QUANTIFICATION AND EVALUATION OF DUST RESUSPENSION PM_{10} EMISSIONS IN TWO LARGE URBAN CENTERS IN GREECE

Markakis Konstantinos[1]

[1]Aristotle University of Thessaloniki, Laboratory of atmospheric physics, Thessaloniki, Greece

Abstract: In the last years resuspended dust is gaining more scientific attention as it is believed to be a significant source of particles. In many modeling studies exhaust-pipe emissions alone, are inadequate to explain the observed ambient concentrations values. In Greece, a country with PM_{10} concentrations well above the ambient threshold limits, resuspension could be the missing link between modeled and observed concentration levels. A quantification of dust resuspension emissions in the city of Thessaloniki was attempted based on real traffic counts and various statistical parameters and the influence of resuspended dust was investigated with the help of an emission model developed for this purpose. The results indicated that resuspension of dust emissions was several times more the exhaust part emissions. Moreover an evaluation method implemented in two measuring stations with different characteristics, showed a very good agreement with the ambient concentration measurements. As exhaust-pipe emissions are expected to go down during the next years due to the introduction of better engine technologies in the circulating fleet, non-exhaust sources are expected to raise due to the increased number of circulating vehicles.

Key words: *emissions, PM10, resuspension, Greece.*

1. INTRODUCTION

Pollutants emissions are a vital component in our effort to understand the impact of human activity on air quality, particularly in the large urban areas. Spatial and temporarily quantitative emission data are considered a fundamental parameter to air quality models which help to indentify local polluting sources and introduce abatement measures. While the performance of contemporary air quality models is considered satisfactory regarding the chemical and transport features of the gaseous pollutants and their precursors like ozone, CO, NOx and SO_2 they still present large uncertainties in the case of particulate matter. The chemical complexity of aerosols, including the interactions of particles with the atmospheric components as well as the driving mechanisms which control the processes of particle growth like nucleation are not yet fully understood. More importantly one major limitation is input emission data e.g. the emissions inventories. Important emission sources are often not included or are roughly estimated in air quality simulations. Resuspension of road dust is considered as one of these sources. The significance of the latter has been pointed out by many authors in the past (Jaecker-Voirol and Pelt, 2000; Samara et al., 2003). Harrison et al. (2008) suggests that resuspension maybe the missing link between modeled and observed PM_{10} concentrations in European level.

In Greece, particularly in the two largest urban agglomerations of Athens and Thessaloniki, restriction policies implemented in the last years reduced gaseous pollutants levels below the ambient EU thresholds with small exceptions, depending on location and time period. On the contrary, PM_{10} continues to present extensive exceedences in both Thessaloniki and Athens. 24 h averaged PM_{10} concentrations at four monitoring stations distributed through the greater Athens area reveal a substantially higher number of days, than the allowed frequency of 35 days per year, for which the concentrations exceeded the 50 $\mu g\ m^{-3}$ limit. Moreover, in the aforementioned stations, the annual mean concentrations are well above the threshold goal limit of 40 $\mu g\ m^{-3}$. The situation is even worse in the city of Thessaloniki where at an urban traffic monitoring station the 24 h concentration threshold is exceeded almost every day of the year ranking the city among the most polluted in Europe regarding PM_{10}.

2. MODEL DESCRIPTION

The model performs in 4 major steps. In the first step exhaust emissions of PM_{10}, CO and NOx are calculated with the bottom-up methodology. The input data for the bottom-up calculation are based on 24h traffic counts and vehicle speeds for 1910 road segments of the city of Thessaloniki. This approach can provide an insight of the spatial characteristics of traffic emissions in the city but it lacks to give information about the annual total emissions. For this, in the second step, emissions are calculated with the top-down approach. The input data for implementing the top-down approach consist of statistical data provided by local authorities and databases e.g. fuel consumption, circulating fleet (per vehicle type and engine technology). In the third step resuspension emissions are calculated based on the bottom-up data. Finally in the fourth step the bottom-up and top-down emissions are combined to provide gridded PM_{10}, CO and NOx emission fields for the city.

3. QUANTIFICATION OF EMISSIONS

The quantification of exhaust-pipe emissions with the bottom-up and the top-down methodologies was based on the latest revision of the EMEP/CORINAIR atmospheric emissions guidebook. The latest revision includes three major changes compared with the previous one. The first is the updated emission factors for the heavy vehicles (Heavy duty vehicles, Busses and Coaches) based on the new classification of the ARTEMIS project (Rigid, articulated as well as different class weights). The second one is the PM emission factors of gasoline powered vehicles (passenger cars, light duty vehicles and 2-wheelers). The third one is the emission factors for tire wear, break lining and road abrasion PM_{10} emissions.

The input data used for the two approaches are tabulated in Table 1. In order to provide quantified gridded emission fields for the reference year 2003 it was necessary to update the traffic counts. The latter were gathered under the framework of the EIST project (Emissions inventory system for transport) and it consists of traffic data for the year 1998 (Symeonidis et al., 2003). The traffic counts were considered to change according to the respective changes in the circulating fleet. Thus, fleet growth factors were established based on fleet data differences between the years 1998 and 2003. Traffic loads in the center of the city was excluded from this update as it is considered to be an already saturated area.

Table 1. Input data used for the calculation of traffic exhaust and non-exhaust emissions using bottom-up and top-down approaches.

Bottom-up	Top-down
Road segment length	Mileage driven per vehicle type and engine technology[b]
Emission factors: CORINAIR	Emission factors: CORINAIR[c]
Activity: Hourly traffic loads per road segment and vehicle type[a]	Activity: Vehicle fleet per vehicle type and engine technology[c]

a The hourly traffic counts were measured for passenger cars, light duty vehicles, heavy duty vehicles, busses and 2-wheelers. To split the vehicle types per engine technology fleet composition data were employed.
b Calculated from fuel consumption statistics (Symeonidis et al., 2003).
c Using as vehicle speed the value of 19 km/h corresponding to urban driving behavior.
d Vehicle fleet provided by AUTH/LAT.

The calculation of resuspended dust emissions was based on the bottom-up approach. For this an emission factor for resuspension was calculated (During et al., 2002) as follows:

$$EF_{resusp} = a \cdot k \cdot (sL)^{0.52} \cdot W^{2.14} \cdot [(1/0.85)\cdot(1-0.5\cdot r)] - EF_{exhaust} - EF_{tire\ wear} - EF_{break\ lining} - EF_{road\ abrasion} \quad (1)$$

where EF_{resusp} is the emission factor for resuspension (in g/km), a the correction factor for application in Germany (0.8 for "good" street surfaces and 2 for "bad" street surfaces), k the basic emission factor of US EPA=0.18 gkm^{-1}, sL the PM75 fraction of the silt load of the street gm^{-2} (0.2 gm^{-2} for "good" street surfaces and 0.4 gm^{-2} for "bad" street surfaces), W the mean weight of a vehicle of the fleet (in tn) and r the share of rainy days (precipitation >0.1 mm per day) during the year, for example r=0.3 for 122 days of rain per year.

As the original formula is an empirical formula based on street measurements naturally it includes all PM emission types (both exhaust and non-exhaust). Thus, from the contribution of each vehicle's type traffic counts in each road segment for every hour a mean emission factor for exhaust, tire wear, break lining and road abrasion was calculated (first step of the model). These factors were subsequently subtracted according to equation 2 to provide an emissions factor representing only resuspended dust. Clearly this emission factor is "road oriented" e.g. it depends on the characteristics of each road rather than the characteristics of only the vehicles type itself like the exhaust-pipe emission factor.

The W parameter was also calculated from the contribution of each vehicle's type traffic counts in each segment and the typical weights for individual vehicle types. The share of rainy days was calculated from climatic data and it was found to be 0.184 for Thessaloniki. The silt load factor sL and the correction factor a could not be chosen based on either former experience or scientific data oriented for Greece. Thus the parameters where chosen arbitrarily based on the assumption that the road network maintenance in Greece is rather poor (sL=0.3 gm^{-2} except from highways, sL=0.1 gm^{-2} for highways and a=1.5).

4. SPATIAL DISAGGREGATION OF EMISSIONS

The first two steps resulted in two different levels of information. For CO, NOx and PM_{10} (exhaust and abrasion) the annual totals for the city as well as a portion of the annual totals allocated in a number of streets (in which traffic loads were measured) were available. The following methodology was implemented to map road transport emissions. The line sources (bottom-up) annual emission totals were extracted from the annual area sources (top-down) emission totals and the residual was distributed to those road segments in which traffic loads were not available. As a base to split the residual was the already given distribution resulted from the bottom-up approach. This was done for every vehicle type.

For resuspension, the ratio of resuspension bottom-up emissions to exhaust-pipe bottom-up emissions was produced in each road segment. To provide the distribution of resuspension emissions of the remaining road network the same ratio was applied to the emissions of the neighboring road segments (residual emissions) within a radius of 500 m from the road. As a final step the emissions of every road were allocated to the final 500 m resolution grid.

5. RESULTS

The model was run for the year 2003, being the latest year with a complete dataset of measurements. The annual totals for all pollutants considered calculated with the bottom-up and the top-down approaches as summarized in Table 2.

Table 2. Annual totals (tn yr^{-1}) the city of Thessaloniki.

Pollutant	Bottom-up (tn)	Top-down (tn)	Bottom-up/Top-down	Other sources[a]
CO	3,607	54,939	7%	21,612
NOx	1,075	6,147	17%	3,539
PM10 (Exhaust/Abrasion)	29.7 / 25	303.7 / 188	10% / 13.3%	1,279

a provided by Markakis et al., 2008

The majority of CO originate from the gasoline powered vehicles while NOx and exhaust PM_{10} from the heavy duty vehicles. The former circulate primarily in the center of the city while the latter in the outer parts (entrances and the ring road).

6. EVALUATION OF RESUSPENDED DUST EMISSIONS

In order to provide some degree of understanding about how well the emission inventory represents the reality with and without resuspended dust, an evaluation methodology was implemented. The evaluation method presented in this study is based on the principle that ambient primary pollutant concentrations are mainly influenced by fresh emissions emitted in the vicinity of the ambient monitor. Upwind transport, carryover effects and chemical reactions can also influence ambient concentrations. The influence of these effects on the comparison is minimized (but not eliminated) by selecting monitoring sites located in areas with relatively high emission rates and by examining data collected when wind speeds and photochemical reaction rates are low. In order to reduce the effects of chemistry and the impact of winds, early morning time periods (06:00 – 09:00 LT) are the most appropriate when making ratios comparisons. Typically, during the early morning hours, emissions are high, wind speeds are light, atmospheric mixing depths are low while photochemical reactivity is minimized.

In this study the methodology presented in Mellios et al., 2006 was implemented. The methodology uses three ratios (CO/NOx, NOx/PM and PM/CO) to compare ambient measurements with the respective ratios of road traffic emissions. The authors use a number of conditions that have to be fulfilled in order to ensure that the concentrations captured by the measuring stations originate from close range (mostly road traffic) and from longer distances. They state that ideally the “triple product” (the 3 ratios multiplied) in the morning period should be one. In real world measurements unity is never reached due to a number of reasons. One could be the presence of non-exhaust dust.

In this study two major adjustments were made compared to the study of Mellios et al., 2006. First the emissions of the inventory used for the comparison are the product of a fine resolution grid (500 m) and not the total emissions of the city. The area used for the comparison is a 4 Km^2 area surrounding the station. The reason for the latter is the fact that the measuring station is representative e.g. it can capture the early morning emissions in a close distance, which in the case of Thessaloniki it was considered 2 Km. Secondly, not only road traffic emissions was used. Naturally, in the vicinity of the station (4 Km^2) all emitting sources can contribute to the final concentrations.

The application of the methodology in the station of Agia Sofia (urban station under heavy road traffic) in Thessaloniki for the year 2003 resulted in a value of 0.588 for the triple product. If this value indicates the presence of non-exhaust particles and it is not a product of local or temporal characteristics or measuring errors then in a non-urban station the value should be closer to unity. Indeed in the station of Kordelio where traffic is significantly reduced compared to the center the triple product was close to 0.8.

The results of the modeled and the ambient ratios are presented in Table 3 for the two stations under consideration.

If non-exhaust sources are excluded from the emission inventory the modeled ratios present significant deviations from the ambient ratios for both stations. NOx/PM ratio is almost 19 and 26 times more in the station of Ag.Sofia and Kordelio respectively compared to the ambient ones suggesting that a large source of particles (which would lower the ratio) is missing. This is also suggested by comparing the PM/CO ratio which in the case without the non-exhaust sources the value of the modeled ratio is more than one order of magnitude less than the ambient ratio. The NOx/PM and PM/CO ratio differences are so wide that it is unlikely to be attributed to the amounts of CO or NOx alone. The latter is not expected to be high at all since the annual totals originate from data like fleet composition and fuel consumption which are generally trustworthy. Indeed especially in the case of NOx if the discrepancy was attributed only to the overestimations of NOx emissions in our study the ambient ratio would not be reached even if we removed all road traffic NOx emissions.

Table 3. Annual totals (tn yr^{-1}) in Thessaloniki for the $4km^2$ area surrounding the stations and the ratios as calculated by the model and the ambient concentrations measurements.

Agias Sofias station							
Pollutant	Totals (tn)	Modeled ratios (only exhaust emissions)			ratio modelled / ratio measurements		
CO (road transport)	26,269	CO/NOx	NOx/PM_{10}	PM_{10}/CO	CO/NOx	NOX/PM_{10}	PM_{10}/CO
CO (other sources)	5,756	12.6	26.6	0.0028	1.2	18.9	0.07
NOx (road transport)	1,941	Modeled ratios (All PM sources)					
NOx (other sources)	842	CO/NOx	NOx/PM_{10}	PM_{10}/CO	CO/NOx	NOX/PM_{10}	PM_{10}/CO
PM_{10} (Exhaust only)	99	12.6	1.68	0.0473	1.2	1.2	1.18
PM_{10} (abrasion)	56	Ambient measurements ratios					
PM_{10} (resuspension)	1220	CO/NOx	NOx/PM_{10}	PM_{10}/CO			
PM_{10} (other sources)	281	10.5	1.4	0.04			
Kordelio station							
CO (road transport)	6,423	CO/NOx	NOx/PM_{10}	PM_{10}/CO	CO/NOx	NOX/PM_{10}	PM_{10}/CO
CO (other sources)	2,171	7.19	30.64	0.0045	1.165	25.7	0.043
NOx (road transport)	903	Modeled ratios (All PM sources)					
NOx (other sources)	292	CO/NOx	NOx/PM_{10}	PM_{10}/CO	CO/NOx	NOX/PM_{10}	PM_{10}/CO
PM_{10} (Exhaust only)	39	7.19	1.33	0.1043	1.165	1.115	1.004
PM_{10} (abrasion)	21.7	Ambient measurements ratios					
PM_{10} (resuspension)	704	CO/NOx	NOx/PM_{10}	PM_{10}/CO			
PM_{10} (other sources)	132	6.17	1.193	0.1039			

The results show that resuspension emissions are 12.3 and 18 times more than the exhaust emissions for the 4 km^2 surrounding the stations of Ag.Sofias and Kordelio respectively. The higher ratio in Kordelio is due to the fact that the station is close to the ring road where heavier vehicles are circulating. Heavier vehicles result in higher resuspension emissions. The comparison of the modeled and the ambient ratios, if non-exhaust sources are included, shows that the ratios are in a good agreement for Ag.Sofia while in the case of Kordelio the agreement is noticeably good. In Ag.Sofia the difference of CO/NOx ratio is 20%. In absolute numbers this could be due to overestimation of an amount of 2-3 ktn in CO or an underestimation of NOx in the order of 200-300 tn. For such kind of analyses the differences are within reasonable limits. The other two ratios in Ag.Sofias also present differences in the order of 20%.

7. CONCLUSIONS

In the city of Thessaloniki the concentrations of PM_{10} are well above the threshold limit values. The quantification and evaluations of emission sources other from the exhaust-pipe indicated that the latter cannot possibly explain the observed high concentrations. Resuspended dust, being a PM_{10} source several times above the exhaust emissions is most probably the source that is missing from contemporary emissions inventories, especially in the Mediterranean countries, which are considered to be more influenced by dust compared to the northern counties of Europe. In our study the evaluation method showed a good agreement with the ambient concentration measurements for two stations in the city of Thessaloniki with different characteristics.

Table 4. Annual totals (tn yr^{-1}) in Thessaloniki for the years 2003 and 2005.

Pollutant	2003	2005	Difference
CO	54939	51642	-6%
NOX	6147	6228	1%
PM_{10} (Exhaust)	303.7	288	-5%
PM_{10} (Abrasion)	188	200	6%
PM_{10} (Resuspension)	4613	4982	7%

If indeed resuspended dust is influential in such extend, it raises the question of what should be the nature of the abatement strategies implemented in a city like Thessaloniki. While exhaust emissions are expected to go down due to the introduction of better technologies in the circulating fleet, non-exhaust sources are expected to rise as they depend by the number of circulating vehicles, which in the case of Greece in the last decade raises with a constant rate. Using this rate for each vehicle type and engine technology, the model was run for the year 2005. The results presented in Table 4 indicate a constant or declining trend for exhaust emissions while non exhaust emissions a strong rising trend.

REFERENCES

ARTEMIS, 2006: Assessment and Reliability of Transport Emission Models and Inventory Systems, Research Project funded by the European Commission – Directorate General Transport and Energy. http://www.trl.co.uk/artemis/.

Düring, I, J. Jacob, A. Lohmeyer, M. Lutz and W. Reichenbächer, 200: Estimation of the "Non Exhaust Pipe" PM10 emissions of streets for practical traffic air pollution modelling. *Proceedings of the 11th International Symposium on Transport and Air Pollution*, Graz, Austria, 309-316.

European Environment Agency, 2007: EMEP/CORINAIR Emission Inventory Guidebook, Copenhagen, EEA *Technical Report* No. **16**.

Harrison, R., J. Stedman and D. Derwent, 2008: New directions: Why are PM_{10} concentrations in Europe not falling? *Atmospheric Environment,* **42**, 603-606.

Jaecker-Voirol, A. and P. Pelt, 2000: PM10 emission inventory in Ile de France for transport and industrial sources: PM10 re-suspension, a key factor for air quality. *Environmental modelling & software,* **15**, 575-581.

LAT/AUTH. Data have been obtained from the research project European Database of Vehicle Stock for the Calculation and Forecast of Pollutant and Greenhouse Gases Emissions with TREMOVE and COPERT funded by the European Commission DG Environment.

Markakis K., A. Poupkou, E. Katragkou and D. Melas, 2007: Compilation of an anthropogenic PM_{10} emission inventory for Greece and the two urban centres of Athens and Thessaloniki. *Geophysical Research Abstracts*, **9**, European Geophysical Union, General Assembly 16-20.04.2007, Vienna, Austria.

Mellios, G., R. van Aalst and Z. Samaras, 2006: Validation of road traffic urban emission inventories by means of concentration data measured at air quality monitoring stations in Europe. **40**, 7362-7377.

Samara, C, Th. Kouimtzis, R. Tsitouridou, G. Kanias and V. Simeonov, 2003: Chemical mass balance source apportionment of PM_{10} in an industrialised urban area of Northern Greece. *Atmospheric environment,* **37**, 41-54.

Symeonidis, P., I. Ziomas and A. Proyou, 2003: Emissions of air pollutants from the road transport sector in Greece: Year to Year Variation and Present Situation. *Environmental Technology,* **24**, 719-725.