16th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
8-11 September 2014, Varna, Bulgaria

URBAN MICRO-SCALE INVESTIGATION OF NO_X AND CO EMISSIONS FROM VEHICULAR TRAFFIC AND COMPARISON WITH AIR QUALITY DATA

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Abstract: A key issue for air pollution control is the source apportionment of pollutants in order to estimate the role of specific emission sources to air quality. In urban environments the simultaneous simulation of pollutant concentration fields due respectively to vehicular traffic and stack emissions is needed: in this study we test the micro-scale model suite Micro-Swift-Spray (ARIA INDUSTRY software packages) capability to simulate vehicular traffic emission dispersion through the comparison of the simulation results with air quality measurements. The study takes place within the urban area of Modena, a small town in the Northern Italy (central Po valley), nearby a very busy crossroad and where vehicular traffic is expected to be the main contributor to atmospheric pollutant concentrations. Micro-Swift-Spray simulates micro-scale atmospheric dispersion considering buildings effects and urban canopy. Local meteorological conditions are featured by frequent wind calms and thermal inversion leading to a poor dispersion of pollutants.
The simulations are focused on NO_x and CO emissions; NO_x is the most critical pollutant both for vehicular traffic and methane-fuelled plant emissions, while CO is quite non-reactive chemical specie that can be used for a more reliable comparison between simulated and measured data. Dispersion patterns are investigated on a daily meteorological scenario.
The simulation results show a good correlation with measured data, especially for CO concentrations, that remarks the reliability of Micro-Swift-Spray model as a simulation tool for air quality at urban micro-scale. A weaker correlation was found for NO_x, since atmospheric measured NO_x concentrations are affected by photochemical and chemical reactions that were not taken into account in the simulation.

Key words: *Micro-scale simulation, source apportionment, vehicular traffic emissions, measured concentration data.*

INTRODUCTION

Among the many applications of air quality models for assessment purposes, one of them is the investigation of the various contributions to air pollution due to different emission sources. Findings can be useful to support decision making process about policy strategies for urban air pollution control.
In previous works (Ghermandi *et al.*, 2013 and 2014) the atmospheric impact of NO_x emissions from a power plant stack was studied and discussed by simulating NO_x atmospheric dispersion both at local scale and urban micro-scale. Such plant will be installed in an urban residential area where also high atmospheric impacts due to vehicular traffic emissions are expected. Many datasets are available featuring atmospheric pollutant concentrations primarily affected by traffic emissions. Therefore, to simulate the atmospheric dispersion both from power plant stacks and vehicular traffic emissions, it is worthwhile to verify the compliance of the model simulations of pollutant dispersion from road traffic emissions with air quality data.
The aim of this paper is to test the Micro-Swift-Spray model capability to simulate the dispersion of vehicular traffic emissions: through this test activity some model parameters are optimized, i.e. time modulation pattern of traffic fluxes in Modena, mass flows of emissions according to local vehicle fleet composition and traffic induced turbulence height.
To compare simulation results with measured concentrations of atmospheric NO_x and CO in urban environment, a test simulation of NO_x and CO emissions from vehicular traffic is presented. Both simulation and air quality measurements are accomplished in an urban area very close to a very busy crossroad, where air quality is highly affected by vehicular traffic emissions. Moreover, since atmospheric NO_x is photochemically reactive and chemical reactions are not taken into account by the model, the comparison with air quality measurements was carried out even for CO, which can be

considered conservative (non-reactive) pollutant specie on a daily time scale (Schmitz, 2005; Zhou *et al*., 2008).
Concentration results for a typical workday are presented through spatial concentration maps and compared with air quality measurements of NO_x and CO concentrations in urban environment.
The atmospheric dispersion of NO_x and CO emissions are simulated using the software package ARIA INDUSTRY featuring the Lagrangian Particle Dispersion Model Spray (Tinarelli *et al.*, 1998).
Lagrangian Particle Dispersion Models are widely used in the literature to describe pollutant dispersion in complex atmospheric flows, mainly due to the urban canopy effects and convective atmospheric flows. In the present case the simulations are all accomplished with urban micro-scale model Micro-Swift-Spray (included in the ARIA INDUSTRY package), which is particularly suitable to operate in complex atmospheric condition due to urban canopy, calm wind conditions and thermal inversion events. Micro-Swift-Spray (Moussafir *et al.*, 2004, Tinarelli *et al.*, 2004) is a newer release of Spray code (Arianet, 2010) which has been developed specifically for micro-scale applications in urban environments, in order to take into account urban canopy effects. It consists of a mass-consistent diagnostic wind field model Micro-Swift (Aria Tech., 2010), which interpolates 3D air flows from meteorological observations at urban micro-scale according to building shape and geometry, and the Lagrangian Particle Dispersion Model Micro-Spray (Arianet, 2010) able to simulate dispersion patterns among buildings. The model considers non-homogeneous and non-stationary atmospheric turbulent conditions, plume rise effects (Anfossi *et al.*, 1993) and stochastic velocity fluctuations (Thomson, 1987).

CASE STUDY

The simulation domain deals with an urban crossroad where four roads with high vehicular fluxes converge. This crossroad is placed within the urban area of Modena, near a primary school and a shopping center. High density of vehicular fluxes is expected, according to traffic measurements, in the early morning (from 7:00 to 9:00) and in the late afternoon (from 17:00 to 19:00).
In Micro-Spray roads are modeled through linear segments where pollutant emission flows are specified per unit length. Pollutant emission flows for each road are computed by combining traffic measurements (number of vehicles) with a corresponding emission factor for each category of vehicles: cars, buses, light and heavy trucks. Emission factors are retrieved from the national emission inventory by the National Institute for Environmental Research and Protection (ISPRA, 2010), while traffic flow measurements were collected by the Environmental Service of the Municipality of Modena during periodical measurement campaigns.
Table 1 reports the total number of vehicles per hour (vehicular fluxes) at the early morning rush hour (from 7:00 to 8:00) for the four roads considered. Measures were collected on a typical workday in early spring, Wednesday 28th March 2007. Vehicles are divided into: cars, light duty vehicles, heavy duty vehicles and buses, according to the classification used also during the traffic flow measurement campaigns.

Table 1. Vehicular fluxes per hour for each road for a typical workday in early spring.

Road Nr. (figure 1, left)	Cars	Light duty vehicles	Heavy duty vehicles	Buses
1	1389	84	8	57
2	1633	121	17	53
3	1680	152	26	5
4	1422	83	15	9

$$MF_{i,j} = EF_{i,j} \cdot N_j \quad (1)$$

Mass flows of emissions are estimated according to Equation 1 (Finzi et al., 2000), where $MF_{i,j}$ is the hourly mass flow per road length unit (kg h^{-1} m^{-1}), $EF_{i,j}$ the emission factor, N_j the number of passing vehicles; the subscripts denote *i* the pollutant (NO_x and CO) and *j* the vehicle category.
Since the mass flows of emissions result quite different according to vehicle fleet composition, data for Modena have been derived from the Italian Automobile Club (ACI, 2007). Table 2 reports the resulting values for pollutant mass flow, expressed in $kg \cdot h^{-1} m^{-1}$, for each vehicle category and each pollutant specie according to the total number of passing vehicles between 7:00 and 8:00 (Table 1).

Table 2. NO_x and CO mass flows ($kg \cdot h^{-1}m^{-1}$) for each vehicle category and each road between 7:00 and 8:00.

Road Nr. (figure 1, left)	Cars		Light duty vehicles		Heavy duty vehicles		Buses	
	NO_x	CO	NO_x	CO	NO_x	CO	NO_x	CO
1	8.82E-04	7.62E-03	1.36E-04	7.05E-05	6.90E-05	2.04E-05	7.56E-04	2.22E-04
2	1.04E-03	8.96E-03	1.96E-04	1.02E-04	1.47E-04	4.35E-05	7.03E-04	2.06E-04
3	1.07E-03	9.21E-03	2.46E-04	1.28E-04	2.24E-04	6.65E-05	6.63E-05	1.94E-05
4	9.03E-04	7.80E-03	1.35E-04	6.97E-05	1.29E-04	3.83E-05	1.19E-04	3.50E-05

Figure 1 (left) shows map (UTM WGS 84), for the crossroad where the simulation is focused on. Each road that has been considered in the simulation is numbered from 1 to 4. An air quality monitoring station of the Local Environmental Protection Agency is located at the edge of road 1 and is reported in Figure 1 (Measuring site).

In order to modulate traffic emissions according to the hourly variation of traffic fluxes, two hourly modulation patterns (Figure 1, right) were taken into account in the simulation, for light and heavy vehicles respectively; light vehicles comprises cars and light duty vehicles while heavy vehicles comprises buses and heavy duty vehicles. The software package ARIA INDUSTRY contains several modulation patterns which can be chosen by model user according to traffic condition. The two curves shown in Figure 1, right, deal with the traffic trend of a typical workday and are calibrated using traffic measurements performed by Modena Municipality. For each vehicle category, the pattern consists of a time series of 24 hourly coefficients that identify the traffic intensity at each hour as a percentage of the traffic fluxes at a conventional hour (from 7:00 to 8:00); rush hours are clearly visible through the peaks of light vehicular fluxes at 8:00 and 18:00.

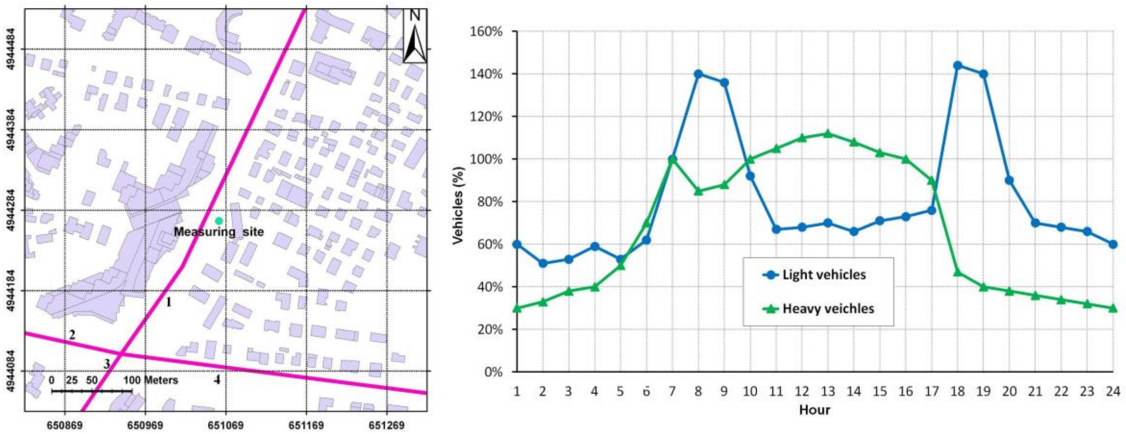

Figure 1. Left: simulation domain map (UTM WGS84): measuring station (E = 654 069 m, N = 4 944 284 m) and road sources (1, 2, 3, 4) for traffic emissions. Right: hourly modulation pattern for traffic intensity (light and heavy vehicles) in typical workday (in percent of the number of vehicles of the same category passing from 7:00 to 8:00).

MODEL SETUP AND METEOROLOGICAL DATA SET

The simulation domain is 500 m x 500 m large (Figure 1, left), centered at the Measuring Site and with a horizontal resolution of 2 m x 2 m. The vertical grid consists of 31 vertical layers, while the domain top is 10 m high above ground level and the first layer for concentration computing is 2 m high above ground. Building arrangement and road geometry were outlined from a high resolution 3D vectorial cartography of the studied domain (E. R., 2011).

A non-negligible effect on pollutant dispersion near roads is given by the traffic induced turbulence, i.e. the turbulent motion due to the passing vehicles. Such complex phenomenon mainly depends on traffic flow density, vehicle speed and aerodynamics. Hence traffic emissions are simulated as dispersed at a height above ground level computed according to Hertel and Berkowicz (1989), whose model takes into account vehicle average speed, vehicle front section geometry and the number of vehicles passing per time unit. According to the Hertel and Berkowicz model the range of traffic induced turbulence height in the studied case results between 1 - 2 meters above ground level, and this value has been used for Micro-Swift-Spray simulation.

The simulation period spans over some workdays, from Monday 26th to Wednesday 28th March 2007, chosen form 2007 meteorological dataset according to the availability of meteorological and simultaneous traffic measurements data. The results focus on 28th March 2007 average daily and hourly pollutant concentrations (as reported in the following section), nevertheless the simulation period starts some days before 28th March, in order to take into account the persistence in atmosphere of stable pollutants. The optimization of the simulation period is still under investigation.
Wind speed data used in the simulation have been sampled by a meteorological station within urban environment (ground observations by Osservatorio Geofisico of Modena and Reggio Emilia University); mixing height data derive from CALMET model simulations provided by the Local Environmental Protection Agency (Deserti *et al.*, 2001). Mean wind speed during the simulation period is 2.82 $m \cdot s^{-1}$, i.e. similar to the mean wind speed of 2.61 $m \cdot s^{-1}$ for spring 2007; given the typical wind conditions in the Po valley, the investigated day appears fairly favourable to pollutants dispersion.

RESULTS

Average daily concentration map in the first atmospheric layer is presented in Figure 2 both for NO_x and CO emissions from vehicular traffic (averaged values over 24 hours of simulation). The simulated emissions deal with the whole traffic fluxes for each vehicle category on Table 1 and with the whole set of roads converging in the crossroad (see Figure 1 left). It is worthwhile to underline that vehicular fluxes are assumed steady throughout road length, leading to a constant pollutant mass flow for the whole road length (see Table 2).

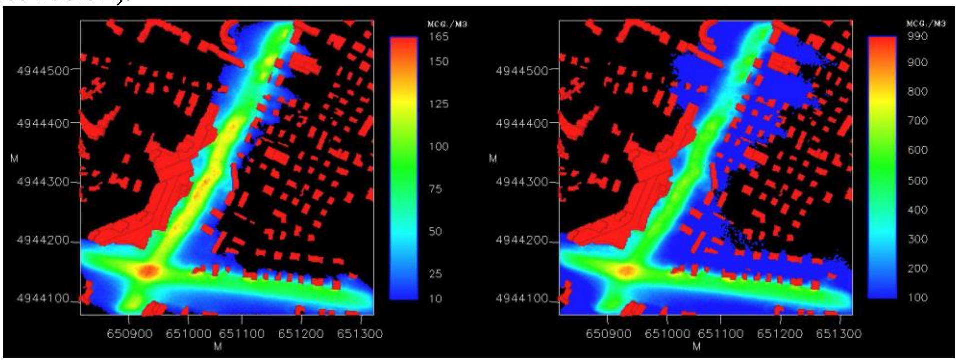

Figure 2. Average daily concentration map in the first atmospheric layer for NO_x (left) and CO (right) traffic emissions.

Maximum values for average daily concentrations are equal to 162 and 987 $\mu g \cdot m^{-3}$ for NO_x and CO emissions respectively. Pollutant concentration maps clearly show that pollutant concentrations peak along the road lines, but rapidly decreases away from the road. Exhaust emissions from vehicles occur very close to the ground level where wind speed is very low and, in urban areas, the presence of urban canopy strictly inhibits pollutant dispersion: therefore, pollutant concentration values at ground level are mainly controlled by pollutant emission rate, along with possible chemical reactions. On the contrary, when emissions by elevated sources are investigated (i.e. gas plumes from stacks), both meteorological conditions, gas exit velocity and stack height highly influence pollutant concentration at the ground (Ghermandi *et al.*, 2014).
Figure 3 shows the comparison among the simulated average hourly concentrations, extracted from 24 hourly concentration arrays at the position of the measuring site, and the observed hourly data at the measuring site (Figure 1, left) both for NO_x and CO. Simulated and measured data refer to the selected day, 28th March 2007.

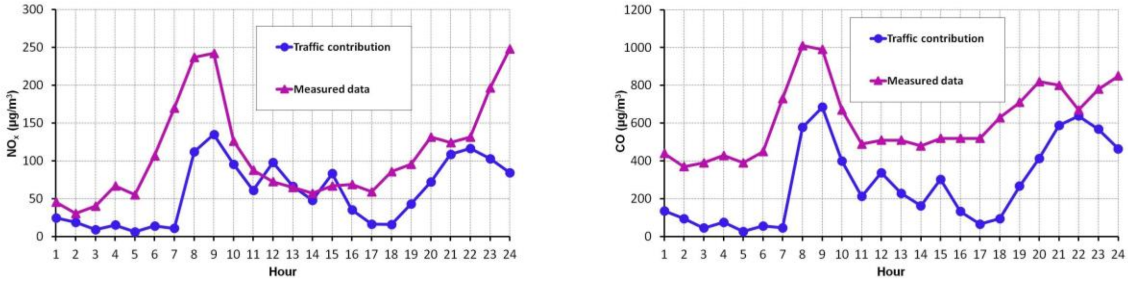

Figure 3. Daily patterns of hourly average simulated and measured concentrations for NO_x (left) and CO (right) at the measuring site. Data refer to 28th March 2007.

The trend of hourly measured and simulated concentration values are quite similar for CO and a good statistical correlation was found (Pearson's linear correlation coefficient $r = 0.80$) while the similarity is weaker for NO_x and the $r = 0.64$. The increase in traffic emissions during early morning rush hour is clearly visible both in measured and simulated concentration trends for CO, while is less remarkable for NO_x.

Moreover, the time matching between observed and simulated concentration peaks suggests a good reliability of hourly modulation pattern (Figure 1, right) in reproducing traffic fluctuations over the course of a typical workday.

The good correlation found for CO between measured and simulated concentrations is due both to the large contribution of vehicular traffic on CO emissions and to the chemical stability in urban environment; furthermore, the possible pollutant persistence in atmosphere was taken into account in the simulation, as previously mentioned. Hence Micro-Spray simulation results greatly match with experimental observations, even if, according to the 2007 emission inventory for the province of Modena edited by Local Environmental Protection Agency (ARPA E. R., 2010), the contribution of vehicular traffic is equal to 49.8 % of the whole CO emissions.

On the contrary, atmospheric NO_x is photolabile and undergoes several chemical reactions (Finlayson-Pitts et al., 2000), thus, although the contribution of vehicular traffic is equal to 72.3 % of the whole NO_x emissions (ARPA E.R. 2010), the correlation between observed and simulated NO_x concentrations results lower than for CO.

CONCLUSIONS

A numerical simulation of vehicular traffic emissions for NO_x and CO has been done in the urban district of Modena, central Po Valley, Northern Italy. The simulation was accomplished with Micro-Swift-Spray model that is a reliable air quality model suite widely used for urban micro-scale applications. The hourly average simulated concentrations have been compared with the hourly measured patterns for atmospheric NO_x and CO concentrations. The aim of the study was to test the reliability of calculated parameters needed for vehicular traffic simulations, especially mass flows of emissions, hourly modulation pattern for traffic fluxes and traffic induced turbulence effects, and also the suitability of pollutant emission factors from national inventory, through the correspondence between simulation outputs and air quality observations. Only dispersion of vehicular traffic emissions have been simulated and no chemical reaction is taken into account for the simulated pollutant species. Simulated concentrations show a good correlation with measured data for CO, a pollutant chemically stable in the atmosphere and largely emitted by vehicular traffic emissions. On the contrary a weaker correlation was found for NO_x concentrations, probably due to its highly reactivity in the atmosphere.

Main outlooks leading from these encouraging results are the reliable simulation of pollutant dispersion for vehicular traffic emissions and the source apportionment of specific emissions sources within an urban environment, i.e. traffic and power-plants mainly, and also industrial plants.

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