IMPACT OF ROAD TRANSPORT ON URBAN AIR QUALITY: GIS AND GPS AS A SUPPORT FOR A MODELLING FRAMEWORK

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Abstract

Urban areas face today the challenge of making transport sustainable. However, road traffic is still one of the main sources of deterioration of the air quality in urban areas. The principal purpose of this work is the application of an integrated approach for quantifying emissions from road transport in urban areas and its impact on air quality using Geographic Information System (GIS) and Global Positioning System (GPS) as supplementary information tools. For this purpose, three numerical tools: (i) the microsimulation traffic model (VISSIM); (ii) the Transport Emission Model for Line Sources (TREM) and (iii) the air quality model (URBAIR) were linked and applied to characterize traffic flows, to quantify emissions, and finally to evaluate the air quality in a European medium sized city (Aveiro, Portugal).

Data related with road configuration and vehicle dynamics collected using GPS data-logger equipped vehicles were used to validate traffic volumes estimated by VISSIM, and then the outputs of this model were used by TREM to quantify traffic emissions with high temporal and spatial resolution. In order to facilitate the spatial processing of data, TREM was directly linked to GIS. Main roads were processed as line sources and on-road hot emissions were calculated by the TREM model based on daily mean traffic and emission factors distinguished for several road classes, different technologies (engine type, model year) and engine capacities.

The good performance of the integrated modelling approach evidences the benefit of integrated use of the modelling tools and GPS and GIS to estimate the impact of atmospheric emissions induced by traffic. Also, the amount of air pollutants emitted and their spatial distribution provides important information to be used by decision-makers for air quality assessment.

Keywords: transport modelling, emissions modelling, urban air quality, numerical modelling, GIS, GPS.

INTRODUCTION

Nowadays, the whole world largely depends on individual mobility, which has contributed to a general increase in comfort standards. However, atmospheric emissions induced by vehicles have become a considerable problem to a sustainable city development. The rapid demographic growth of the last decades has increased the concentration of human population in cities. Consequently, total emissions from road traffic have risen significantly, assuming the main responsibility for the disregard of air quality standards (EEA, 2012).

During the last years, a large set of air quality legislation was adopted in Europe and plans had to be established with the aim of controlling air quality. Also, there has been an improvement on fuel quality and treatment technologies, which contributed to a reduction of the air pollution loads. However, urban areas continue to congregate problems inherent to large population clusters, like inappropriate urban planning and growing of private transportation, with significant consequences on air quality and human health.

To reduce this environmental pressure, the application of an integrated approach that combines different modelling tools can have an important role in the development of an urban air quality management system. In this context, numerical modelling is an important methodology to supply the decision makers with information about source-receptor relation (Borrego et al., 2006). Based on modelling predictions, several scenarios for transportation planning can be analysed and a better development scenario can be chosen taking into account the air pollution problems associated with traffic. The estimation of atmospheric emissions induced by traffic and the evaluation of air pollutants concentration is required for this type of application. The quality of the emission data can significantly contribute to the total uncertainties of air pollution model prediction and, in this concern, improvement of the emission estimation is of great importance (Coelho et al., 2014).

Currently, several methodologies to quantify the pollutant amount emitted by the vehicles to the atmosphere are available. They range from calculations at microscopic scale (i.e. for a single vehicle, or for a street) to macroscopic calculation (i.e. regional, national and global levels) (Agostini et al., 2005; Gkatzoflias et al., 2007). However, the modelling tools usually provide emissions with low temporal and spatial resolution that is not sufficient for urban scale studies. To be applicable at this scale, the currently existing methodologies for the emission quantification have to be adapted taking into account the availability of the input data and the final use of the estimated emission results.

Urban emission inventories with higher temporal and spatial resolution are needed for a number of applications, such as urban air pollution modelling, population exposure modelling, definition of sustainable urban development policy, etc.. The most commonly used technique to quantify the emissions is based upon the principle that the average emission factor for a certain pollutant and a given type of vehicles vary according to the average speed during a trip (Boulter et al., 2007). For urban applications, hourly emissions for each road link are usually required. For this purpose, hourly traffic flows attributed to detailed road network should be specified.

In this concern, to analyse the high spatial and temporal variability of road transport-related air pollution within the urban environment, it is required to characterize the transport activity in order to quantify the corresponding emissions and air pollutants levels. For this purpose, a system based on the transportation modelling linked with the emissions and dispersion modelling is considered as one of the most suitable approaches to provide detailed information concerning traffic flow for each road segment and related pollution (Borrego et al., 2006). In this context, enhanced resources such as Geographic Information System (GIS) and Global Positioning System (GPS) could be used to better understanding of the contribution of emissions from road transport in urban areas. GIS technology is a useful tool to explore spatial information. GIS allows environmental data to be stored, analysed, and displayed spatially, improving data integration and consistency by providing means of capturing and linking spatial data within a single geographical structure. On other hand, GPS technology could be used to increase the resolution of transport activity data and consequently to improve the precision of emission estimations.

The present paper reports the application of an integrated modelling approach to assess the road transport emissions impact on the urban air quality with high spatial and temporal resolution, based on emerging tools as GIS and GPS. To achieve this objective, a numerical system based in three modelling tools: (i) microsimulation traffic model (VISSIM); (ii) the Transport Emission Model for Line Sources (TREM) and (iii) the air quality model (URBAIR) were linked and adapted in order to estimate the atmospheric pollution induced by road traffic in urban areas. An example of application this integrated methodology to the Aveiro urban area (in Portugal) for a typical working day of May 2011 is presented.

METHODOLOGY

The main steps of the integrated methodology used to assess the impact of road traffic on air quality and applied to the Aveiro urban area are schematically shown in Figure 1. The city of Aveiro, a coastal urban area, acts as important Iberian terminal, where essential roads that cross all the country and that are connected to influential European highways converge. Figure 2 presents the simulation study domain, which covers an area of 3.9 x 4.5 km^2, and the main roads that were considered.

Firstly, data related with road configuration, vehicle dynamics collected using GPS data-logger equipped vehicles were used to validate traffic volumes estimated by VISSIM. The outputs of this model were used as inputs in the TREM model to quantify the emission amounts with high temporal and spatial resolution, and finally the URBAIR model was applied to evaluate the urban air quality (Figure 1). Next sections present the main details of each of these steps.

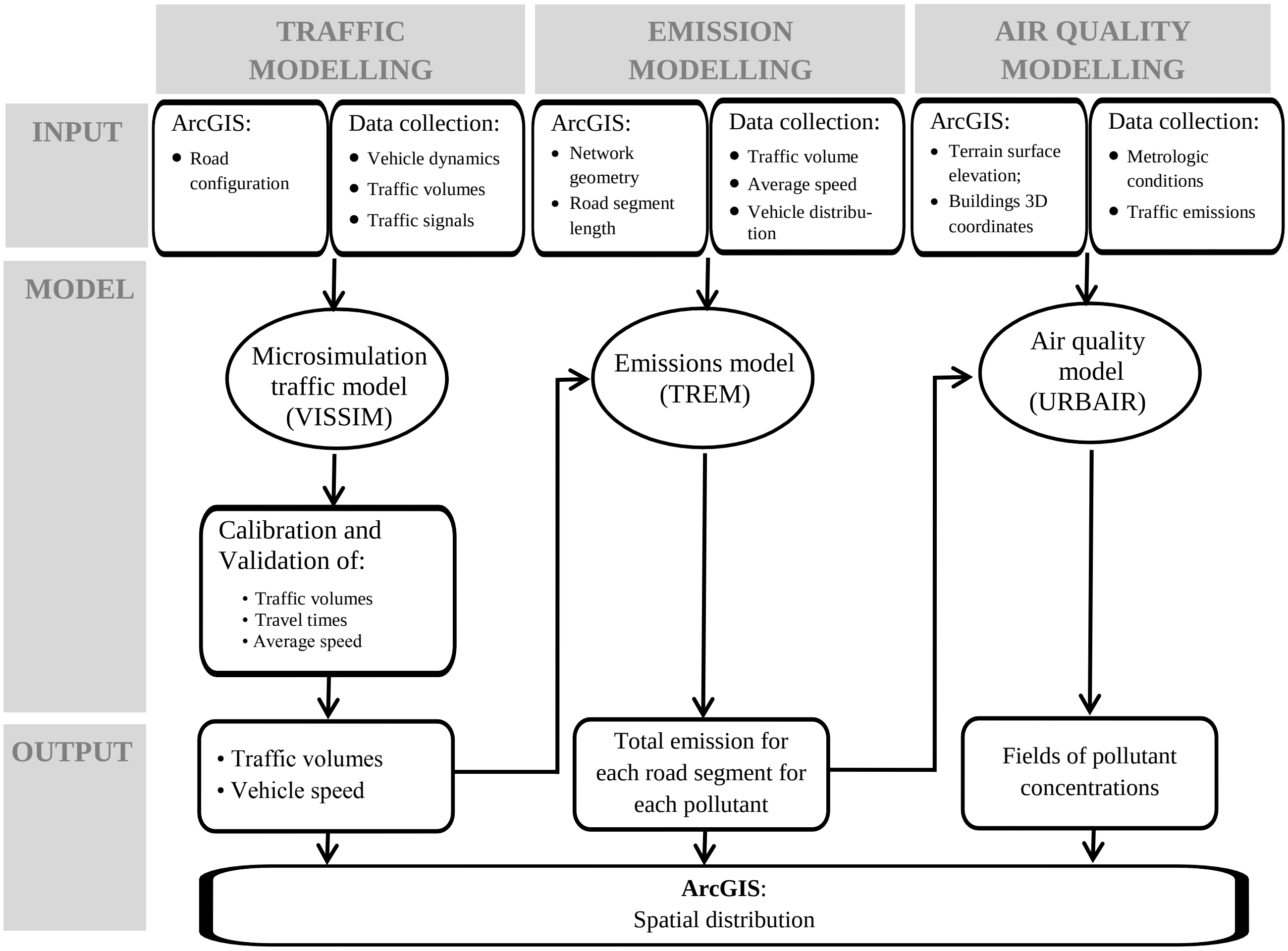

Fig. 1. Methodological simulation framework.

Transportation modelling: VISSIM model

VISSIM 5.30 model was applied to simulate individual vehicle movements during peak and non-peak periods. This model was selected because of the possibility to define different road-user behaviour parameters and the possibility to define different sub-models for different vehicle types and traffic controls. Furthermore, it allows different vehicles performance such as desired maximum braking and acceleration per vehicle and class (PTV, 2011). Previous studies have documented the effective use of this traffic model in assessing management strategies in real world case studies (Fontes et al, 2013; Mahmod et al., 2010).

To assess the urban network, field tests were conducted to collect vehicle dynamics, traffic volumes and traffic signals timing:

1) Vehicles dynamics: ten different routes with heterogeneous traffic conditions across the study domain were covered using GPS data-logger equipped vehicles to collect second-by-second vehicle dynamics. For each route, 15 trips during peak hour were performed using a passenger car. Approximately 550 km over 15 hours were collected;
2) Traffic volumes: traffic was counted in 56 strategic points of the study network (Figure 2). Based on these data, O/D matrices were defined for each intersection and assigned to the overall study domain;
3) Traffic signals timing: the cycle length and phasing was measured six times in the traffic lights in five points of the domain (Figure 2);

Field campaigns were performed for peak (7-9 AM and 5-7 PM) and non-peak (10 AM-5 PM) periods, between Tuesdays to Thursdays and under dry weather conditions during March 2011. To reduce systematic errors, the tests were performed using different drivers and vehicles. A detailed description of the field work can be found in Bandeira et al. (2012; 2013).

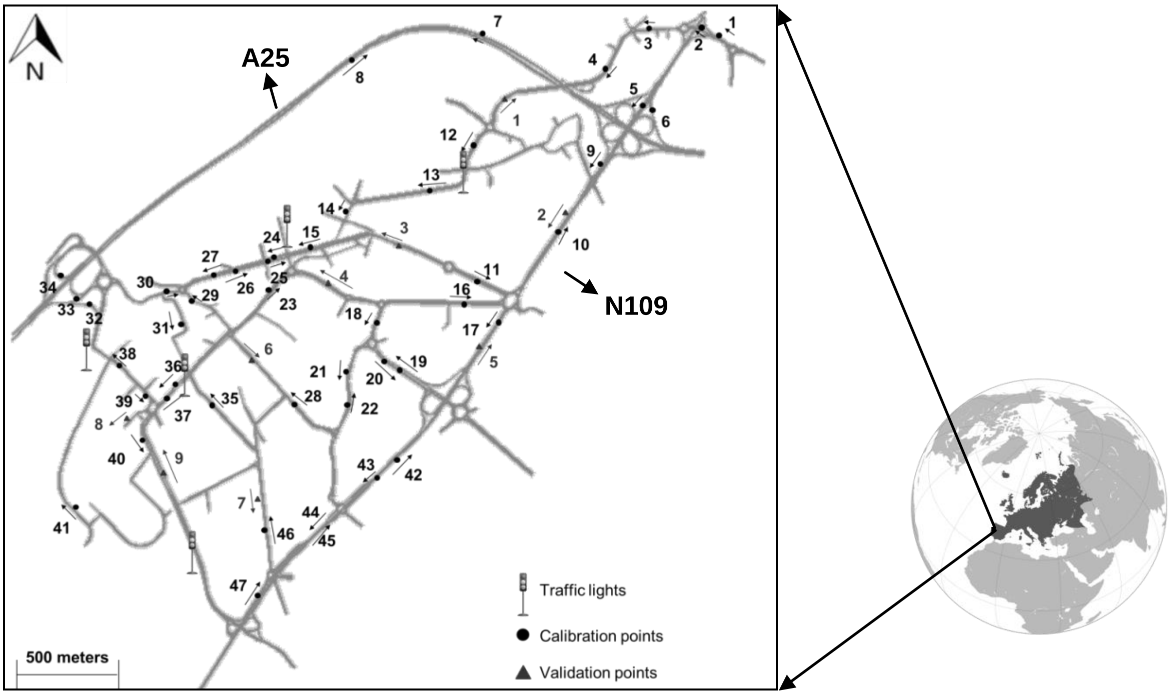

Fig. 2. Study domain and data collection points.

The model evaluation was made in two main phases: calibration and validation. The calibration addressed the parameters related to the number of simulation runs, driver behaviour parameters (car-following and lane-change parameters) and desired speed distributions. This step consists of fitting above traffic model parameters according to the study domain characteristics. The validation step was focused on the comparison between field data parameters and traffic model outputs. The validated parameters include: a) traffic volumes; b) travel times and c) average speed. To obtain an accurate representation of network traffic conditions, two goodness of fit measures were used: 1) Geoffrey E. Havers (GEH); and 2) Root Mean Square Error (RMSE). The GEH compare observed and estimated traffic volumes (Dowling et al., 2004) while RMSE quantifies the average magnitude of the error (Cambridge Systematics Inc, 2010). A detailed explanation of both calibration and validation of this study domain can be found in Fontes et al. (2013).

Calibration and validation were based on different datasets. Therefore, 47 points were used for calibration while the remaining points were used to validate traffic volumes, as illustrated on Figure 2. The same procedure was applied for travel times and average speeds. These data from VISSIM have been used as input to a detailed modelling of traffic emissions with TREM (Figure 1).

Emissions modelling: TREM model

The Transport Emission Model for Line Sources (TREM) was applied to Aveiro in order to estimate pollutant emissions released to the atmosphere by road traffic.

TREM was firstly developed on the basis of COST319/MEET approach and focused on carbon monoxide (CO), nitrogen oxides (NO_x), Volatile Organic Compounds (VOC) including methane, carbon dioxide (CO_2), sulphur dioxide (SO_2) and particulate matter with aerodynamic diameter less than or equal to 10 mm (PM10) (Tchepel 2003; Borrego et al., 2003, 2004; Martins et al., 2009; Bandeira et al., 2011). Also, a new module to calculate the emissions of traffic-related hazardous air pollutants was included in this model (Tchepel at al., 2011). The TREM model is based on the emission factors determined according to average speed and vehicle class (based on engine age, type, and capacity, vehicle weight, fuel type, and emission reduction technology).

The prime objective of TREM is the estimation of road traffic emissions with high temporal and spatial resolution to be used in air quality modelling. Although the average-speed approach for the emission factors implemented in the model follows the European guidelines (EMEP/EEA 2010) the way how transport activity data are considered for the emission inventorying is conceptually different. Roads are considered as line sources and emissions induced by vehicles are estimated individually for each road segment considering detailed information on traffic flux. Therefore, a link between the emission model and a transportation model, which is able to provide traffic volume in each road segment, is essential to provide the high-resolution information needed to the air quality simulations (Borrego et al., 2004; Bandeira et al., 2011). The reason for this priority relies on the dependency of emissions resolution calculations, both spatial and temporal, on traffic volume data set.

Overall, the input data required by the model have been compiled on the basis of: (i) road network spatial data; (ii) statistical information on fleet composition; and (iii) VISSIM outputs of traffic volume and vehicle speed for each road segment. The road spatial data were compiled for the Aveiro urban area and processed in ArcGis format.

The total emission of the pollutant p (E_p) for each road segment is estimated by the model as follow:

$$E_p=\Sigma(e_{ip}(v).N_i).L \qquad (1)$$

where $e_{ip}(v)$ is the emission factor (g.km^{-1}) for pollutant p and vehicle class i defined as a function of average speed v (km.h^{-1}); N_i is the number of vehicles of class i and L is the road segment length (km). Besides the average speed, emission factor depends on fuel type, engine capacity and emission reduction technology. Therefore, an adequate aggregation of vehicles by categories and classes in order to provide an accurate estimation of air pollutant emissions is an important task. In TREM, classification of vehicles is performed in order to satisfy two criteria: (i) to maintain the level of details available from the original methodology; and (ii) to allow the use of the model when a detailed description of vehicle fleet is not possible. In addition to the current vehicles classified on the basis of model year, engine type, emission standards and engine capacity, future vehicle technologies are implemented in the model. These data are not available for each counting point and statistical information was used to characterise vehicle fleet composition.

The model output data contains the emission rate for each road segment with a temporal resolution identical to the input information on traffic volume. In this way, emissions could be estimated on an hourly, daily or even yearly basis. To facilitate the processing of spatial data and to improve conversion of the resulting emission data to the format required by air quality models, TREM is linked to GIS (Borrego et al. 2004). TREM is prepared to read the input data directly from the *.dbf file and save the calculations results by adding new columns to the original file. In this way the original GIS data format is preserved and the emission estimations may be visualized, analysed and processed using the GIS.

Air quality modelling: URBAIR model

To obtain concentration levels and to evaluate the air pollution associated with road traffic in the study domain, URBAIR was applied. The air quality model URBAIR (Borrego et al., 2011) was designed to assess the impact of urban planning and traffic management on air quality. It provides concentrations patterns for a given spatial domain (with up to about 50 km from the domain centre) and time period (e.g. hourly, daily or one year, in compliance with Directive 2008/50/EC) for different air pollutants, namely: PM10, NO_2, SO_2 and CO.

This modular system includes the pre-processing of land use and urban elements geometry, meteorological conditions and air pollutant emissions, coupled with a dispersion module. In the core of URBAIR is an advanced Gaussian model, which has been enhanced with a number of functionalities, in particular the treatment of road traffic emissions and 3D urban elements.

Because topography and build-up structures characteristics have a significant influence on the dispersion of atmospheric pollutants, particularly in urban areas, URBAIR requires the characterization of the spatial variation of terrain surface elevation, land use, buildings 3D coordinates and emission sources location and dimensions. ArcGIS was used in the pre-processing of the geographic/geometric characteristics of the study domain, which is usually complex and time-consuming. This procedure involves the rearrangement (assembling of elements, shape simplification, etc.) of the existing buildings based on their position and configuration, allowing to generate a simplified shapefile of the domain (as shown in Figure 4), which will be read by URBAIR. GIS is also used to show the spatial distribution of the pollutants concentration estimated by URBAIR.

To estimate pollutant concentrations hourly simulations were conducted with URBAIR model taking into account hourly meteorological conditions, such as wind direction and wind speed, measured at one monitoring station located in sub-urban area of the city.

RESULTS AND DISCUSSION

The results obtained from the application of the integrated modelling system are presented in this chapter in order to quantify emissions from road transport and its impact on urban air quality.

A summary of traffic model validation results is presented in Table 1 for 10 initial simulations with varying random number seeds (Hale, 1997). It was found that all traffic points recorded GEH values below 4 while RMSE did not exceed 18%. According to Dowling et al. (2004) and Cambridge Systematics Inc. (2010), these results were considered to be satisfactory given that this study domain has a considerable size with heterogeneous traffic conditions. Similarly, the comparison between observed and estimated means for travel times and speed also resulted in RMSE rather below the recommended thresholds (6-9% for travel times and 5-12% for average speeds). The highest travel times and speed differences were achieved on roads sections with a significant number of intersections with traffic signals. From these results, it was concluded that 10 simulation runs are considered as acceptable to this study.

Table 1. Summary of traffic model validation results.

Parameter	n	Goodness of fit measure	Result
Traffic volumes	9 points	GEH	Max. 3.7; Min. 1.1
		RMSE	Max. 18%; Min. 6%
Travel times	10 road sections	RMSE	Max. 9%; Min. 6%
Speed profiles	10 road sections	RMSE	Max. 12%; Min. 5%

As mentioned before, the vehicle speed is estimated by the VISSIM model based on the speed data collected from GPS data-logger equipped vehicles. The frequency distribution of the average vehicle speed in each road segment of 1 meter is presented in Figure 3 for a typical working day in the Aveiro urban area. As can be seen, the vehicle speed is not uniformly distributed within the study domain, ranging from 2.7 to 110.7 $km.h^{-1}$). It is important to highlight that vehicle speed is one of the principal parameters used for deriving emissions functions. For urban applications, the vehicle speed of 50 $km.h^{-1}$ (road speed limit) is usually considered, ignoring thus the real vehicles dynamics across the urban network. Therefore, the importance of considering the vehicle speed data with high spatial resolution in emission quantification, as provided by GPS technology, is evident.

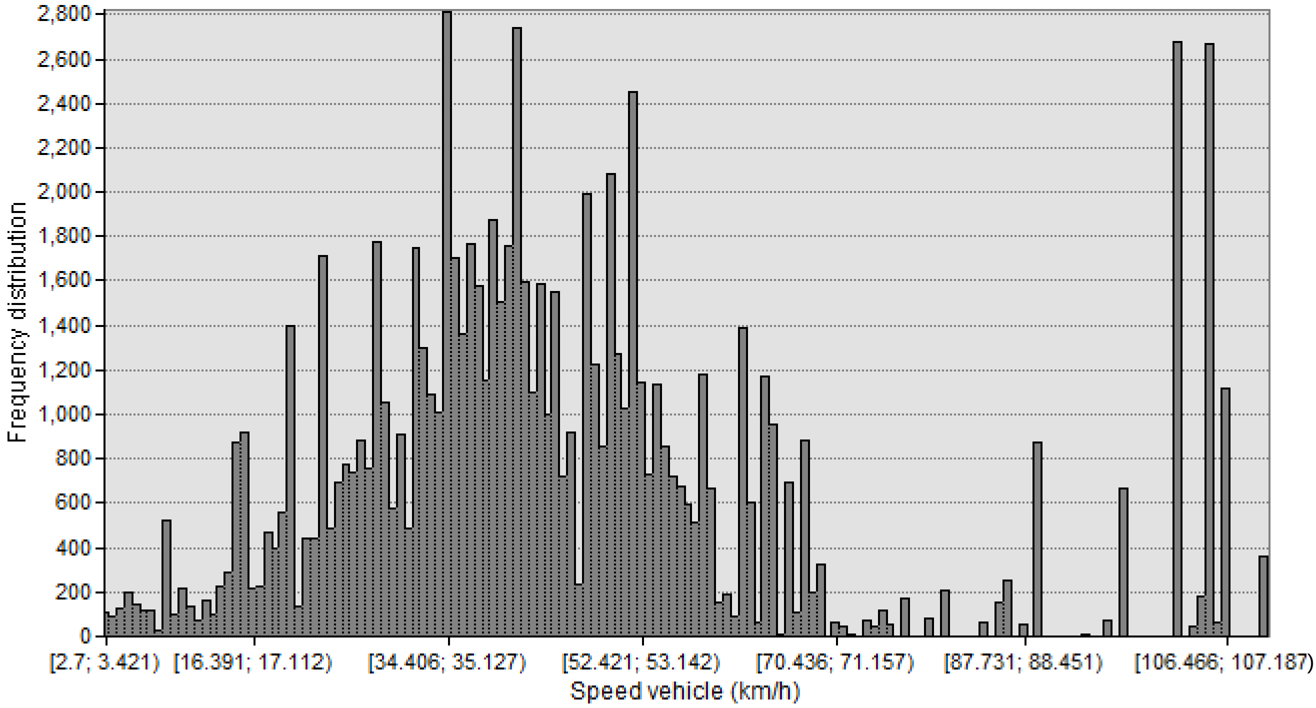

Fig. 3. Frequency distribution of vehicle speed per 1 meter of road for a typical working day in Aveiro urban area.

Based on TREM, traffic emissions were estimated on an hourly basis for each road segment according to the average vehicle speed and the traffic volumes provided by VISSIM. The total daily emissions estimated for the Aveiro urban area, their spatial distribution and some indicators were estimated and analysed for different pollutants (CO, PM, NO_x and VOC) (Table 2 and Figure 4). Also, based on the previous work, where the importance of road traffic impact on Aveiro air quality at regional scale was analysed (see details in Coelho et al., 2014), the estimated road traffic emissions were compared in order to understand the contribution of traffic emissions in the Aveiro urban area to the total traffic emissions in the coastal region between Aveiro and Oporto (Table 2).

As can be seen from the results (Table 2), the emissions induced by traffic in the Aveiro urban area contribute from about 1% for PM and CO to 4% for VOC to the total traffic emissions in the Aveiro/Oporto region. Also, it is important to recognize that emissions per area are higher in Aveiro, thus evidencing the importance of traffic as an emission source in urban areas.

Table 2. Daily emission estimation results for the modelling domain.

	CO	**PM10**	**NO_x**	**VOC**
Total emissions (kg)				
Aveiro urban area	1,347	23	378	361
Aveiro/Oporto region[1]	63,300	1,800	34,220	9,340
Emissions per area (kg.km^{-2})				
Aveiro urban area	78.7	1.3	22.1	21.1
Aveiro/Oporto region[1]	16.7	0.5	9.1	2.3

[1] Values from Coelho et al. (2014).

A spatial distribution of the emissions is obtained by linking TREM outputs to GIS maps. Figure 4a illustrates, as an example, the CO emissions at each road for the evening peak hour (6 PM) in a typical working day. Traffic volumes recorded during this period correspond to about 9% of the daily traffic. As could be seen in the figure, higher pollutant amount emitted by road transport to the atmosphere is observed for urban roads and main city entrances, verifying the same behaviour for remaining pollutants.

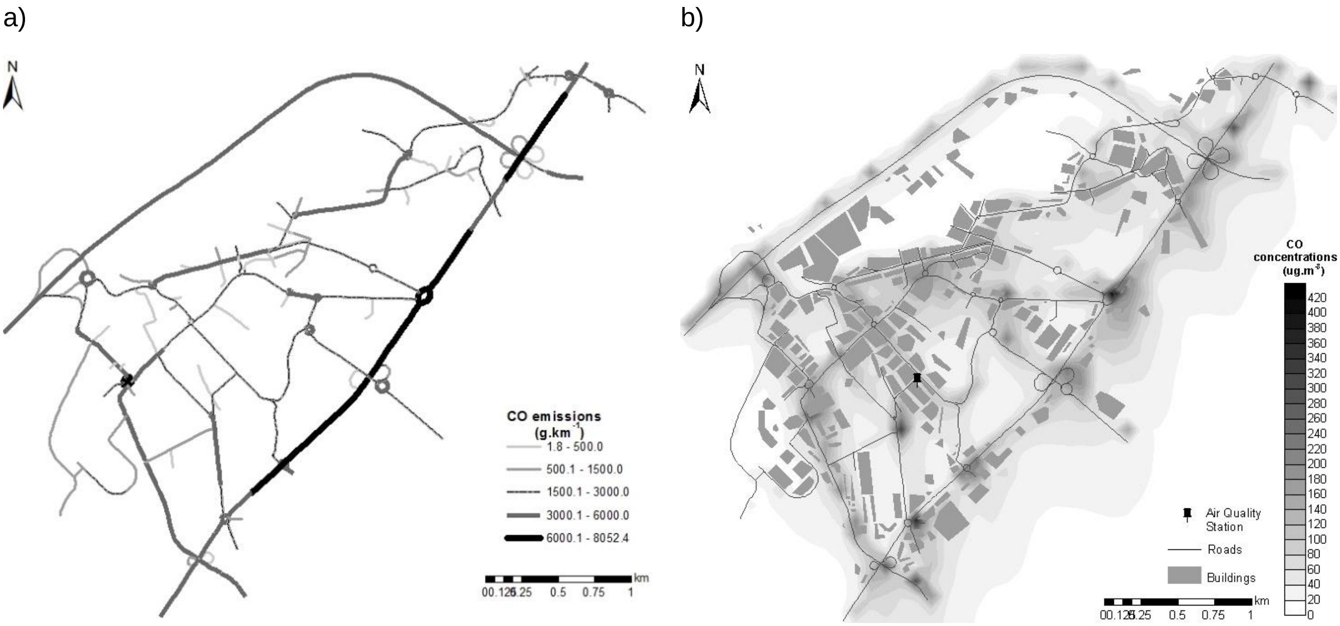

Fig. 4. Spatial distribution of a) hourly CO emissions (g.km^{-1}) and b) CO dispersion simulation (µg.m^{-3}) at 6 PM in a typical working day of May 2011.

In typical conditions, CO emissions assume higher on highways, since this pollutant is mostly generated during the occurrence of higher speed regimes. However, in the present case the higher emissions values are observed for the N109, an interurban road, where, as would be expected, traffic volume is higher, since it is one of the main points of connection to the Aveiro urban area and the main access to an industrial area. The spatial distribution of the CO concentrations is illustrated, as an example, in Figure 4b by linking dispersion fields estimated by URBAIR to GIS environment. As illustrated by the figure, the distribution of CO levels within the study domain is not homogeneous, reflecting thus the contribution of road transport emissions.

The maximum value of 8-h average CO concentrations obtained by URBAIR (175 µg.m^{-3}) and measured by the air quality station (182 µg.m^{-3}) are significantly low compared to the 8-h average limit value (10,000 µg.m^{-3}) defined by the current European Directive (Directive 2008/50/CE). On the other hand, a non-significant difference between the model output and the air quality measured data was found, indicating a good modeling system performance.

CONCLUSIONS

In the scope of this work the application of a modelling system for quantifying emissions from road transport in urban areas and its impact on air quality is presented. For this purpose, three numerical tools were linked and applied to predict the air quality in Aveiro urban area with high spatial and temporal resolution, based on GIS and GPS information tools.

The results obtained from the modelling system are in a good agreement with the air quality measured data, evidencing thus the benefit of integrated use of the modelling tools and GPS and GIS in order to improve the quantification of the traffic emissions contribution to urban air quality. In addition to explore and visualize spatial information, providing additional features for data processing and data analysis, GIS allows to store and to display spatially traffic data in each road segment, which is essential to provide the high-resolution information needed to the air quality simulations. Also, GIS in combination with air pollution dispersion models allows to analyse the ways in which pollutants propagate in environment and the consequent impact of emissions sources. For urban scale application, the collection of the time-location information using GPS technology is essential, as demonstrated in this work. The GPS technology provides continuous tracking of the vehicles dynamics with high data resolution in time and space, allowing an accurate characterization of traffic emissions.

The good performance of the integrated modelling approach presented in this work has demonstrated its importance towards the air quality assessment and management. An adequate results analysis allows to obtain air quality reference values at the considered area, which can be used in traffic management as a way to improve citizens' quality of life.

ACKNOWLEDGEMENTS

This work was partially funded by FEDER Funds through the Operational Program "Factores de Competitividade – COMPETE" and by National Funds through FCT –Portuguese Science and Technology Foundation within project SMARTDECISION (PTDC/SEN-TRA/115117/2009). Also, the authors thank FCT for the Strategic Project PEst-C/EME/UI0481/2011, E. Sá (SFRH/BD/60474/2009), J. Bandeira (SFRH/BD/66104/2009), P. Fernandes (SFRH/BD/87402/2012) and Post-Doctoral scholarship of J.H. Amorim (SFRH/BPD/48121/2008).

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