Modelling the effects of traffic emissions on the air quality

G. Genon & E. Brizio
Turin Polytechnic, Italy

Abstract

European directives 1999/30/CE and 2000/69/CE set severe limits for ambient concentrations of sulphur dioxide, nitrogen dioxide, fine particles, lead, benzene and carbon monoxide; in particular, the concentrations of PM_{10} and nitrogen dioxide, measured in urban areas (even in towns of 20,000 inhabitants) of Northern Italy, often don't respect the air quality limits. The forementioned pollution levels are heavily determined by traffic emissions. In order to match the imposed limits, public administrations have to plan strong actions such as the restriction of car circulation; therefore, it is very important to have at their disposal a reliable instrument to model the effects of different traffic restriction policies on the air quality. In the present paper we modelled the effects of the traffic emissions on the air quality for two streets of a 50,000-inhabitant town in Piedmont, NW Italy, by means of different atmospheric dispersion models, the Industrial Source Complex 3 model (U.S. EPA), AERMOD (U.S. EPA) and the Operational Street Pollution Model (N.E.R.I., Denmark). We also had at our disposal measured concentrations for the pollutants CO and NO_x in the analysed streets, so we could validate the results. We obtained the best results by applying the OSPM model: the mean deviation from the measured concentrations of CO came out between 50 % and 80 %, according to the analysed period, while ISC3 and AERMOD results were 10–15 % worse. Consequently, the OSPM model has been applied to foresee air quality scenarios corresponding to different traffic restriction policies.

Keywords: traffic, emissions, street, OSPM, concentration.

1 Introduction

The pollution levels (in particular PM_{10} and NO_2) measured in Northern Italy are very high because of the low wind conditions of the Po Valley that don't help the dilution of the pollutants. Industrial emissions, civil heating and traffic are held the main responsible for this situation, but the last source is considered the worst one because of its emissive characteristics: as a matter of fact, vehicles emit smoke at the ground level so that pollutants can't be diluted as it happens, on the contrary, for the emissions from a chimney.

Regional laws require public administrations of the towns with more than 10.000 inhabitants to limit car circulation, to rationalize and improve urban transports. The present paper wants to be an example of how traffic emission and atmospheric dispersion modelling could be a support of this kind of traffic policies.

2 Data at disposal

The analysed site is Cuneo, a 50.000 inhabitants town in Southern Piedmont, NW Italy (see Figure 1); our simulations consider 2 streets, Via Roma and Corso Galileo Ferraris, having different orientation with respect to the prevalent wind directions and different physical configurations (width of the street, height of the surrounding buildings, continuity of the buildings, etc.).

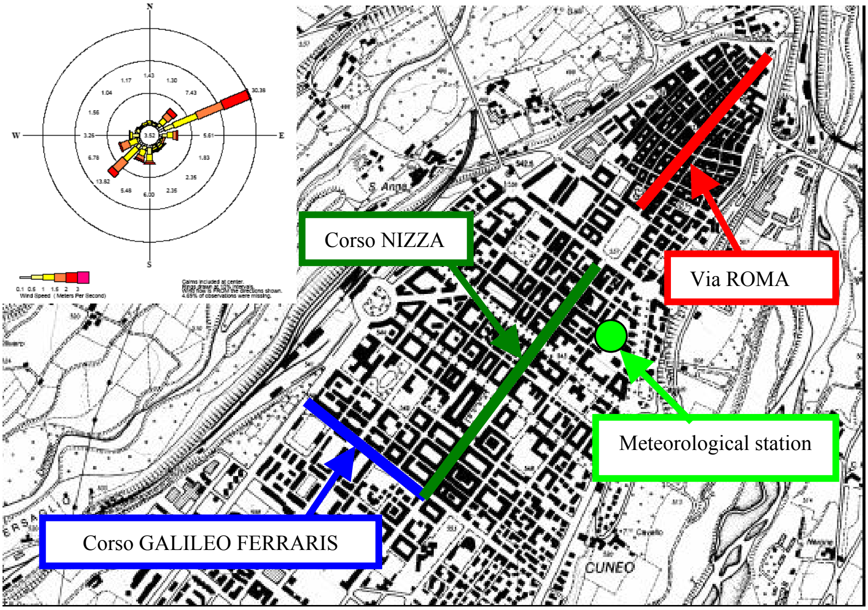

Figure 1: The analysed area (the wind rose is reported in the left corner).

We have at disposal the meteorological data measured by the regional station placed on the roof of the Chamber of Commerce: wind direction, wind speed, solar radiation and ambient temperature. In the analysed area, the winds have a typical bimodal behaviour around 40-60 degrees clockwise from the N: during the night the wind comes from N-E and in the night it blows towards N-E. The mean wind speed in the area is quite low, around 1,4 m/s, and there is a high percentage of calm hours (< 1 m/s), almost 30%.

As for the traffic data, magnetic counters provide continuous records of traffic flows divided into three length categories, 0-6 m (passengers car and motorcycles), 6,5-8 m (light duty vehicles) and 8,5-11,5 (typically buses). This way, in order to determine the composition of the vehicle park, we used the Automobile Club Italia data referring to the registered vehicles of the town in 2001 (see Table 1).

Table 1: Registered vehicles in Cuneo (2001).

	gasoline passenger cars	***diesel passenger cars***	***motorcycles***	***light and heavy duty vehicles***
< EURO I	11.480	1.143	3.091	1.802
EURO I	6.735	664	612	910
EURO II	7.850	3.551	-	806
EURO III	1.442	1.024	-	129
total	27.507	6.382	3.703	3.647

In order to assess the emissions of the measured traffic flows, we used the emission factors provided by the European model Copert3 (EEA, [1]): according to this methodology, the vehicle park can be divided into 105 categories depending on the typology, the fuel and the legislation class. The emission factors are speed-dependent functions and they can take into account the transient thermal engine operation (cold start) and the increase of the emissions due to the degradation of the catalytic converters with the mileage of the vehicles.

Finally, we have at disposal the concentrations of CO and NO_x measured during 4 monitoring campaigns carried out in Via Roma (23/27October-5 November 2003; 15/21 July 2004; 27/30 September 2004) and in Corso Galileo Ferraris (4/11 October 2004). On the basis of the measured traffic flows and the concentration of pollutants in the analysed street, we could validate the applied atmospheric dispersion modelling results for almost 540 hours, distributed in different seasons and different urban canyon configurations. In the present paper we considered carbon monoxide a good tracer for traffic emissions because it can be considered an inert compound on the time scale of the street canyon dispersion processes while nitrogen oxides undergo strong chemical reactions in atmosphere (NO_x can form ozone even at very short residence times); this way we found out the best model by simulating the concentrations of carbon monoxide and then we applied this model to other pollutants.

3 Atmospheric dispersion modelling

In order to simulate the effects of traffic emissions on the urban air quality we used three different atmospheric transport and dispersion models: the Industrial Source Complex Model 3rd version (ISC3) by U.S. EPA [2], the AERMOD model by U.S. EPA [3], and the Operational Street Pollution Model (N.E.R.I., Denmark, [4]); these models need to know some atmospheric turbulence parameters (the sensible heat flux, the friction velocity, the convective velocity scale, the Monin-Obukhov length, the mixing height and the stability classes) that have been determined on the basis of the land cover, the cloud cover and the solar radiation.

ISC3 and AERMOD have Gaussian plume formulation and are mainly applied to industrial point sources, area sources and linear sources placed in open space; as a matter of fact, they can't reconstruct the wind field that is produced by a street canyon.

AERMOD was born to replace ISC3 and it has been designed for the short-range simulations (distances from sources generally smaller than 50 km), both for simple and complex orography. AERMOD is a steady state plume model; when the boundary layer is stable (SBL), it assumes the concentration distribution to be Gaussian in both the vertical and the horizontal. On the other hand, in the convective boundary layer (CBL) the horizontal distribution is also assumed to be Gaussian but the vertical distribution is described with a bi-Gaussian.

On the contrary, OSPM has its main focus on the physical processes governing the dispersion of pollutants in urban streets: as a matter of fact, the most characteristic feature of the street canyon wind flow is the formation of a wind vortex so that the direction of the wind at street level is opposite to the flow above roof level (Berkowicz et al., [5]). OSPM calculates concentrations of exhaust gases using a combination of a plume model for the direct contribution and a box model for the recirculating part of the pollutants in the street (see Figure 2).

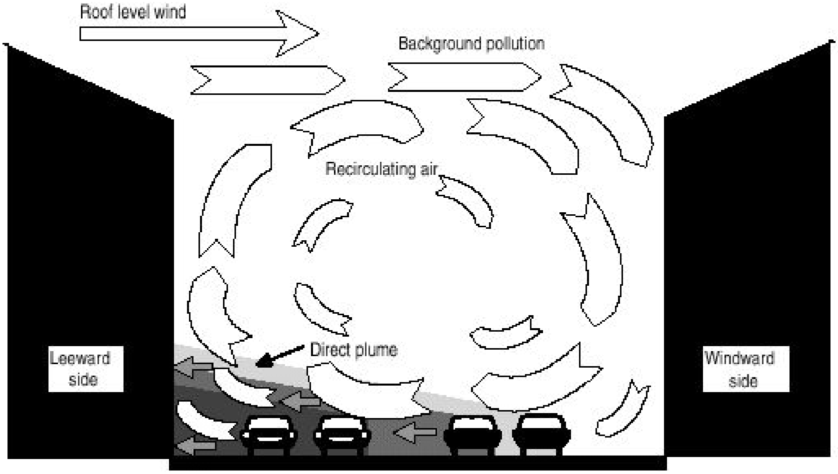

Figure 2: Conceptual scheme of the OSPM model.

The direct contribution (C_d) is calculated using a simple integral along the wind direction x, where W is the width of the street, u_b is the wind speed at the street level, Q is the emission in the street (g/m/s), N_{veh} is the number of cars passing the street per time unit, S^2 is the horizontal area occupied by a single car and V is the average vehicle speed.

$$Cd = \sqrt{\frac{2}{\pi}} \int \frac{1}{u_b} \cdot \frac{Q/W}{\left\{\left[(0{,}1 \cdot u_b)^2 + \left(0{,}09 \cdot N_{veh} \cdot V \cdot S^2 \cdot 1/W\right)\right]^{1/2} \cdot x/u_b + 2\right\}} dx$$

The recirculation part (C_{rec}) is calculated considering a simple box model which assumes that the canyon vortex has the shape of a trapeze and the inflow rate of pollutant is equal to the outflow rate through the top and side edges (see Figure 3), where u_t is the wind speed at the top of the canyon and σ_{wt} is the canyon ventilation velocity (depending on u_t and traffic induced turbulence σ_{wo}):

$$Crec = \frac{Q/W \cdot L_{rec}}{\sigma_{wt} \cdot L_t + u_t \cdot L_{s1} + u_b \cdot L_{s2}}$$

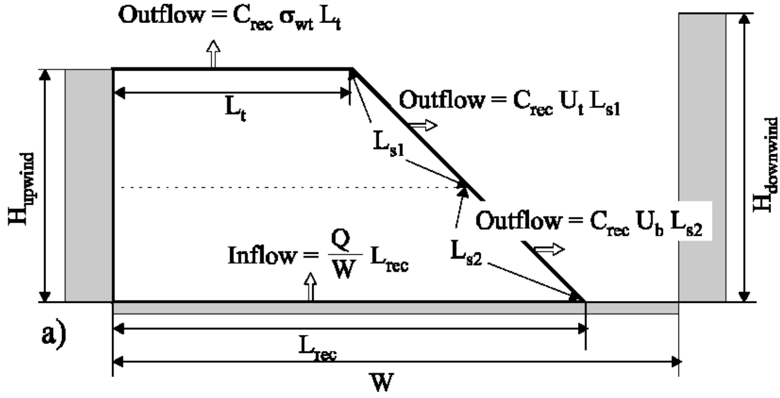

Figure 3: Geometry and features of the recirculation zone.

OSPM needs as input the vehicle list, the street configuration (width and orientation of the street, height and disposition of the surrounding buildings), the meteorological data (temperature, wind speed and direction, solar radiation, background concentrations), traffic flows and the average vehicle speed.

4 Results

In order to compare the results deriving from different atmospheric dispersion models with measured concentrations, the most reliable statistic parameter came out the mean deviation E, defined as follows:

$$E = \sum_{i=1}^{n} \frac{|Cm_i - Cc_i|}{n} \cdot \frac{1}{\overline{Cm}} \cdot 100$$

where Cm_i is the measured concentration of the ith hour, Cc_i is the calculated concentration, Cm is the mean measured concentration of the period.

As for the models ISC3 and AERMOD, we obtained good results by using area sources, whereas the volumetric sources configuration and the point sources one strongly underestimate the measured CO concentrations.

As for OSPM model, which has a formulation more suitable to the street canyon dispersion conditions, the results were from 10 to 15 % better than the ISC3 and AERMOD ones. Table 2 reports the statistic results achieved by using OSPM, both for CO and NO_x: the average vehicle speed, reported in the third column, represents a variable of the analysis.

Table 2: Statistic results of the OSPM simulations.

Period	Valid hours	Average vehicle speed (km/h)	CO Mean deviation E (%)	NO_x Mean deviation E (%)
Oct/Nov 2003	100	10	66,4	77,3
Jul 2004	98	30	50,9	85,3
Sep 2004	74	10	81,3	66,9
Oct 2004	267	25	57,8	84,2
		Mean values	64,1	80,9

Figure 4 reports the CO simulation outcome for the period October/November 2003, for which ISC3 and OSPM give almost the same statistic results.

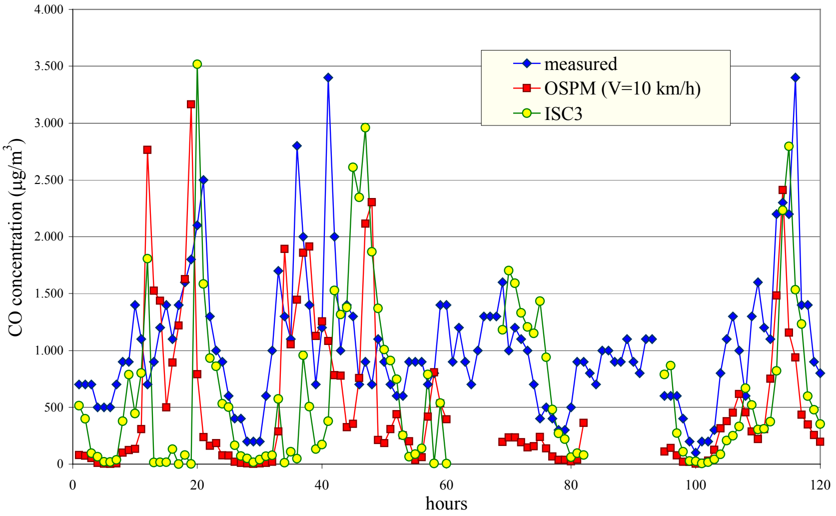

Figure 4: Measured and calculated CO concentrations for the period Oct/Nov 2003 in Via Roma.

As reported in Table 2, the period with the lowest mean deviation from the measured CO concentrations is July 2004; for this period, we tried to improve the results by simulating the effect of the stagnation of the pollutants emitted in the street canyon in the previous hours. This way, we assumed a larger hourly traffic flow depending on the mean number of vehicles circulating in the previous hours (we found the best agreement using 3 hours), the wind speed and the atmospheric stability class:

$$N = N_t + \alpha \cdot \overline{N_{t-1 \div t-3}} = N_t + k \cdot \frac{z}{u} \cdot \overline{N_{t-1 \div t-3}}$$

where N is the total number of vehicles, N_t is the number of the circulating vehicles in the t hour, $N_{t-1:t-3}$ is the mean number of vehicles passing in the 3 hours before the t hour, u is the wind speed, z is the expression of the atmospheric turbulence (z=6 during the night, z=1 during the day; these values are chosen on the basis of the ratio of different Pasquill-Gifford dispersion coefficients at a very local scale) and k is the numeric coefficient which varies from 0,01 and 0,6.

Moreover, for the same period, we considered a background concentration of 50 μg/m^3, that we obtained from the night hours without traffic.

We found very good results using a k value of 0,02 and adding the described background value; in this case, the mean deviation E become 42,7% and also the plot shows a very good agreement. Figure 5 reports the comparison of the measured data with the OSPM simulations, both with and without the effect of stagnation and background concentration.

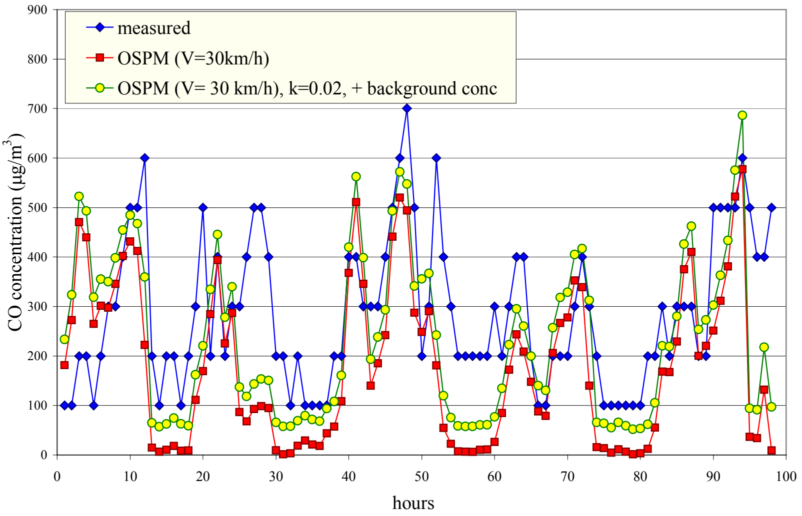

Figure 5: Measured and calculated CO concentrations for the period July 2004 in Via Roma.

On the basis of the described simulations, we carried out some statistic correlations between the measured and calculated CO concentrations, the mean deviation and the meteorological parameters. The relation between the deviation from the measured CO concentrations and the wind direction ("CO deviation vs. wind direction") came out to be the most interesting: as a matter of fact, for Via Roma the results are better (the deviations are lower) during the day, whereas Corso Galileo Ferraris shows the opposite behaviour. This way, we can observe that OSPM gives more reliable results when it calculates concentrations for the leeward side of the street canyon, that is during the day (when the wind comes from NE) for Via Roma and during the night (when the wind blows towards NE) for Corso Galileo Ferraris (see Figure 6).

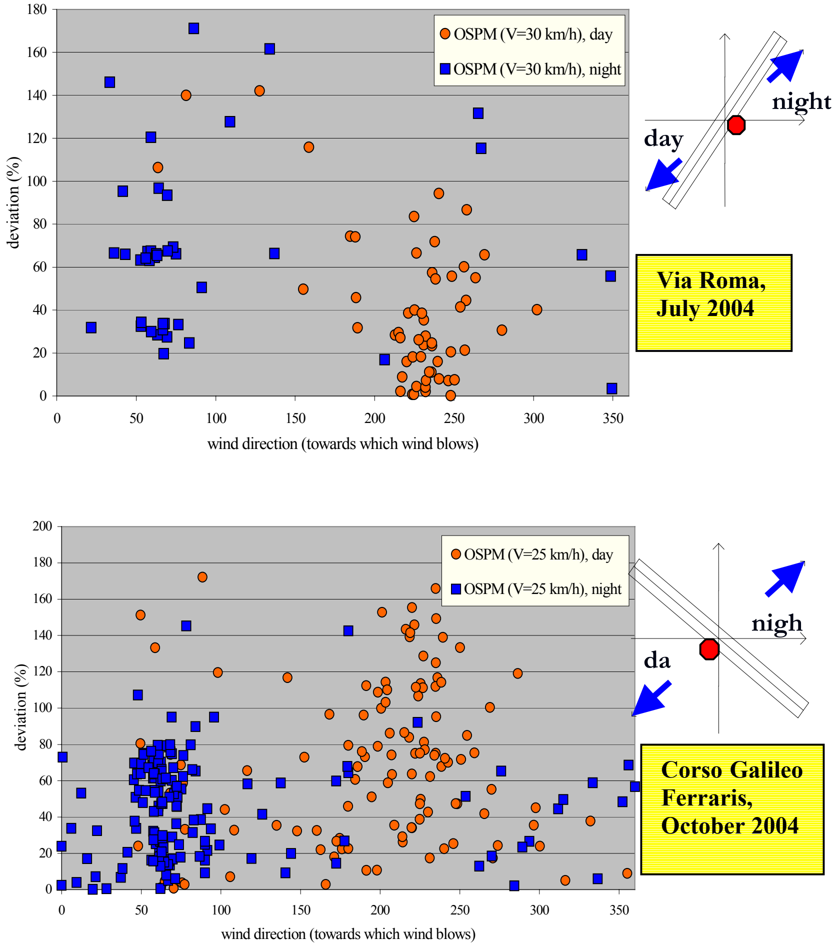

Figure 6: Correlation "CO deviation vs. wind direction", for Via Roma and Corso Galileo Ferraris (the street configuration is reported on the right).

The described behaviour of the OSPM model for Via Roma, due to the orientation of the street, is confirmed by the mean deviation E calculated over the 3 monitoring periods, taking into account only the day hours, which is smaller than 50%.

The present analysis shows that OSPM calculates reliable concentrations for both CO and NOx, in particular during the day hours if the investigated street has the same orientation than Via Roma. Based on this result, we applied OSPM to predict the effects of different traffic restriction policies on the air quality for Corso Nizza, a very important street of 4 lanes placed in the middle of the town like a backbone, with the same orientation than Via Roma. We assumed the following traffic scenarios:

1. actual traffic flow;
2. prohibition for vehicles not respecting the EURO I directive;
3. prohibition for vehicles not respecting the EURO II directive;
4. prohibition for vehicles not respecting the EURO III directive;
5. prohibition for gasoline vehicles not respecting the EURO I directive and for diesel vehicles not respecting the EURO III directive.

We simulated the effects of the described traffic scenarios both for nitrogen dioxide (NO_2) and fine particulates (PM_{10}), which are the most critical parameters for urban areas. The simulations have been carried out for 2 different meteorological conditions, the summer (15 July) and the late autumn (10 November). Figure 7 reports the results referring to the second condition (which is more significant because of the lower wind speed during the cold seasons) for the NO_x.

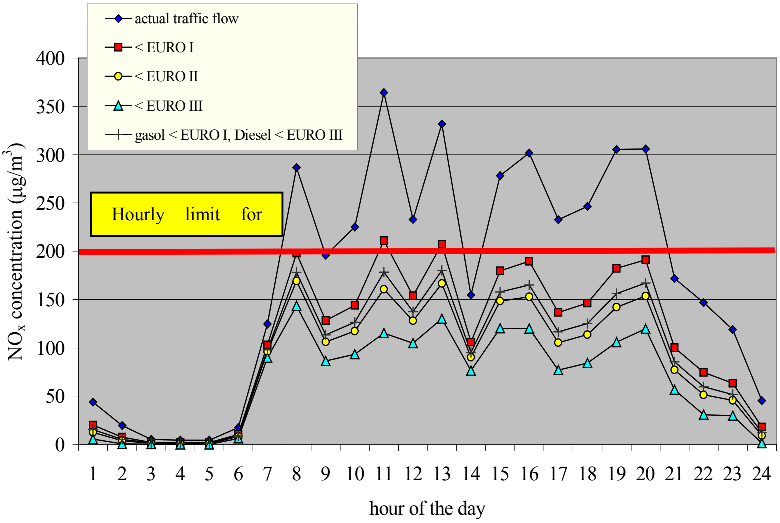

Figure 7: NO_x concentrations due to different traffic scenarios for Corso Nizza.

The reported plot shows a strong overcoming of the limit NO_x concentration for 11 hours of the analysed day. The traffic restriction policies can drive the pollutant concentrations below the law limit. The same kind of analysis can be carried out for the PM_{10}; we underline that, in this case, Copert3 emission factors refer only to the exhaust emissions from the diesel vehicles, while also gasoline, LPG vehicles and motorcycles emit particles; moreover, the non exhaust emissions of particles (due to wear and corrosion of road pavement and vehicle components like tyres and brakes) can be a part not negligible of the total PM_{10} emissions from traffic.

5 Conclusions

In the present paper we applied 3 different atmospheric dispersion models (ISC3, AERMOD and OSPM) in order to simulate the effects of traffic emissions on the urban air quality; then these results were compared with measured concentrations of CO and NO_x. The model OSPM, which has its main focus on the physical processes governing the pollution dispersion in street canyon, gave the best results: the mean deviation from the measured CO concentrations over the 4 monitoring campaigns (539 hours) came out 64,1%. If one considers the simulations for the day hours in Via Roma, the mean deviation over 3 campaigns (272 hours) was smaller than 50% and if the background concentration and the stagnation effect are taken into account the mean deviation for July 2004 become 42,7% and the plot shows a very good agreement with the measured data. This way, the OSPM model can be a reliable analytical instrument to predict the effects of different traffic restriction policies on the ambient air; based on the results of the simulation, one can choose the traffic scenario in order to respect the air quality limits. The traffic restriction policy can be determined by limiting either the circulation of certain classes of vehicles (influencing the quality of the vehicle park) or the number of vehicles per hour that can run along the street.

References

[1] Ntziachristos, L., Samaras, Z., *COPERT III Computer programme to calculate emissions from road transport*, European Environmental Agency, 2000.

[2] U.S. EPA, Office of Air Quality Planning and Standards, *User's guide for the Industrial Complex (ISC3) Dispersion Models – Volume I – User Instructions*, U.S. EPA, 1995.

[3] U.S. EPA, Office of Air Quality Planning and Standards, *Revised Draft user's guide for the AMS/EPA regulatory model AERMOD*, U.S. EPA, 2002.

[4] Berkowicz, R., Olesen, H., Jensen, S., *Operational Street Pollution Model, User's Guide to Win OSPM,* National Environmental Research Institute, Denmark, 2003.

[5] Berkowicz, R., Hertel, O., larsen, S., Nielsen, M., Sorensen, N., *Modelling traffic pollution in street,* Ministry of Environment and Energy / National Environmental Research Institute, Denmark, 1997.