (Zone 1 – 14.2% and Zone 2 – 7.0%)

Going into more detail into the methodology, in order to estimate traffic-related $PM_{2.5}$ and CO concentration, an air quality dispersion model was used. The model chosen was CALINE4 [42], which is based on a Gaussian diffusion 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. 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: link coordinates, receptor coordinates, link height (set as zero), mixing zone width², aerodynamic roughness coefficient (400 cm, typical value for a Central Business District [42]) and ambient pollutant concentration (considered to be zero). Table 4 presents an overview of the type of information used, its description and data sources.

² Width of the roadway plus 3 meters on either side and was considered to be variable according to the number of lanes.

Table 4: 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 minute basis	7 years average (2008-2014)	University of Lisbon ³	Monthly averages
Traffic volumes	Traffic volume (in number of vehicles) in a 15 minute basis for 3 different hierarchical street levels	1 year (2014)	Municipality	Monthly averages for each hierarchical level
Typical vehicle speed	Average vehicle circulation speed in each street obtained from large-scale vehicle monitoring project for 3 different hierarchical street levels	June to October 2014	i2D project [43]	Monthly averages for each hierarchical level
Vehicle fleet characterization	Vehicle fleet characterization (number of vehicles, engine displacement, fuel, etc.) based on the average national fleet composition to obtain average fleet emission factors	2012	ACAP [44]	Copert4 (a European reference vehicle emission model)

Regarding vehicle emissions, Copert4 (a reference vehicle emission model developed for the European Environmental Agency) [45] was used to estimate the emission factors (in grams per kilometer) for the existing 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 [40] for the case study was considered.

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 six months with an on-board data logger connected to the vehicle OBD port, allowed to build an extensive database of 1 Hz geo-referenced driving data [43]. 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 described in a previous study [40].

The average emission factors, estimated with Copert4, for the fleet of light-duty vehicles, public buses and passenger cars are shown in Table 5. LEZ restrictions are not applicable to motorcycles and the circulation of heavy-duty vehicles is negligible when compared to passenger cars in the city center [46], therefore they were not considered in this analysis. Considering PM_{2.5}, in Scenario 1, the emission factors decreased by 16% and 14% for Zone 1 and Zone 2, respectively, when comparing to the baseline case (BAU). As for Scenario 2, the emission factors decreased 31% and 26% for Zone 1 and Zone 2, respectively. Under Scenario 3 a higher reduction of the emission factors was obtained (76% for both zones). Regarding CO emission factors, higher reductions were obtained for the considered scenarios. Reductions ranging from 74% to 92% in Zone 1 and from 65% to 92% in Zone 2 were obtained.

Table 5: Average emission factors (in g/km) for the baseline case and for the developed scenarios

Pollutant	Level	Scenario													
		BAU		S1 - Zone 1		S1 - Zone 2		S2 - Zone 1		S2 - Zone 2		S3 - Zone 1		S3 - Zone 2	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
PM _{2.5}	2	0.038	0.045	0.032	0.037	0.032	0.038	0.026	0.031	0.028	0.033	0.009	0.010	0.010	0.011
	3	0.040	0.049	0.034	0.041	0.034	0.042	0.027	0.033	0.029	0.036	0.009	0.010	0.010	0.011
	4	0.045	0.050	0.038	0.041	0.039	0.043	0.031	0.034	0.034	0.037	0.010	0.010	0.011	0.011
CO	2	0.754	1.146	0.247	0.288	0.309	0.399	0.187	0.222	0.245	0.319	0.077	0.083	0.113	0.139
	3	0.866	1.442	0.258	0.315	0.336	0.449	0.197	0.243	0.267	0.360	0.078	0.088	0.121	0.154
	4	1.183	1.545	0.292	0.322	0.406	0.463	0.225	0.250	0.325	0.371	0.084	0.089	0.141	0.158

This data sample applied in CALINE4 allowed building a baseline case for streets that are representative of the traffic circulation conditions in Lisbon. For the LEZ scenarios (S1 to S3), different average emission factors were computed due to vehicle fleet modifications. For that purpose it was considered that, in Scenario 1, a fleet renewal would occur so vehicles older than Euro 2 standard (before January 2000) [16] were replaced by newer vehicles (Euro 3, 4 and 5) maintaining the current fleet distribution. 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, vehicles older than Euro 2 standard were replaced by electric vehicles leading to different emission factors and to traffic reductions on Zone 1 (18.4%). In Scenario 3, 50% of older passenger cars and all light-duty vehicles were replaced by electric vehicles. As in

³ Meteorological data was provided by the investigation group MARETEC/LARSYS, Grupo de Previsão Numérica do Tempo, Instituto Superior Técnico, Universidade de Lisboa.

Scenario 2, this led to different emission factors and to traffic reductions on both zones. For Zone 1 a traffic reduction of 14.2% (50% of the vehicles registered before January 2000) was considered, while for Zone 2 traffic volume was assumed to decrease by 7.0% (corresponding to 50% of the vehicles registered before January 1996).

The model validation was performed by comparing the BAU results with the measured values (from a nearby air quality monitoring station). The validation results are presented in a previous study [40].

Other important assumptions for these scenarios were that EVs would be fully adopted, that a full compliance of the restrictions would happen and that the LEZ operates 24 hours per day. Even though the authors are aware of the fact that LEZ entry restrictions will lead to an increase on vehicles kilometers travelled outside the LEZ, the impacts in terms of pollutants concentrations were only analyzed within the LEZ where traffic reductions are expected to occur.

3 RESULTS AND DISCUSSION

In order to evaluate the impacts of different policies on traffic-related PM and CO concentrations, 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 Zone 1 and 2. In both Zones, the impacts of seasonal effects are observed, particularly on August 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 three scenarios (from 14 to 81% for both Zones).

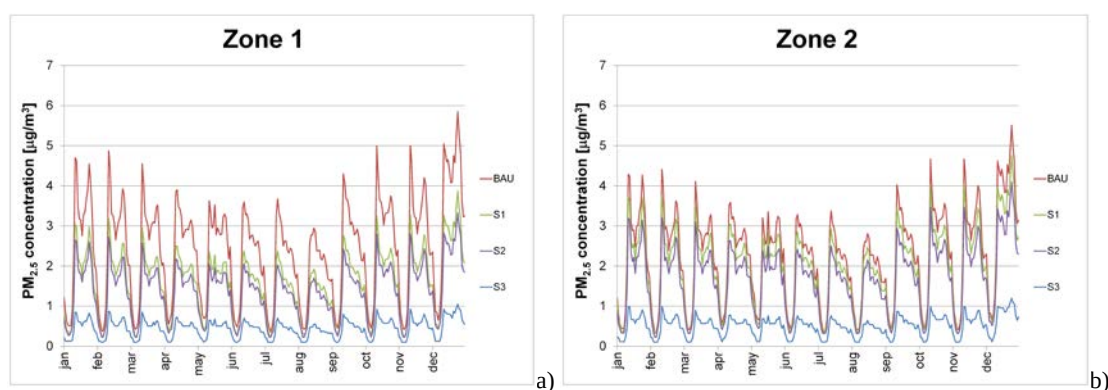


Figure 3. Estimated traffic-related PM_{2.5} concentrations for: a) Zone 1 and b) Zone 2

The same trend is observed for the average CO concentration (Figure 4), with reductions from 62 to 99% for both Zones.

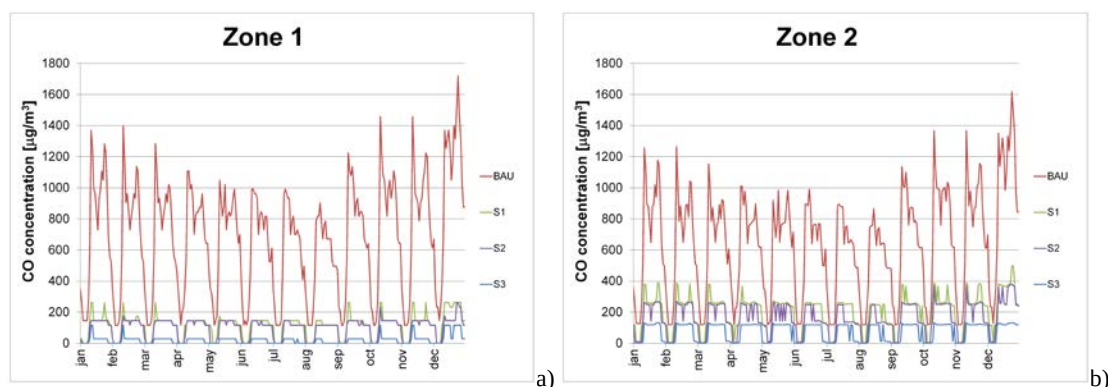


Figure 4. Estimated traffic-related CO concentrations for: a) Zone 1 and b) Zone 2

Due to the tighter restrictions imposed in Zone 1 (only vehicles complying with Euro 3 standard or higher can circulate within this area), the scenarios are most effective in this area, presenting an improvement of $34.9 \pm 0.2\%$, $43.5 \pm 0.2\%$ and $81.7 \pm 0.2\%$ in traffic-related PM concentration and of $83.1 \pm 0.7\%$, $85.5 \pm 0.7\%$ and $97.2 \pm 1.3\%$ in traffic-related CO concentration, respectively for S1, S2 and S3. In Zone 2 the reductions

presented by S1, S2 and S3 are $13.9 \pm 0.4\%$, $25.7 \pm 0.3\%$ and $77.9 \pm 0.2\%$ for PM concentration, and $68.5 \pm 0.8\%$, $75.0 \pm 1.0\%$ and $88.9 \pm 0.9\%$ for CO concentration, respectively.

Figure 5 and Figure 6 present the hourly average traffic-related PM_{2.5} and CO concentrations over an average annual day. It can be observed that for all tested scenarios, the morning peak starts at 7 h, the highest traffic-related concentrations occur at 8 h and reduces gradually until lunch hour (13 h). The afternoon peak starts at 17 h and finishes by 20 h. A high electric vehicle penetration scenario (S3) allows to significantly decreasing the pollutant concentrations and simultaneously smoothing the concentration peaks. As a result, future emission control strategies should include vehicle volume hourly shift and specific measures according to the time of the day.

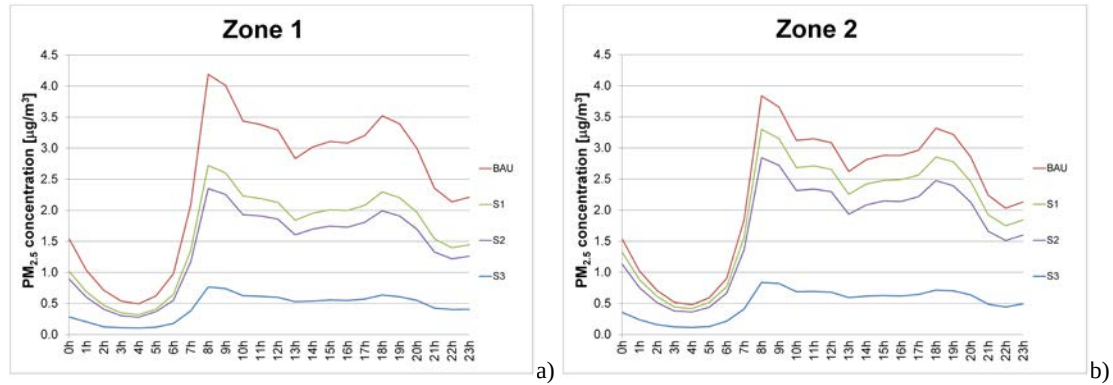


Figure 5. Average traffic-related PM_{2.5} concentration ($\mu\text{g}/\text{m}^3$) for the BAU and for the scenarios along the day for: a) Zone 1 and b) Zone 2

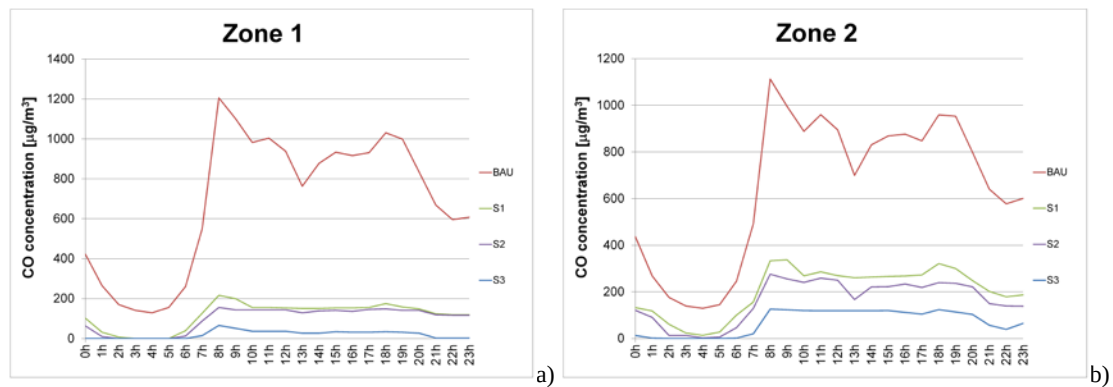


Figure 6. Average traffic-related CO concentration ($\mu\text{g}/\text{m}^3$) for the BAU and for the scenarios along the day for: a) Zone 1 and b) Zone 2

Table 6 presents the mass emission of traffic-related PM_{2.5} and CO for each of the scenarios considered, with different fleet emission factors and traffic volumes for Zone 1 and 2. It can be observed that the introduction of S1 present savings of 1.8 and 117.8 ton for Zone 1 and 23 and 3276.4 ton for Zone 2 for PM_{2.5} and CO, respectively. More extreme scenarios, considering the implementation of a LEZ and introduction of electric vehicles in the fleet lead, as expected, to higher reductions (44% and 86% for Zone 1 and 26% and 75% for Zone 2 for PM_{2.5} and CO, respectively in scenario 2 and 82% and 95% for Zone 1 and 78% and 90% for Zone 2 for PM_{2.5} and CO, respectively in scenario 3). Comparing the scenarios allow to conclude that the main impact on concentration contributions resulted from the replacement of 50% of the passenger cars and 100% of the light-duty vehicles by electric vehicles (S3). The replacement of only older vehicles (previous to Euro 1) by electric vehicles (S2) was of lesser importance.

Table 6. Total PM_{2.5} and CO emitted (in ton) for the BAU and for the scenarios

Pollutant	Zone	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
PM _{2.5}	Zone 1	BAU	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	5.0
		S1	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.4	3.2
		S2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	2.8
		S3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.9
	Zone 2	BAU	12.6	12.8	13.0	14.0	14.6	13.3	13.6	12.2	13.7	13.9	13.4	18.6	165.8
		S1	10.9	11.0	11.2	12.0	12.6	11.4	11.7	10.5	11.8	12.0	11.6	16.0	142.8
		S2	9.4	9.5	9.7	10.4	10.9	9.9	10.1	9.1	10.2	10.3	10.0	13.8	123.2
		S3	2.8	2.8	2.8	3.1	3.2	2.9	3.0	2.7	3.0	3.0	2.9	4.1	36.2
CO	Zone 1	BAU	11.1	11.3	11.4	12.0	12.5	11.5	11.7	10.3	11.6	11.8	11.5	15.7	142.4
		S1	1.9	1.9	2.0	2.1	2.2	2.0	2.0	1.8	2.0	2.0	2.0	2.7	24.6
		S2	1.6	1.6	1.6	1.7	1.8	1.6	1.7	1.5	1.6	1.7	1.6	2.2	20.2
		S3	0.6	0.6	0.6	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.9	7.7
	Zone 2	BAU	365.7	371.5	377.6	403.3	422.6	384.1	394.0	352.8	395.8	402.5	389.3	539.0	4,798.2
		S1	115.9	117.7	119.7	128.1	134.2	121.9	125.0	111.9	125.5	127.6	123.4	170.9	1,521.8
		S2	92.8	94.3	95.8	102.5	107.5	97.6	100.1	89.6	100.5	102.2	98.8	136.9	1,218.6
		S3	37.0	37.6	38.2	40.9	42.8	38.9	39.9	35.7	40.0	40.7	39.4	54.5	485.5

The obtained results indicate that a reduction of up to ~78% in the annual PM_{2.5} emissions and a decrease of 90% in the annual CO emissions can be achieved. These reductions confirm the high potential electric mobility has in reducing emissions in urban centers and, consequently, improving air quality, which required an integrated policy framework that fastens the adoption of this alternative vehicle technology.

4 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 towards the introduction of electric vehicles and of LEZ are effective in reducing traffic-related PM_{2.5} and CO concentrations and, consequently, have beneficial health effects. Overall, reductions on traffic-related PM_{2.5} concentrations from 14 to 81% may be obtained from the implementation of the tested scenarios. As for CO, reductions from 62 to 99% may be achieved. Furthermore, the results allow concluding that the most effective measure to implement is the scenario 3 (based on the White Paper targets [41]) since it is an ambitious scenario considering both the implementation of a LEZ and a replacement of 50% of the passenger cars and all the light-duty vehicles by electric vehicles (with no tailpipe emissions). 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.

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