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Road traffic emissions impact on air quality of the Greater Athens Area based on a 20 year emissions inventory

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ABSTRACT

During the last decades, the Greater Athens Area (GAA), among many other urban agglomerations, faces atmospheric pollution problems mainly associated with high levels of particulates, nitrogen dioxide and ozone. The major pollution source for the GAA is road transportation. In this sense, the aim of this work was to investigate the existence of a direct relationship linking air pollutant concentration levels and road traffic emissions. To this aim, air pollutant emissions from road traffic were calculated for the period 1990–2009 and then the relationship with the corresponding air pollutant concentrations was investigated. The calculated results have revealed that all pollutants examined show a strong decreasing trend whereas the age of the vehicles and the corresponding engine technology determine the amount of the pollutants emitted. In addition, the NO_2/NO_x emission ratio presents a constant increase in the course of the years, according to the respective NO_2/NO_x concentration ratio. Furthermore, the comparison between emission calculations and the corresponding measured concentrations shows a highly significant correlation providing therefore evidence to policy makers that all pollution abatement measures can be defined and assessed with regard to their anticipated effect on air pollutant emissions. Detailed analysis of the 2009 emissions shows that, in general, passenger cars are the major polluters for CO, NMVOCs and CH_4, whereas PM_{10} and NO_x are mostly associated with heavy duty vehicles (HDVs). Finally, it appears that vehicles aged more than 15 years are responsible for the major part of the air pollutants emitted.

1. Introduction

Road transport has become by far the major source of atmospheric pollution and traffic congestion in urban areas. Additionally, road traffic emissions contribute to global warming as they are also associated with CO_2, NH_3, CH_4 and N_2O emissions (Uherek et al., 2010; Smit et al., 2010). Especially for the area of Greece, the total national emissions of the main pollutants as well as those associated with road transport emission data officially submitted by the country in the framework of the Convention on Long Range Transboundary Air Pollution (CLRTAP) and the European Monitoring and Evaluation *Programme* (EMEP) via the UNECE secretariat (CEIP, 2010), are presented in Table 1.

As shown in the table, road transport plays a major role in CO emissions, contributing with 67% of total emissions, and represents an important part of NO_x and NMVOCs emissions with a contribution of 29 and 23% correspondingly. Obviously, in the scale of a city these contributions become even higher resulting in high air pollutant levels. This is the case of Athens, the capital and largest city of Greece, whose complex geomorphology along with its Subtropical Mediterranean climate are considered responsible for the air pollution problems the city is facing (Ziomas, 1998).

In this framework, the knowledge of the mechanisms leading to high air pollutant emissions remains critical. A lot of research has been carried out to investigate the existence of a direct relationship linking air quality levels and air pollution emissions from transport in several urban agglomerations (Zamboni et al., 2009; Mellios et al., 2006; Kassomenos et al., 2006, 2004; Karakitsios et al., 2006; Borrego et al., 2000). However, a further improvement in the perception of this relationship seems to be needed. The aim of this study is to analyse if there is such a relationship between road traffic emissions and air quality concentrations for the Greater Athens Area. First, air pollutant emissions were calculated and then the probable relationship with air pollutant concentrations was investigated. Obviously, a prerequisite for investigating this relationship is to have accurate emission calculations. Actually, the main rationale for accurately calculating road traffic emissions, except current requirements from European and International Conventions, is to connect them to air pollutant levels and to set and assess measures for air pollution abatement as well as to conduct emission predictions (Bellasio et al., 2007). In this sense, to ensure the efficiency of strategies to reduce air pollutants caused by road traffic, it is essential to evaluate the emission data to be used in emission calculation models or other decision support systems and tools.

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Table 1
National emissions versus road transport emissions in Greece for the year 2008 (as reported under the CLRTAP).

2008 emissions (Gg)	NO_x	NMVOC	SO_2	NH_3	CO
Total national emissions	356.87	218.66	447.55	63.1	685.01
Road transport emissions	104.41	50.33	2.03	2.67	461.11
% contribution of road transport	29.26%	23.02%	0.45%	4.23%	67.31%

Road transport emission trends of various pollutants in the Greater Area of Athens (GAA), Greece, are calculated and presented here and are linked to the evolution of pollutant concentrations. In the present work calculations of air pollutant emissions from road transportation in the Greater Athens Area (GAA) were carried out applying the COPERT IV code, a user-friendly MS Windows software application (Ntziachristos et al., 2009). The software contains all the algorithms and the necessary input parameters to estimate total road transport emissions on a national, regional or local/urban scale with the possibility of a year to day-long resolution.

2. Methodology and data used

In the framework of the present work, as already mentioned, the idea is to perform calculations of total emissions of the GAA on a yearly basis covering the whole time period from 1990 to 2009. The calculation results are compared to the corresponding yearly mean pollutant measurements for the same time period. The determination of a statistically significant relationship between emissions and concentrations, for those pollutants mainly associated with road traffic, can provide stakeholders and policy makers with interesting ideas in the field of air pollution abatement in an urban environment. The estimation of the effect of on-road vehicle emissions on air quality in urban areas, as well as the use of existing pollutant concentration measurements as a validation tool for the emission calculations performed have already been studied in previous works (Mellios et al., 2006). Roustan et al. (2010), have estimated the effect of on-road vehicle future emissions on air quality levels of Paris through model application.

In the GAA, an extended air pollutant measurement network operates under the supervision of the Ministry of the Environment, Energy and Climate Change (MEECC). The network covers places with different source characteristics. More explicitly, in the GAA in 2009, the MEECC operated 15 stations as follows: a) five urban-traffic, b) two urban-background, c) three suburban-industrial, d) one suburban and e) four suburban-background (MEEC, 2011). From the above stations, nine of them are used as they are operating since 1990 and their data cover the whole period of study, whereas most of the rest of the monitoring stations have started their operation after 2000. Five of these stations are urban-traffic; two are urban-background; one is suburban-background and one is suburban-industrial. Geographically, the stations used cover the whole area of interest and more specifically areas with dense road traffic emissions as well as residential urban and suburban areas. Moreover, in order to avoid local particularities influencing each station measurements, the yearly mean concentrations, resulted as the average of all monitoring stations were used.

In the present emission calculations, the methodological approach applied is a top–down approach, without hence taking into account detailed traffic load data in main road axes. When total emissions of an urban area are to be calculated, it is difficult to specify traffic loads and other activity data for the main road network. Furthermore, there is difficulty in determining traffic characteristics of secondary, though particularly important, road network. On the contrary, in the case of a top–down approach, as the activity data used are based mostly on statistical and, therefore, less uncertain data, the calculations results are considered more reliable and accurate. A comparison of top–down and bottom–up emission calculation was conducted in previous works and was found that, if required, the spatial and temporal disaggregation of total emissions can be consistently achieved with the aid of statistical data based on population density, road network length per road type and professional activity data as well as with applying known daily traffic patterns. Such methods have already been developed and successfully applied elsewhere (Saide et al., 2009; Tuia et al., 2007).

In the present work calculations of air pollutant emissions from road transportation in Greece were carried out applying the COPERT IV code (Ntziachristos et al., 2009). It is to be noted that the same edition of the code (COPERT IV version 7.1) was applied in order to assure the comparability of the emissions during the whole calculation period. Moreover, emphasis was given to the improvement of the quality of the input data used. These data include fleet statistical data as well as fleet circulation data. The first data category can be defined with minor uncertainties especially after the reconstruction of the Greek vehicles fleet (Progiou and Ziomas, 2011). Until recently, due to the lack of the information required in order to determine the fleet composition in terms of population and engine type and technology, the vehicles fleet data were incomplete and not homogenised. This was a problem of the national vehicle registration system operating in the Greek Ministry of Transport which did not include some helpful information concerning the vehicle types coming in circulation as well as the population and type of vehicles that were deregistered. A first complete estimation of all the circulating vehicles was accomplished in 2002. This offered a challenge to reconstruct the Greek car park for the whole period of interest in a common and consistent way. In addition, except from the data from the Ministry of Transport, detailed complementary statistical data from the Association of Motor Vehicles Importers and Representatives (AMVIR) were used. These data provide supplementary information as they are based on the same database from the Ministry of Transport but they are further elaborated, enriched and verified through the use of the Association's statistical data.

Contrary to the above discussed fleet statistical data, circulation data might correspond to major uncertainties as they cannot be provided from statistical records.

Such type of input data is the mileage driven for each vehicle type and category. In order to determine this type of data which are directly proportional to the emissions, hence they significantly affect the calculations result, data from on-site vehicle controls conducted from the Greek Ministry for the Environment and Climate Change were used (MEECC, 2008). These data have shown that older vehicles travel fewer kilometres (Symeonidis et al., 2003) and, consequently, different mileage was used for each vehicle category. Additionally, as the number of private vehicles per capita (the vehicles ownership per capita) has grown, especially the last decade, it is considered that the mileage driven by each private vehicle decreases with time. In order to finally determine the mileage for each vehicle type, a survey was conducted and data were gathered from several vehicle service workshops with the aid of the Association of Motor Vehicles Importers and Representatives. Finally climatic data, as minimum and maximum monthly mean temperature for the area of interest, or information about the fuel characteristics are needed but they can be defined without significant uncertainty.

At this point it should be noted that the vehicle fleet constructed for the period 1990–2009 is improved compared to any other pre-existing not only because it covers the longest time period but also because it includes the following:

- Updated and new statistical data for the whole time series,
- reconstruction of all years vehicle fleet with use of the extended dataset of vehicle types of COPERT IV (compared with COPERT II and III), and
- application of consistent approaches and assumptions for the whole time period.

Fig. 1 presents the evolution of the GAA vehicle fleet for each vehicle category. As shown in the figure, a strong increasing trend of the population of passenger cars (PCs) and of 2-wheel vehicles is

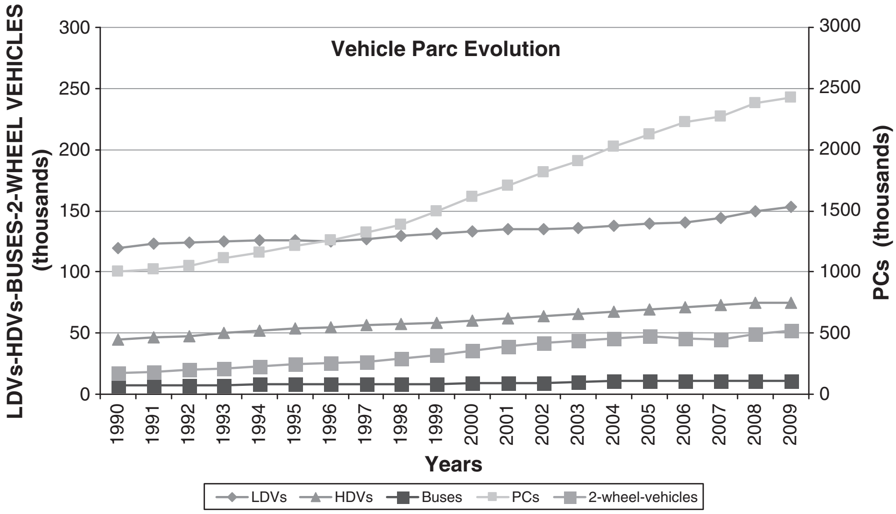

Fig. 1. Vehicle parc evolution for all vehicle categories.

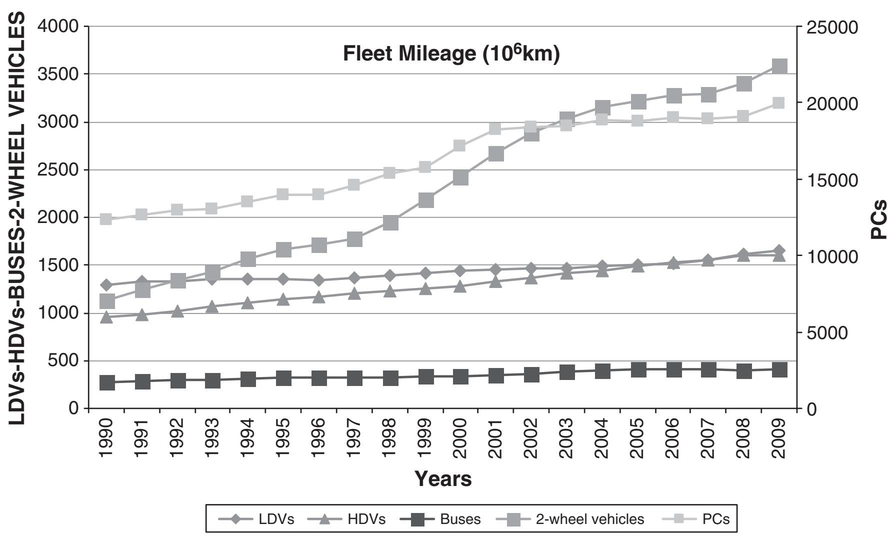

Fig. 2. Fleet mileage evolution for all vehicle categories.

observed. Professional vehicles (Light Duty Vehicles — LDVs and Heavy Duty Vehicles — HDVs) and buses present a considerable but weaker increase during the whole time period. In Fig. 2, the temporal evolution of the annual mileage for each vehicle category is illustrated. It is worth mentioning that the increasing trend of the mileage does not fully follows the corresponding trend of the population, as the annual mileage of each vehicle category is not constant but varies according the vehicle age and the year.

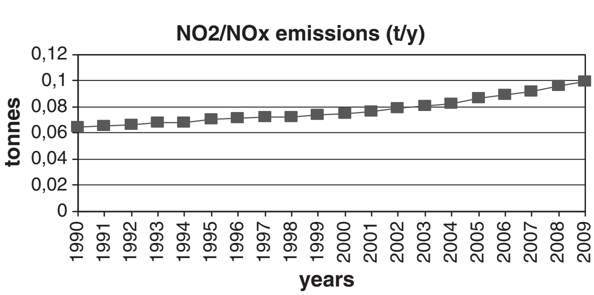

Fig. 3. NO_2/NO_x emission ratio in the GAA from 1990 to 2009.

3. Results and discussion

3.1. Temporal variation

Calculations of the whole period 1990–2009 road traffic emissions were performed.

Figs. 4–6 illustrate the temporal variation of carbon monoxide (CO), nitrogen oxides (NO_x) and exhaust particulates (PM_{10}) in comparison to the corresponding annual mean concentrations, resulted as the average of all monitoring stations. The PM_{10} concentration time series, due to lack of measurements available, covers the period 2001–2009. Especially for NO_x, the measurements have been produced as the summing up of NO and NO_2 concentrations. In Table 2, the linear best fit equation simulating the long term evolution of air pollutant concentrations and emissions are presented along with the correlation coefficients calculated for the three pollutant time

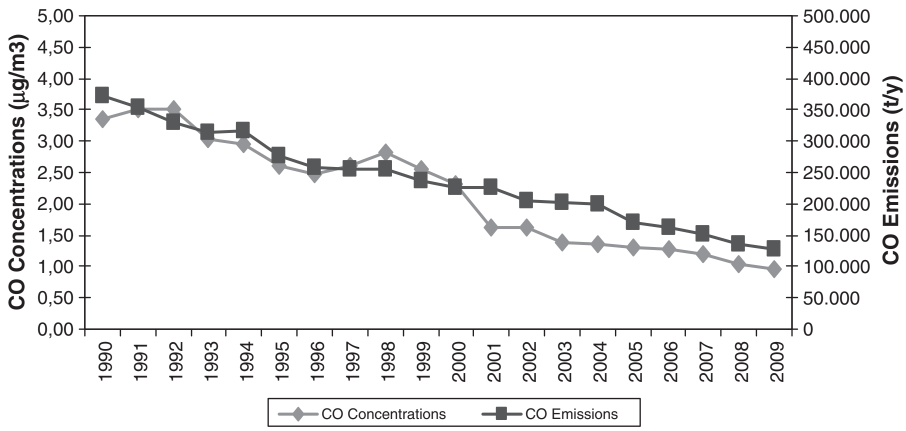

Fig. 4. Carbon dioxide emission and concentration evolution in the GAA from 1990 to 2009.

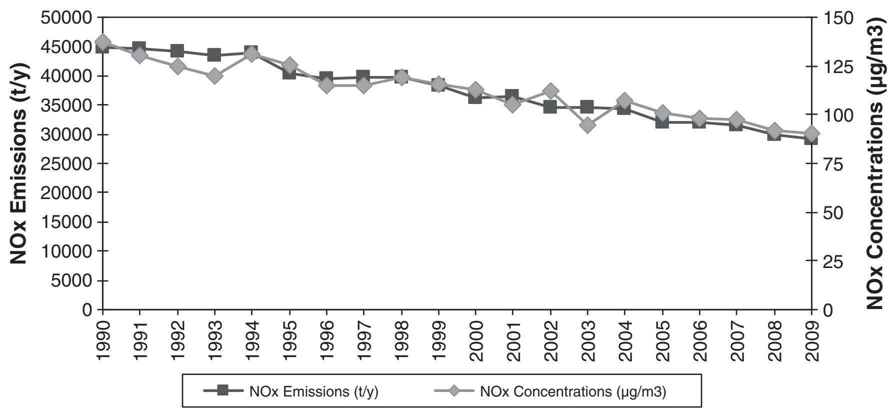

Fig. 5. Nitrogen oxides emission and concentration evolution in the GAA from 1990 to 2009.

series. With regard to their temporal evolution, all three pollutants present a strong decreasing trend ranging from 36% for NO_x to 65% for CO for the 20 years of study, with the corresponding decrease for PM_{10} being around 25% for the 9 years of study. It is to be noted that, despite the significant increase of the number of vehicles (especially PCs and 2-wheel vehicles), the vehicles engine anti-pollution technology evolution overcomes the corresponding anticipated emissions increase and leads to significant emissions decreases. It is expected that, with the "business as usual" vehicles fleet renewal scenario, most air pollutant emissions will be further decreased or stabilised.

Similar results were shown in other works concerning European road transport emissions (Vestreng et al., 2009). It is found that the implementation of strict measures to control NO_x emissions is a main reason for the continued Western European emission reductions. An interesting finding was that despite the general increase of fuel consumption and especially in diesel consumption, the effect of such technical abatement measures is traceable in the evolution of European road traffic emissions from 1990 to 2005. As a result of the combined reductions, the total road transport NO_x emissions in Europe decreased by 23% between 1990 and 2000 and by 11% between 2000 and 2005. In contrast, despite the emission reduction, another study for the area of Athens has demonstrated that the corresponding reductions in ambient NO_2 concentrations are inferior to the emission reductions (Mavroidis and Chaloulakou, 2010). As a result, according to the measurements of the existing monitoring network, the mean NO_2/NO_x ratio in the GAA has increased from 1990 to 2009 by 18%. Yet, the mean NO_2/NO_x ratio in 2009 tends to decrease again in comparison to the previous years with the same behaviour being observed for the corresponding NO_2/NO_x ratio from the Patission urban-traffic monitoring station. In Fig. 3 the NO_2/NO_x emission ratio is presented for the whole calculations period. As shown in the figure, the NO_2/NO_x ratio presents a constant increase in the course of the years, as a result of the decrease of NO_x emissions and a concurrent slight increase of NO_2 emissions. Hence, the rising NO_2/NO_x concentration ratio seems to be connected to the corresponding emission ratio. Therefore, the above calculations and the general decreasing trend of NO_2 levels in the GAA show that there is still place to decrease NO_2 levels with measures towards vehicles fleet renewal.

Furthermore, in the framework of the present study, the most interesting finding drawn from the calculations comparison to the annual mean corresponding concentrations is their good correlation. More explicitly, as shown in Table 2, the CO emissions are found to

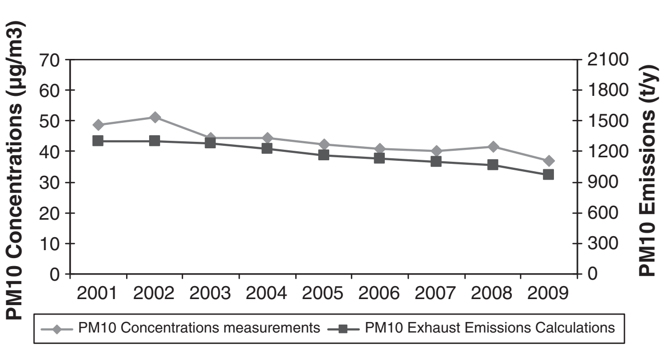

Fig. 6. PM_{10} emission and concentration evolution in the GAA from 1990 to 2009.

Table 2
Linear best fit equation for NO_x, NO_2 and NO concentration and emission variations, average yearly change (%) and correlation coefficients.

	Linear best fit equation		Average yearly change (%)		Correlation coefficient
	Emissions	Concentrations	Emissions	Concentrations	
NO_x	$-859.26*x+46{,}500$	$-2.2106*x+135.46$	−1.79%	−1.58%	0.95
CO	$-12{,}049*x+365{,}195$	$-0.1438*x+3.6847$	−3.24%	−3.86%	0.96
PM_{10}	$-40.868*x+1376$	$-1.4824+50.737$	−2.72%	−2.68%	0.91

have a correlation factor of 0.96 with the corresponding average annual concentrations for the whole period 1990–2009. Furthermore, the NO_x emissions have a correlation factor of 0.95 with the corresponding average annual concentrations. Finally, the same procedure was followed for particulates exhaust emissions with the corresponding concentration values but for the period 2001–2009 for which measurements were available. The correlation factor with the corresponding average annual concentrations was found to be 0.91. For all three correlations, the correlation level is considered statistically important with a significance level of 0.995. It seems that, despite the fact that all pollutant concentrations are interconnected through complex photochemical processes, the short time variations introduced by photochemistry are eliminated due to the temporal (yearly) and spatial averaging of the correlated data. The above findings show that all three pollutants, mainly related to road transport emissions, present a trend similar to the corresponding road transport emission trend and therefore, this strong correlation provides evidence to policy makers that all pollution abatement measures can be defined and assessed with regard to their anticipated effect on air pollutant emissions. Another insight of the above conclusion is that the evolution of engines technology and other restriction measures have a significant effect on ambient concentrations. The fact that this finding in a first view does not seem to coincide with previous works for NO_x emissions in Europe (Vestreng et al., 2009), where a more flattened trend was observed for the most recent years, can be explained if the emission trend is calculated for three distinct periods: 1990–2000, 2001–2005 and 2006–2009. In Table 3 the NO, NO_2 and NO_x emission reduction trends are presented. Actually, a reduced decrease is observed for the period 2001–2005 but, interestingly, the decrease trend becomes again more significant for the third period 2006–2009, most probably due to the new technology vehicles circulation. Noticeably, the NO_2 decrease is more important relatively to the NO_x and NO decreases for both 1990–2000 and 2006–2009 periods when the reductions are most important.

3.2. Current situation

Calculations of the year 2009 road traffic emissions were performed for the GAA. On-road traffic emissions are calculated only. In Fig. 7, the total number of vehicles per each vehicle category and for two age groups (<15 years and >15 years), is presented. This classification was considered as it is assumed that the age of 15 years represents the maximum age of the group of newer technology vehicles. Interestingly, the number of older and, hence, more polluting vehicles, is a significant part of passenger cars (PC) population (32%) as well as of light duty vehicles (40%), buses (42%) and two-wheel vehicles population (43%). The corresponding number for heavy duty vehicles (HDV) is much more important, representing the 71% the HDVs population.

Table 3
Mean yearly NO_x, NO_2 and NO concentration variations in the GAA for the periods 1990–200, 2001–2005 and 2006–2009 (average from all monitoring stations).

	NO_x	NO_2	NO
1990–2000	−1.64%	−2.39%	−0.79%
2001–2005	−0.78%	−0.57%	−0.95%
2006–2009	−1.90%	−2.24%	−1.61%

Table 4 illustrates the estimated road traffic emissions in the GAA for the most important air pollutants and the contribution of each vehicle category whereas in Figs. 8–12 emissions from each age group of all vehicle categories are shown. As presented in Table 4, CO, NMVOCs and CH_4 are mainly associated with PCs; PM and NO_x are mainly associated with HDVs. Passenger cars are the major polluters, with a more than 50% contribution, for CO, NMVOCs and CH_4. On the contrary, PM_{10} and NO_x are connected to HDVs with a contribution of 66 and 65% respectively. Finally, CO_2, as directly related to fuel consumption, is mainly associated with passenger cars and heavy duty vehicles.

It is to be noted that the other vehicle categories also contribute to air pollution but their contribution either due to the number of vehicles, in the case of LDVs, or the number of kilometres driven, in the case of 2-wheel vehicles, is rather limited. Of course, even with these limitations, LDVs represent approximately 12% of CO and 19% of NMVOCs emitted, whereas 2-wheel vehicles represent more than 20% of CO and CH_4 emitted. Obviously the significance of these emissions is related to the severity of the corresponding environmental problem the specific pollutant is associated with. The major part of the above emissions, as presented in Figs. 8–12, is associated with the older vehicles.

Especially for those vehicle categories considered as major polluters, the older vehicles are those mainly contributing in their emissions. Urban agglomerations as the GAA are facing atmospheric pollution problems dealing mainly with particulates, nitrogen dioxide and less with ozone (MEEC, 2011). Hence, from the above results, it can be extracted that a policy towards a cleaner atmosphere in terms of particulates and nitrogen dioxide should include circulation restriction measures or fleet renewal for older HDVs. On the other hand, PCs seem to be more implicated with hydrocarbons, and thus, ozone concentrations. Finally, as in the GAA circulation of diesel PCs is prohibited, in case this measure is haltered, the fact that diesel engines emit more PM and NO_x should be taken into consideration.

4. Conclusions

Road traffic emissions represent a major part of air pollutant emissions in a national scale and contribute noticeably to greenhouse

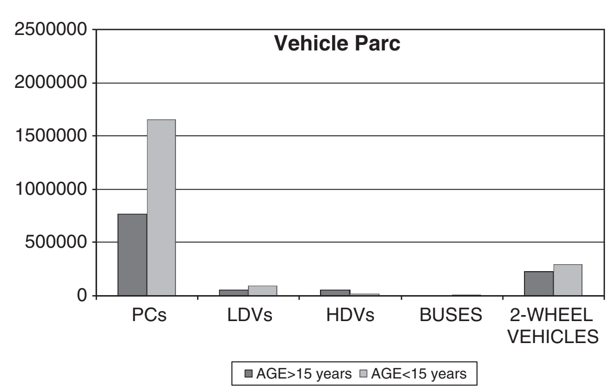

Fig. 7. Vehicle parc of the GAA presented for each vehicle category and two age groups for 2009.

Table 4
Contribution of each vehicle category to road transport emissions in the GAA.

	CO	NMVOC	CH_4	NO_x	PM_{10}	CO_2
PC	76,105	29,496	2028	23,082	1076	11,799
	59%	51%	54%	17%	17%	47%
LDV	15,657	10,741	387	12,644	569	2707
	12%	19%	10%	9%	9%	11%
HDV	4018	8532	429	88,651	4166	7519
	3%	15%	11%	65%	66%	32%
Buses	960	536	78	9936	327	986
	1%	1%	2%	7%	5%	4%
2-wheel vehicles	31,235	8045	843	2151	185	733
	24%	14%	22%	2%	3%	3%
Total	*127,975*	*57,351*	*3765*	*136,463*	*6322*	*23,744*

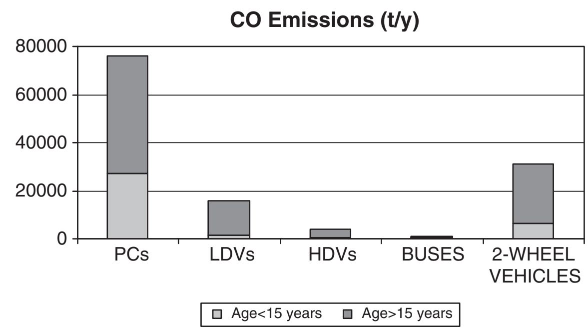

Fig. 8. Carbon monoxide emissions in the GAA for year 2009 for all vehicle categories according their age.

gases emissions. The GAA is facing atmospheric pollution problems dealing mainly with particulates, nitrogen dioxide and less with ozone levels. In this framework, a new detailed and updated road traffic emission inventory for the GAA was compiled to be used for policy measures towards air pollution abatement.

During the calculations period (1990–2009), NO_x emissions have decreased by an average yearly change of 1.79%, whereas the respective value for CO is −3.24%. Concerning PM_{10} emissions for the period 2000–2009 the average yearly reduction is 2.72%. The corresponding spatially and yearly average concentrations show a similar behaviour with reductions ranging from −1.58% for NO_x to −2.68% for PM_{10} and −3.86% for CO. Emission calculations of CO, NO_x and PM_{10} from 1990 to 2009 show a significant correlation coefficient with the corresponding annual mean concentration levels that varies from 0.96 for CO, to 0.95 for NO_x and 0.91 for PM_{10}, thus verifying the accuracy of the calculations performed. It seems that, despite the fact that all pollutant concentrations are interconnected through complex photochemical processes, the short time variations introduced by photochemistry are eliminated due to the temporal (yearly) and spatial averaging of the correlated data. Furthermore, the above result provides evidence to policy makers that all pollution abatement measures can be defined and assessed with regard to their anticipated effect on air pollutant emissions. Also, the NO_2/NO_x emission ratio presents a constant increase in the course of the years, according to the respective NO_2/NO_x concentration ratio. Thus, from all the calculations carried out and the general decreasing trend of NO_2 levels in the GAA it can be concluded there is still place to decrease NO_2 levels with measures towards vehicles fleet renewal.

In 2009, passenger cars are the major polluters for CO, NMVOCs and CH_4 contributing with 59%, 51% and 54% respectively, whereas PM_{10} and NO_x are mostly associated with HDVs with a corresponding contribution of 66% and 65%. The major part of the above emissions is associated with older vehicles. At present, the GAA suffers from an old and polluting vehicles fleet. Old professional vehicles as HDVs represent 71% of the HDVs population whereas aged more than 15 years PCs, LDVs, buses and two-wheel vehicles correspond to a significant part of their population.

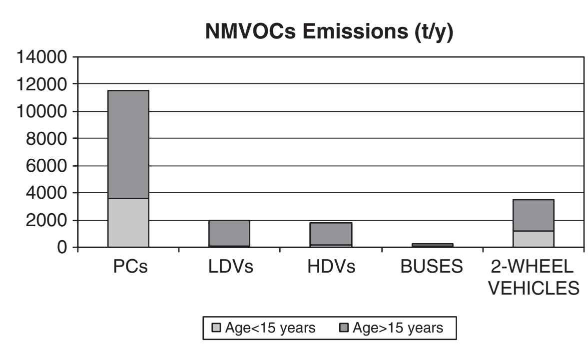

Fig. 9. NMVOCs emissions in the GAA for year 2009 for all vehicle categories according their age.

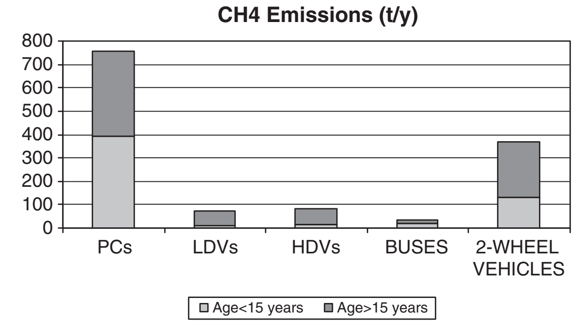

Fig. 10. Methane emissions in the GAA for year 2009 for all vehicle categories according their age.

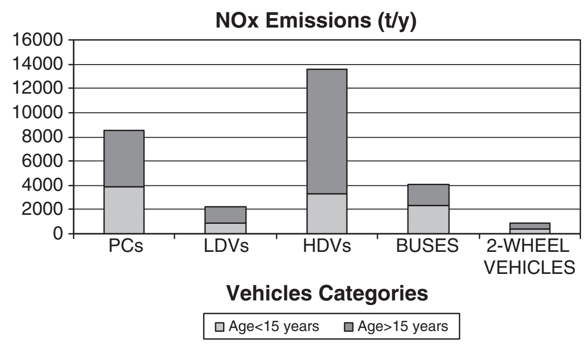

Fig. 11. Nitrogen oxides emissions in the GAA for year 2009 for all vehicle categories according their age.

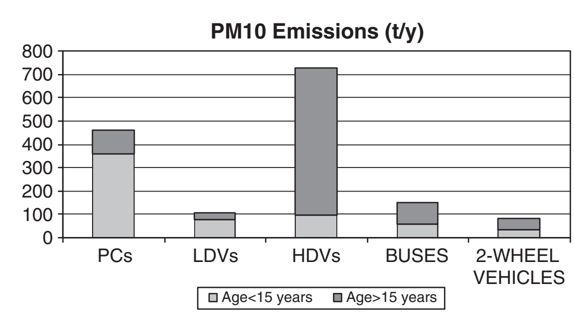

Fig. 12. Particulates emissions in the GAA for year 2009 for all vehicle categories according their age.

As shown from the results, the age of the vehicles and the corresponding engine technology determine the amount of the pollutants emitted. This was mainly observed in both passenger cars and heavy duty vehicles. Moreover, the correlation found out between air pollutant emissions and the corresponding air pollutant levels leads to the conclusion that an effective air pollution abatement strategy in terms of particulates and nitrogen dioxide should include circulation restriction measures or fleet renewal for older HDVs whereas PCs seem to be more implicated with hydrocarbons, and thus, ozone concentrations.

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