Atmospheric Environment 127 (2016) 196–204

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Evaluating strategies to reduce urban air pollution

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HIGHLIGHTS

- We investigate measures to reduce PM and NO_2 ambient levels over Porto urban area.
- We use the TAPM numerical modelling tool.
- Measures for traffic sector, industry and residential combustion have been selected.
- To reduce PM10 measures should be focused on residential combustion and industry.
- For NO2 the strategy should be based on the traffic sector.
- Implementation of all scenarios allows a maximum reduction of 4.5% for both pollutants.

ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
14 December 2015
Accepted 16 December 2015
Available online 20 December 2015

Keywords:
PM10
NO_2
Urban air pollution
Air quality plan
Emission reduction scenarios
Numerical modelling

ABSTRACT

During the last years, specific air quality problems have been detected in the urban area of Porto (Portugal). Both PM10 and NO_2 limit values have been surpassed in several air quality monitoring stations and, following the European legislation requirements, Air Quality Plans were designed and implemented to reduce those levels. In this sense, measures to decrease PM10 and NO_2 emissions have been selected, these mainly related to the traffic sector, but also regarding the industrial and residential combustion sectors. The main objective of this study is to investigate the efficiency of these reduction measures with regard to the improvement of PM10 and NO_2 concentration levels over the Porto urban region using a numerical modelling tool – The Air Pollution Model (TAPM). TAPM was applied over the study region, for a simulation domain of 80×80 km^2 with a spatial resolution of 1×1 km^2. The entire year of 2012 was simulated and set as the base year for the analysis of the impacts of the selected measures. Taking into account the main activity sectors, four main scenarios have been defined and simulated, with focus on: (1) hybrid cars; (2) a Low Emission Zone (LEZ); (3) fireplaces and (4) industry. The modelling results indicate that measures to reduce PM10 should be focused on residential combustion (fireplaces) and industrial activity and for NO_2 the strategy should be based on the traffic sector. The implementation of all the defined scenarios will allow a total maximum reduction of 4.5% on the levels of both pollutants.

1. Introduction

Air quality is one of the environmental areas in which the European Union (EU) has been most active, in particular designing and implementing legislation on air quality and on the restriction of pollutant emissions to the atmosphere. The Directive on Ambient Air Quality and Cleaner Air for Europe (Directive 2008/50/EC), published in May 2008, highlights modelling as a fundamental tool to improve air quality assessments and management. The Directive also reinforces the obligation of EU member states to elaborate and implement Air Quality Plans (AQP) to improve air quality when standards are not fulfilled. The implementation of AQP, when pollutant concentrations exceed the air quality standards in zones or agglomerations, should be based on the development of measures that reduce the pollutant atmospheric concentrations and meet the legal requirements (Miranda et al., 2014, 2015).

Exceedances of the thresholds of particulate matter (PM10) and nitrogen dioxide (NO_2) have been reported in the urban agglomeration of Porto Litoral, where human exposure is also high

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http://dx.doi.org/10.1016/j.atmosenv.2015.12.043

(Borrego et al., 2009; Miranda et al., 2014). Air Quality Plans were developed for both pollutants: during the period 2005–2008 for PM10 (Borrego et al., 2010) and in 2010 for NO_2 (Borrego et al., 2012a). Despite improvements in air quality, verified after the 2008–2010 period, there is still a requirement for the reduction of the concentrations of these pollutants, because some of the legislated limits continue to be exceeded every year in particular monitoring sites.

Due to their ability in assessing the efficiency of different emission reduction measures, air quality numerical models are useful tools for air quality management. They estimate pollutant concentrations in areas that are not covered by air quality monitoring stations and quantify the impact of projected emission scenarios on air quality. Air quality models have been used by several Member States in the scope of designing AQP for European zones/agglomerations (Nagl et al., 2007). Eulerian Chemical Transport Models (CTM) are the most frequently used (APPRAISAL, 2013), requiring the emissions estimated for several activity sectors, meteorological variables and initial and boundary conditions as input data. The Air Pollution Model (TAPM) (Hurley et al., 2005) is particularly suited to evaluate the impact of emission reduction strategies due to its flexibility, user friendly environment and short time demands in terms of computational efforts for long term simulations (1 year) compared to other CTM models. TAPM has been previously applied and validated over several Portuguese areas (Borrego et al., 2012b).

The main objective of this study is to investigate the most efficient measures to reduce PM10 and NO_2 concentration levels, quantifying this reduction and supporting future additional AQP and policy makers for the air quality management over urban areas, such as the Porto Litoral agglomeration. The present work is organized as follows: Section 2 presents the PM10 and NO_2 concentrations registered over the last decade, followed by description of the air quality modelling system and its setup/application over the Porto urban region in Section 3. The measures (emission reduction scenarios) to reduce PM10 and NO_2 concentrations are proposed in Section 4, their efficiency/impact analysed and discussed in Section 5. Finally, the summary and conclusions are drawn in Section 6.

2. PM10 and NO_2 measured in the porto urban region

Fig. 1 presents the evolution of the annual mean concentrations of PM10 and NO_2, together with the number of days in exceedance regarding the daily legal limits, registered between 2004 and 2013 in the monitoring sites located in the Porto metropolitan area.

Regarding PM10, the exceedances to the annual and daily limit values (Fig. 1a,b) decreased significantly after the implementation of the 2008 AQP for PM10. For NO_2, the air quality improvement after this AQP is less notorious (Fig. 1c, d). Besides the AQP strategy, the financial crisis also contributed to the reduction of pollutant emissions and consequently to the air quality improvement (Ribeiro et al., 2014).

The average daily profiles of PM10 and NO_2, displayed in Fig. 2, enable the understanding and characterization of the major causes of measured levels at the different monitoring sites.

The PM10 daily profiles, grouped by season, show that the highest concentrations are observed at night, reaching maximum values during the winter period which can be related to residential combustion activities. Regarding NO_2, the daily profiles (similar behaviour between the seasons) follow the traffic diurnal cycle, with peaks in the morning and late afternoon. This characterization supported the establishment of more appropriate emission reduction scenarios to mitigate concentrations of these pollutants.

In order to evaluate the impact of the proposed measures on the improvement of atmospheric PM10 and NO_2 levels, the air quality modelling system TAPM (Section 3) was applied to the current situation (base scenario) and to several emission reduction scenarios (Section 4).

3. Air quality modelling system

The model selected to perform the air quality simulation over the study region was “The Air Pollution Model” (TAPM) (Hurley et al., 2005), developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). This model is a 3-D Eulerian model, made of two modules which calculate meteorological conditions and air pollution concentrations based on fundamental fluid dynamics and scalar transport equations. Technical details of the model equations, physical and chemical parameterisations, as well as its numerical methods, are described by Hurley et al. (2005).

In the TAPM meteorological module, global databases of terrain and land use from the Earth Resources Observation Systems (EROS), surface temperature from the US National Centre for Atmospheric Research (NCAR), and synoptic conditions from the Limited Area Prediction System (LAPS) and Global Analysis and Prediction (GASP) models from the Bureau of Meteorology (BOM) were used. This module solves the momentum equations for horizontal wind components, the incompressible continuity equation for the vertical velocity in a terrain-following coordinate system, and scalar equations for potential virtual temperature, specific humidity of water vapour, cloud water and rain water. This first module provides the meteorological forcing necessary for the air quality simulation.

The air pollution module of TAPM consists of an Eulerian grid-based set of prognostic equations for pollutant concentration, with optional pollutant cross-correlation equations to represent counter-gradient fluxes, and an optional Lagrangian particle mode for near-source concentrations. The Eulerian grid module was applied and consists of nested grid-based solutions of the Eulerian mean concentration and optional variance equations representing advection, diffusion, chemical reactions and emissions. Dry and wet deposition processes are also included. Besides the meteorological outputs, the air pollution module considers the air pollutant emissions from several sources, such as: point sources, line sources, gridded surface emissions, biogenic surface emissions, among others. Regarding the simulation of the point sources, plume buoyancy, momentum and building wake effects are considered. The model was run in chemistry mode, with gas-phase based on a semi-empirical mechanism entitled the Generic Reaction Set (GRS), including 10 reactions for 13 species (Hurley et al., 2005).

TAPM was applied over the study region using synoptic data provided by CSIRO. The application considered three domains using a nesting approach: the outer domain includes part of the Iberian Peninsula (D1), D2 covers Northern and Central Regions of Portugal, and the inner domain contains the Porto urban area (D3), with a resolution of 10, 3 and 1 km^2, respectively. The air pollution module, using chemistry mode, was applied for the inner domain (D3) with an area of 80 × 80 km^2 (see Fig. S1-Supplementary material).

TAPM was applied for the year 2012, corresponding to the most updated national emission inventory report (APA, 2014). The annual emissions information is disaggregated by municipality and divided by SNAP categories: commercial and residential combustion (SNAP2); industrial combustion (SNAP3); production processes (SNAP4); extraction and distribution of fossil fuels and geothermal energy (SNAP5); solvent and other product use (SNAP6); road transport (SNAP7); other mobile sources and machinery (SNAP8); waste treatment and disposal (SNAP9). The

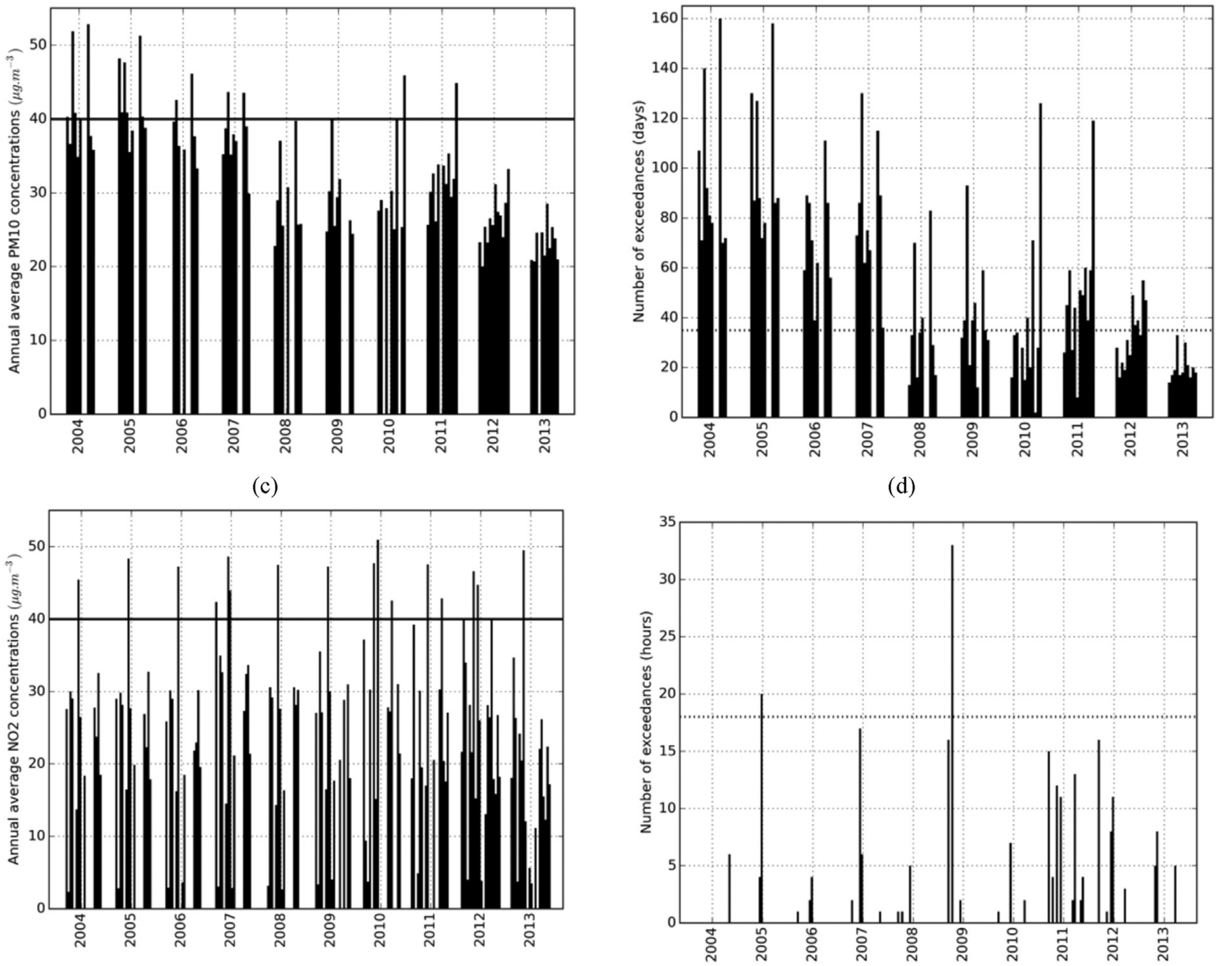


Fig. 1. (a) PM10 annual average concentrations and the respective limit value (black line; 40 μg m^{-3}); (b) number of exceedances of the daily limit value of PM10 (50 μg m^{-3}) (dotted line: number of allowed exceedances – 35); (c) NO_2 annual average concentrations and the respective limit value (black line; 40 μg m^{-3}); (d) number of exceedances of the hourly limit value of NO_2 (200 μg m^{-3}) (dotted line: number of allowed exceedances – 18), registered at the air quality stations of the Porto metropolitan area during 2004–2013.

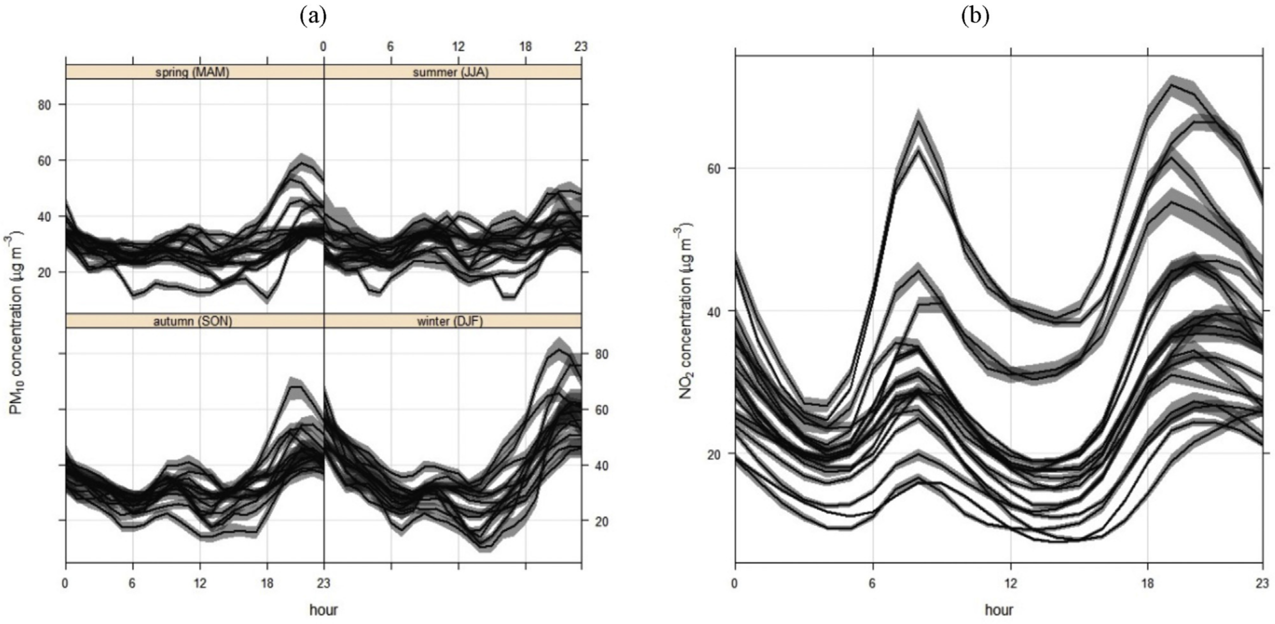


Fig. 2. Averaged daily profiles of (a) PM10 (grouped by season) and (b) NO_2 concentrations, measured in Porto metropolitan area during the 2004–2013 period.

annual emission data for each pollutant and activity sector was spatially and temporally disaggregated using a top-down approach in order to obtain the required resolution for the selected simulation domain (Monteiro et al., 2007). SNAP 1 (energy production) emission sources and the larger sources of SNAP 3 and 4 were considered as point sources, summing a total of 8 within the modelling domain. As for transport emissions (SNAP 7), a fraction of the emissions were considered as line sources, for the urban area of Porto and for the motorways in the domain. Line source emissions were estimated using the TREM model (Transport Emission Model for Line Sources) (Borrego et al., 2004) based on available traffic counts and on statistical data of the fleet composition. The background concentrations, required by the model, were obtained through estimates of the average values of the background air quality stations of the study area for 2012.

This modelling system has already been extensively applied over Portugal and the Porto region, exhibiting good agreement when compared/validated against observational data (Borrego et al., 2012a; Miranda et al., 2014).

4. Emission reduction scenarios

Additional measures, required to reduce the PM10 and NO_2 concentrations and decrease the exceedances to the legislated limits, were investigated and selected for further assessment.

The criteria used for the selection included: (i) relative contributions of each activity sector to the total pollutant emissions; (ii) types of exceedances (annual/daily) and the monitoring sites where they were registered; (iii) actions already included in the defined and implemented AQP.

Following these criteria, and with the prior knowledge that the main contributing sectors are residential combustion, industry and traffic, and that the monitoring sites with higher concentrations are located in urban and traffic sites, a group of 4 main scenarios were defined:

- Scenario 1: Replacement of 10% of vehicles below the EURO3 class (diesel and gasoline) by hybrid model vehicles;
- Scenario 2: Introduction of a Low Emission Zone (LEZ) on a specific polluted area of Porto city, with the restriction for vehicles below EURO3;
- Scenario 3: Replacement/reconversion of 50% of the conventional fireplaces by more efficient equipment (residential combustion);
- Scenario 4: Application of clean technologies that allow a reduction of 10% in PM10 emissions from production processes and industrial combustion.

4.1. *Scenario 1: replacing vehicles below EURO3 by hybrid cars*

The European emission standards (EURO) define, since 1992 (with EURO1) the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards are defined in a series of EU directives staging the progressive introduction of increasingly stringent standards. At the moment, EURO5 and EURO6 already entered into force (September 2009 and January 2014, respectively) aiming to reduce the emissions of PM (EURO5) and NOx (EURO6) from diesel cars (Lopes et al., 2014). In this context, this scenario considers the replacement of 10% of the oldest vehicles (previous to EURO standards, EURO1 and EURO2) by more environmental friendly models, namely hybrid cars, which are powered by both an internal combustion engine and an electric motor, and emit, on average, less pollutants quantities than the conventional diesel/petrol cars (Soret et al., 2014). For the study region, this replacement corresponds to a total of 30,800 vehicles.

Traffic emissions were estimated using the TREM (Transport Emission Model for Line Sources) model (Borrego et al., 2004). This emissions model was already comprehensively applied and tested for urban areas of Portugal (Borrego et al., 2006).

4.2. *Scenario 2: Low Emission Zone (LEZ)*

A Low-Emission Zone (LEZ) is a confined area where access by certain vehicles is restricted or prohibited with the aim of improving the air quality. The LEZ defined in this study includes an area with high traffic density, where one of the air quality monitoring sites with NO_2 and PM10 exceedances is located. Fig. 3 presents the extension of the area (approximately 1.5 km^2), the main streets and avenue together with the location of the monitoring station (Antas). It was assumed that vehicles above and including EURO3 were allowed to pass through this restricted area.

4.3. *Scenario 3: fireplace reconversion*

Residential combustion is a major contributor to the total PM10 emissions, as reported by the Portuguese emission inventory (APA, 2014; Borrego et al., 2010) and also worldwide (Johansson et al., 2004; Jordan and Seen, 2005; Hedberg et al., 2002; McDonald et al., 2000). Johansson et al. (2004) showed that PM emissions are significantly higher from a wood stove or a fireplace, i.e., from uncontrolled combustion devices, than from controlled devices. One of the most important variables, that influences wood combustion emissions, is the air flow supply (Jordan and Seen, 2005). According to studies conducted by the United States Environmental Protection Agency (USEPA, 2009), replacing traditional fireplaces with certified wood burning appliances can result in a reduction of over 80% in PM emissions. In this context, this scenario considers the replacement of 50% of the traditional fireplaces by more efficient equipment (such as heat recovery systems).

The emission reduction associated to this measure was calculated on the basis of: fuel (wood) consumption per district (Gonçalves et al., 2012), type of residential combustion equipment per sub-municipality (CENSUS, 2011) and emission factors used by APA (2014). Considering that the reconversion/replacement of the conventional fireplaces allows a reduction of 70% (GAINS database: http://gains.iiasa.ac.at/models) of PM10 emissions, a maximum reduction (per grid cell of the simulation domain) of 35% of the total emissions from residential combustion was estimated. Fig. S2 (supplementary material) displays this reduction percentage obtained for the study domain.

4.4. *Scenario 4: industrial clean technologies*

Industrial combustion (SNAP3) and production processes (SNAP4) are also important sources of total PM10 emissions, as reported by the Portuguese emission inventory (APA, 2014). The emission reduction associated to this measure was calculated under the assumption that it is possible to reduce 10% of PM10 emissions using new clean technologies on both macro-sectors. These clean technologies include high efficiency de-dusters (cyclones, electrostatic precipitators and good practice in industrial processes-storage and handling, leak detection and repair program). The removal efficiencies associated to these technologies can be found in the GAINS database (technology database), which contains a large dataset collected for Portugal by IIASA (http://www.iiasa.ac.at).

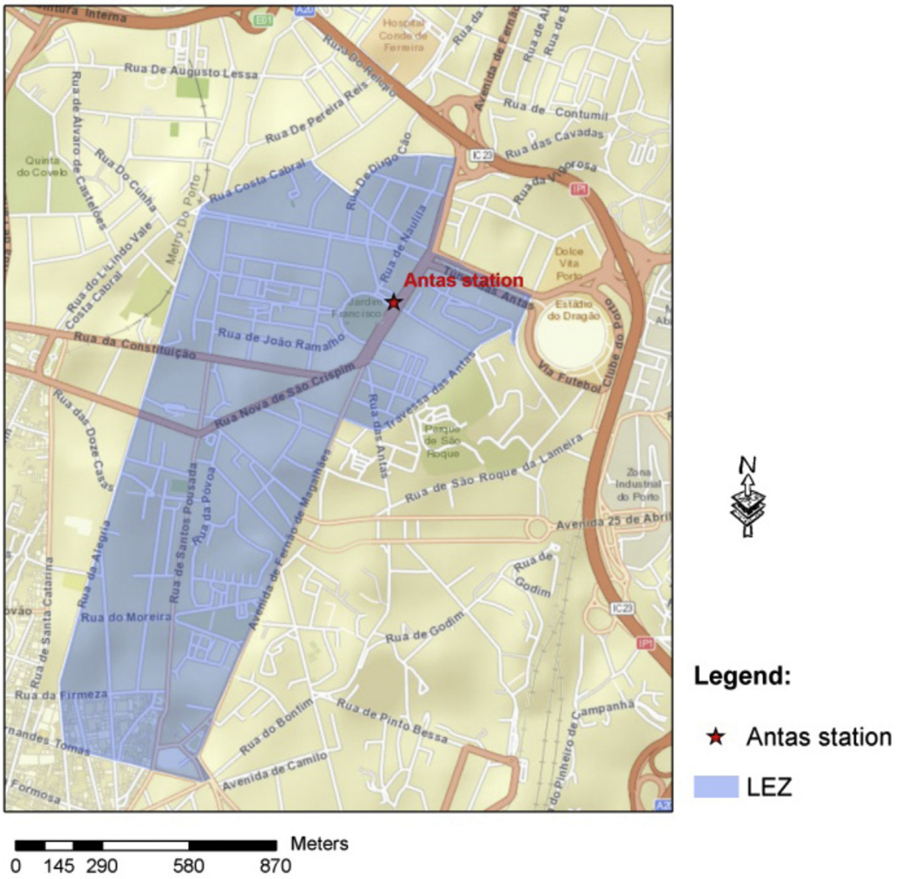


Fig. 3. The selected Low Emission Zone (LEZ).

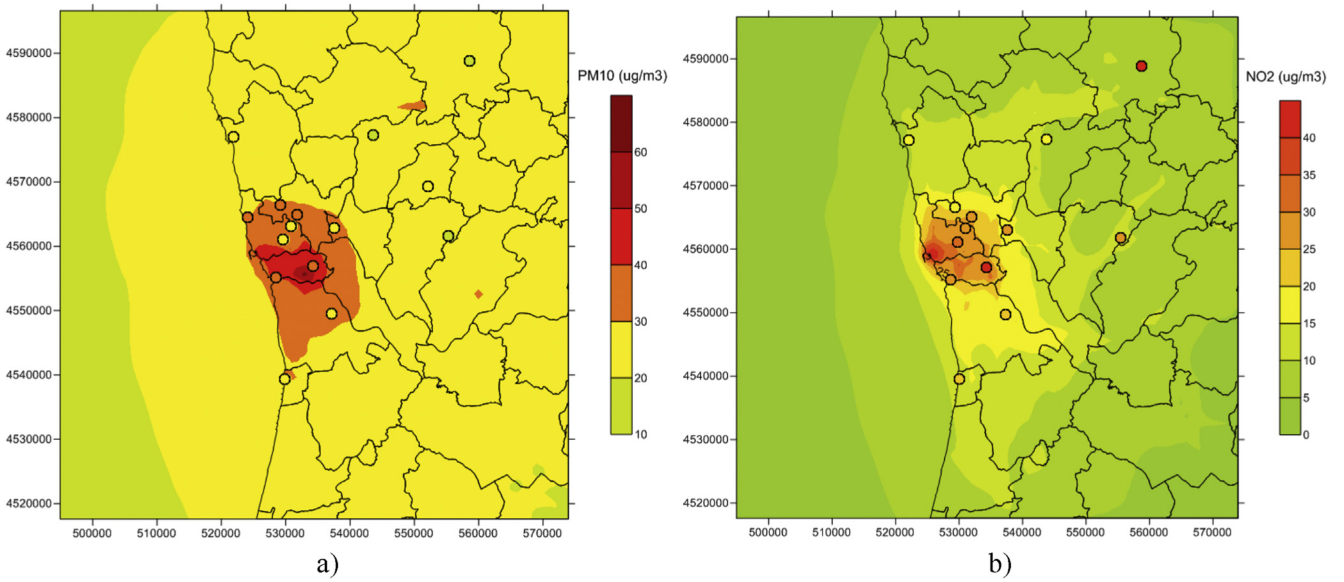


Fig. 4. Annual average concentrations of PM10 (a) and NO_2 (b) simulated with TAPM for the base scenario (year 2012). The small circles indicate the annual average values measured at the monitoring sites. The coordinates (scale) are UTM (meters).

5. Analysis of results

The TAPM model was applied for the base scenario and for each reduction scenario. Fig. 4 displays the results obtained with the TAPM application for the base scenario (year 2012) regarding the annual average of PM10 and NO_2. The measured annual averages (http://qualar.apambiente.pt/) are also represented (by small circles) using the same colour scale.

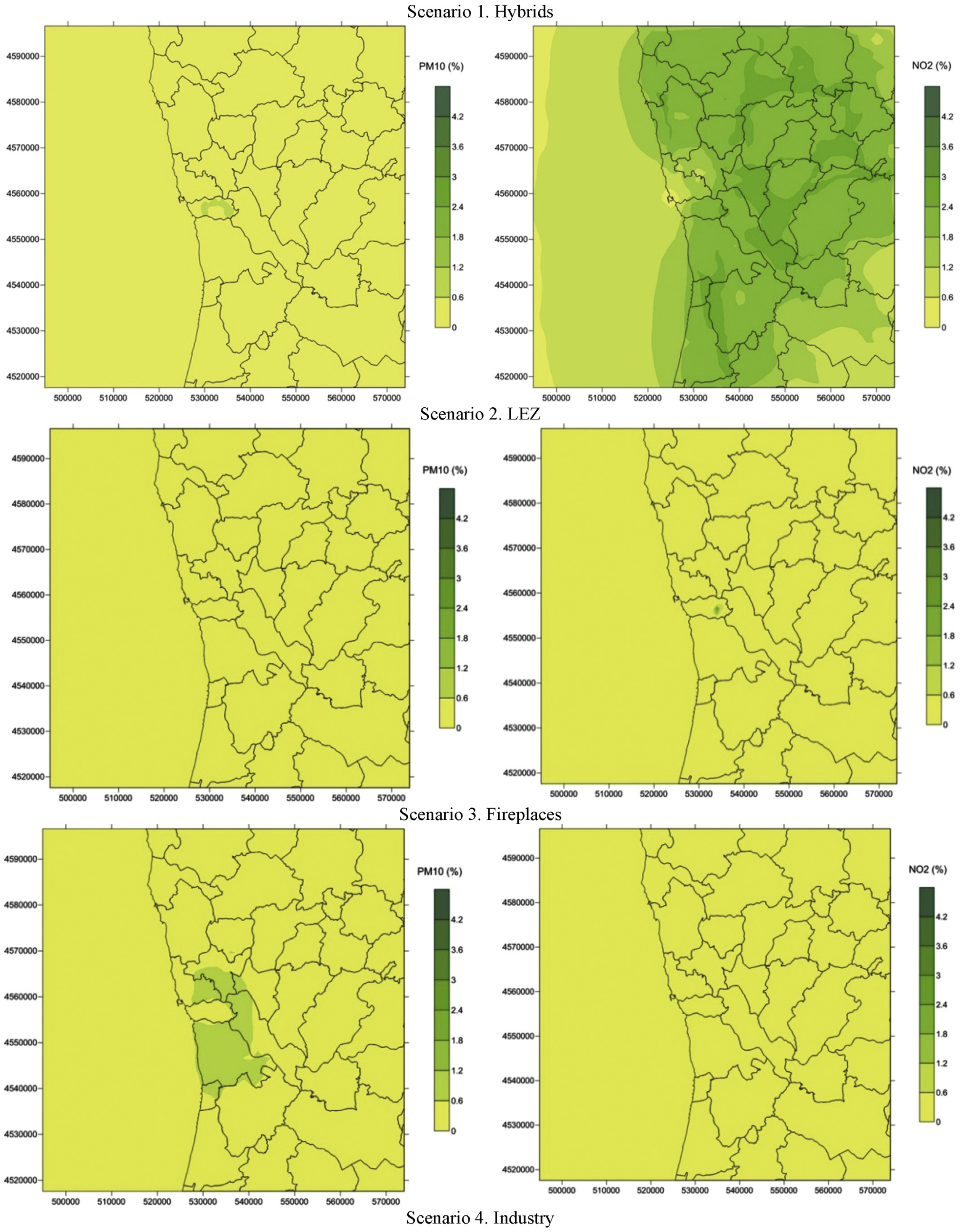


Fig. 5. Modelling results: percentage reduction of PM10 (a) and NO_2 (b) concentrations, comparing each scenario to the base case. The coordinates (scale) are UTM (meters).

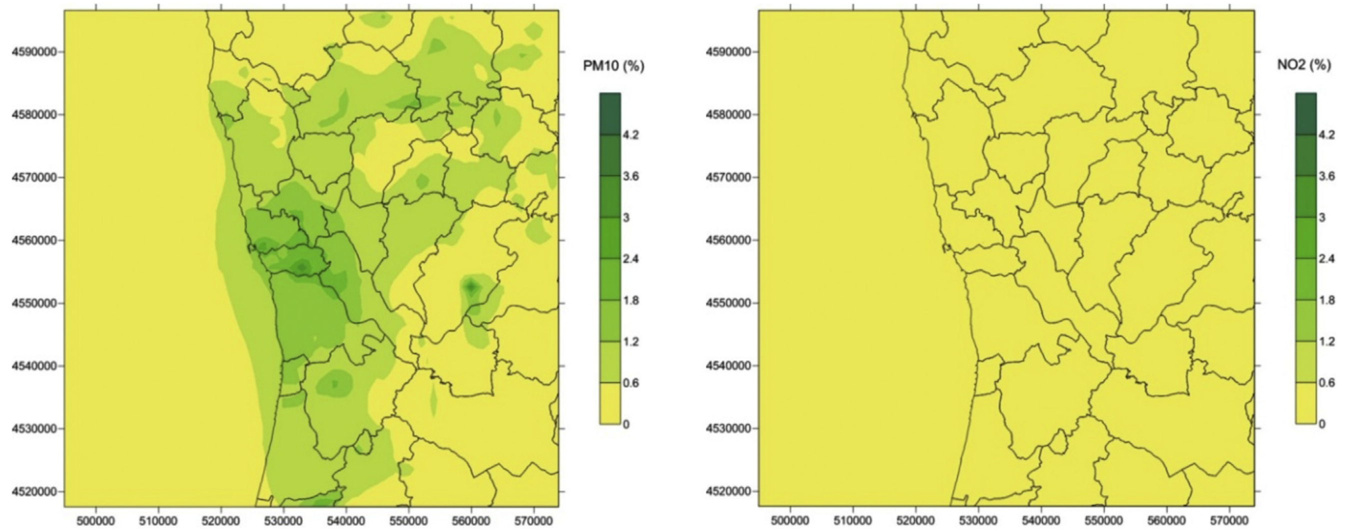


Fig. 5. (*continued*).

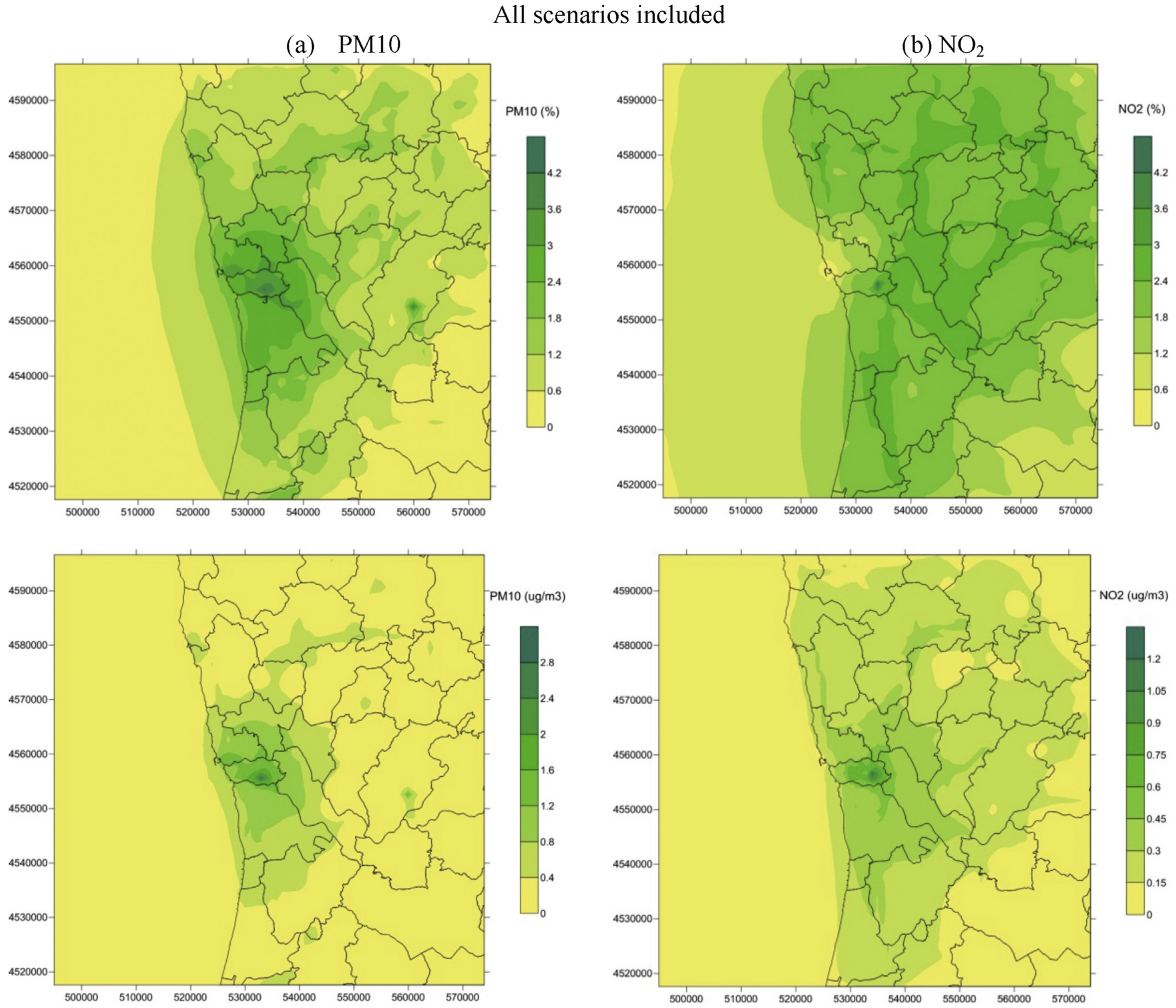


Fig. 6. Reduction (in percentage and absolute concentration) in annual concentrations considering all mitigation measures combined for PM10 (a) and NO_2 (b) (when compared to the base case). The coordinates (scale) are UTM (meters).

The modelling results show higher annual averages of both pollutants ([PM10]>30 μg m^{-3} and [NO_2]>25 μg m^{-3}) mainly over the Porto municipality and the surrounding area, where concentrations higher than the legislated limit values are expected. The rest of the domain is characterized by low annual concentrations ([PM10]≅15–20 μg m^{-3} and [NO_2]≤10 μg m^{-3}). The comparison with observed values indicates that TAPM over-predicts PM10 concentrations in the urban area and under-predicts NO_2. Fig. 5 presents the expected reductions (in terms of percentage) obtained with each scenario for both pollutants (PM10 and NO_2).

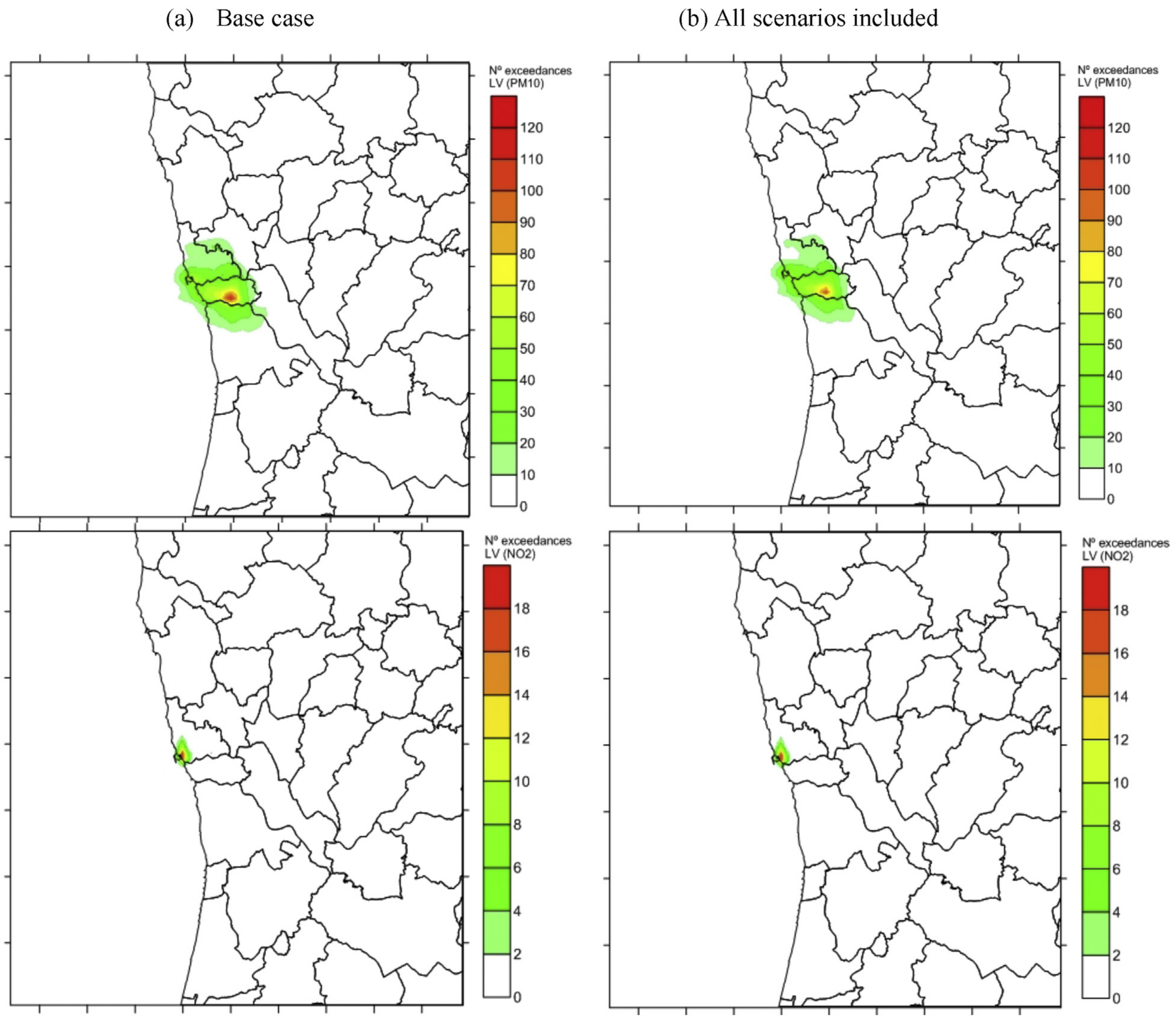
The modelling results show that the traffic measures (Scenarios 1 and 2) are the only ones that have impact on NO_2. Scenario 1 (hybrid cars) results in a reduction of NO_2 levels of up to 4.5% over all the domain, while the LEZ implementation (Scenario 2) only has a local benefit with a local reduction of the annual concentration of NO_2 reaching 3%. The other two scenarios (3 and 4) only result in reductions of PM10 concentrations. The reconversion of fireplaces (Scenario 3) allows reductions of up to 1.5% on the annual average of PM10 in a zone around the municipality of Porto (where a higher density of equipment is located – see Fig. S2, Supplementary Material). Higher reductions are expected with the application of measures to the industrial sector (Scenario 4), in terms of magnitude (up to 3.5%) and spatial coverage.

Fig. 6 displays the simulated reduction when applying all the selected measures simultaneously (all scenarios included) in order to assess the maximum mitigation achieved with the identified measures.

The combination of all the referred measures allows a total reduction of 4.5% for both pollutants, mainly over the area of Porto for PM10 and extended across the overall domain regarding NO_2. This corresponds to reductions of up to 2.8 μg m^{-3} for PM10 and up to 1.2 μg m^{-3} for NO_2.

In order to check the success of these mitigation measures, the fulfilment of the legislated limit values was analysed for both pollutants, regarding the daily and hourly limit values (LV) for human health protection for PM10 and NO_2, respectively. Fig. 7 presents the results expected in terms of exceedances to the LVs comparing both cases (base case and considering all mitigation measures).

In the case of PM10, besides the prevalence of the non-fulfilment condition in both cases, there is a substantial reduction on the number of exceedances to the daily LV foreseen with the mitigation measures scenario (around 30% of reduction). Regarding NO_2, the fulfilment of the legislation already exist in the base case (a maximum of 35 h with exceedances are allowed) and continues in


(a) Base case

(b) All scenarios included

Fig. 7. Number of exceedances to the daily limit value of PM10 and to the hourly limit value of NO_2 expected for base case (a) and all scenarios included (b).

the scenario case (with a reduction of 10% of the maximum values).

These modelling results, together with the corresponding methodology, will be particular important to policy makers in taking future decisions and to define strategy for near future in order to improve and solve current situations of non-compliance of air quality legislation.

6. Summary and conclusions

This study aims to investigate additional mitigation measures to be applied in order to solve the exceedances in concentrations of PM10 and NO_2 registered over the metropolitan area of Porto, verified after the development and implementation of Air Quality Plans. Considering the main contributing emission sectors for these pollutants, four main scenarios were defined: (1) replacement of 10% of vehicles below EURO3 by hybrid models; (2) introduction of a Low Emission Zone (LEZ); (3) reconversion of 50% of the fireplaces; and (4) application of clean technologies to industry. These emission scenarios, together with the base scenario (year 2012), were simulated with the TAPM modelling system (already validated for the Porto region in previous studies) in order to assess their impacts on air quality. The results indicate that none of the identified measures produces significant reductions for both pollutants simultaneously. In the case of PM10, the strategy should focus on industrial activity and residential combustion. Regarding NO_2, measures should be related to the traffic sector. A LEZ is suggested only for specific local pollution problems, always depending on the municipalities' authorization and strategy.

Acknowledgements

The authors wish to thank the North Regional Coordination and Development Commission (CCDR-N) for their support. Also, the authors would like to acknowledge the financial support of FEDER through the COMPETE Programme and the national funds from FCT – Science and Technology Portuguese Foundation for the PhD grant of C. Gama (SFRH/BD/87468/2012), H. Relvas (SFRH/BD/101660/2014), C. Silveira (SFRH/BD/112343/2015) and the post doc grant of J. Ferreira (SFRH/BPD/40620/2007). The funding of the research project MAPLIA (PTDC/AAG-MAA/4077/2012), supported in the scope of the Competitiveness Factors Thematic Operational Programme (COMPETE) of the Community Support Framework III and by the European Community Fund FEDER, is also acknowledged.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.12.043.

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