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Traffic induced air pollution modeling: scenario analysis for air quality management in street canyon

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Abstract

Mathematical models are intensively used in environmental science for various reasons – status quo assessment, statistical modeling, forecasting, and planning, scenario analysis. Traffic flow and related atmospheric pollution modeling is one of the most complex challenges because of various aspects, - wide versa of affecting factors, daily, diurnal, weekly, monthly and yearly variability and non-stability of them. In the present study atmospheric model OSPM (Operational Street Pollution Model) is used to calculate NO_x and PM_{10} concentration levels in the historical center (street canyon) of the city of Riga (Latvia) in order to make further assumptions (e.g., for the traffic load) for minimizing traffic induced air pollution in street canyons. In total five different scenarios were analyzed involving prioritizations of public transport, restrictions for old private cars or flow limitations in traffic jam situations during working days.

Keywords: OSPM; Air quality modelling; Air quality planning; Traffic

1. Introduction

Numerous studies have demonstrated various health effects associated with short-term and long-term exposure to atmospheric nitrogen oxides (NO_x) and particulate matter PM_{10} [1], but there are only several types of models that

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have been applied to assess and simulate concentrations of pollutants in urban areas: 1) land use regression models [2, 3]; 2) Gaussian dispersion models (AERMOD, CALPUFF), usually used for areas without obstacles or with obstacles of simple geometry [4, 5]; 3) Street-canyon models (OSPM, SIRANE), useful for cities with high buildings, simulating pollutant transfer along the street and intersections thus providing more accurate estimation of air pollution in dense urban areas compared to Gaussian dispersion models [6, 7]; and 4) Computational Fluid Dynamics models providing detailed representations of the atmospheric flow; they are limited to local applications such as the impact of a single pollution source in complex street geometry and flow characteristics [8].

Intensive traffic loaded streets are significant air pollution spots in urban areas; an urban street canyon is characterized by the presence of buildings on both sides of the street. The pollutant levels in urban streets are strongly affected by emissions taking place inside the street itself and concentration level and distribution of air pollution inside the street is maintained by surrounding physical conditions. Physical conditions heavily affect the wind speed and especially the wind direction inside the street [9, 10]. The classical example is the street vortex flow that governs pollutant distribution inside the street canyon. When wind flows are close to perpendicular to the street canyon a spiral or helical type flow develops within the canyon. Within the vortex flow relatively clean air from rooftop height is drawn down at the windward face of the street, across the road at street level, in the reverse of the wind direction at a rooftop, bringing pollutants in the road to a leeward face of the canyon [9]. The concentration inside the urban street canyon can be considered as a result of two contributions, one from emissions from local traffic in the street itself and one from background pollution entering the street canyon from above roof level.

2. Materials and methods

2.1. Study site

OSPM model was used to estimate NO_x and PM_{10} hourly concentrations in the street canyon of K. Valdemara Street (Riga, Latvia). This street canyon is busy and irregular as presented in Fig. 1. K. Valdemara Street has four lanes, it is 20 m wide and orientated south-west to north-east. Buildings on both sides are 25 m high, traffic flow is approximately 52 000 vehicles per day with a fraction of heavy vehicles about 2 - 5 %. Average traffic speed is around 30 - 40 km/h. Fig. 2. illustrates the diurnal variation of hourly average traffic flow for working days. Information on traffic flow, average road traffic speed, and vehicle fleet composition was obtained from local (Riga) municipality.

Street Geometry
Height (m): 25
Width (m): 20
Length 1 (m): 50
Length 2 (m): 50
Orientation (deg): 45
Street Name: Valdemara 18
Receptor Height (m): 2
☑ Receptor 1
☑ Receptor 2
☑ AutoRedraw

Fig. 1. Representation of study site: (a) Google Map photography; (b) description in OSPM model.

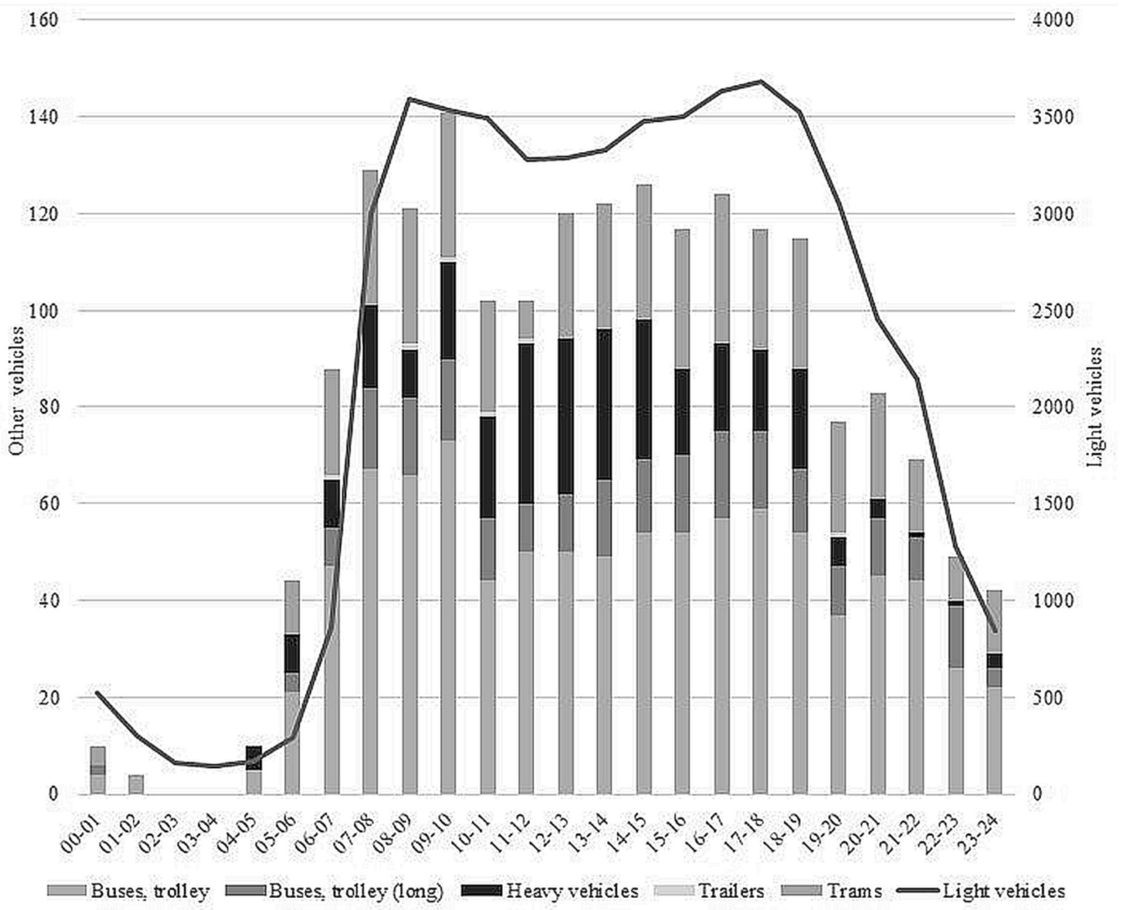

Fig. 2. Diurnal traffic flow in K. Valdemara Street during working day (April 21, 2010).

2.2. Model description

Air quality models calculate pollutant concentrations and deposition fluxes at various locations and times using mathematical equations describing the atmospheric transport processes and chemical and physical transformation processes between the points of emissions and the receptor location(s) [10]. For situations where the atmospheric dispersion of pollutants is constrained by obstacles such as buildings, noise-barriers or vegetation, parameterization based on the assumption of a well-mixed zone within the canyon can be used that is included in OSPM model [6].

OSPM is a model for vehicle induced urban street pollution. The model is designed to consider differences in atmospheric conditions and types of street. The main characteristics of OSPM are (model parameters are summarized in Table 1):

- Model consists of emissions calculated with COPERT IV [11] and a dispersion model running in series. To limit the scope of the present study the focus was on the parameters related to the dispersion model
- OSPM simulates resulting hourly average pollution concentrations of specific substances at the side of the street. That is calculated as a sum of direct contribution (C_{dir}) and recirculating contribution (C_{rec}) plus background concentration. The direct contribution is modeled using a simplified Gaussian plume model with a top hat distribution applied to the emission plume. The recirculating contribution is modeled using a trapezium-shaped box model [12, 13, 14]
- Wind direction, especially for low wind speeds, cannot be assumed as constant over a full hour. To account for this, a numerical wind direction averaging procedure is implemented in the model [15]

- The model also contains an algebraic expression for traffic produced turbulence. The expression depends on the number of cars in the street, their respective driving speeds and traffic composition [15]
- Most traffic pollutants are assumed to be inert on the time scale of the residence time in a street canyon

Table 1. Table of model parameters in model OSPM.

Parameter	Description
α	Slope of emission dispersion plume. Proportion between roof level wind speed and roof level vertical turbulence. Element of denominator in the calculation of chemical residence time.
c	Length of recirculation zone divided by the upwind building height for wind speeds higher than g.
L_t	Upper length of the recirculation trapezium divided by the length of the baseline.
d	Angle of integration in radians for wind speeds higher than i.
f_{roof}	Scale factor to reduce the wind speed from a meteorological mast to roof level.
h_0	Initial dispersion height in the wake of a car.
z_0	Aerodynamic roughness height used to relate roof level wind to street level wind in a logarithmic profile.
g	Wind speed where the recirculation zone reaches its full extent.
i	Upper limit for increased wind direction averaging.
j	Upper limit of interval for which the general building height is taken as the average.
H_{min}	Minimum general building height.
S_p	Aerodynamic frontal area of light duty vehicles.
S_t	Aerodynamic frontal area of heavy-duty vehicles.
g	Scale factor for traffic produced turbulence.
k	Scale factor to reduce the impact of traffic produced turbulence at the top of the street canyon. Element in the denominator in the calculation of chemical residence time.
γ	Scale factor for ground level wind speed reduction from parallel to perpendicular wind directions.

2.3. Model inputs

The concentration and meteorology input data come from the Latvian Environment, Geology and Meteorology Centre and Riga city council monitoring programme. In this programme hourly air quality measurements have been performed since 1993, complementary meteorological data was obtained for the same period. The intensity of traffic in the streets of Riga Centre largely determines the flow intensity on bridges. Feed daily records during the period 2001-2014 shows that up to the year 2009 as a whole flow distribution are unchanged: average 44% car crosses the Salu Bridge, 30%-26% Vansu Bridge and Akmens Bridge (last two of them closely connected to city centre).

2.4. Scenarios description

Based on a real (the year 2013) analysis several possible future traffic scenarios were elaborated. To examine these cases, it was assumed that the meteorological conditions, the geometrical configuration of the street, traffic load and vehicle technology were identical to the values of 2013. Following scenarios were estimated:

- SCEN1: restrictions for a light vehicle (private car) flow during working days from 7:00 AM to 7:00 PM
- SCEN2: restrictions for old cars, the movement is allowed for EURO5 or higher standard light cars
- SCEN3: light vehicle traffic is allowed only on holidays
- SCEN4: light vehicle traffic is reduced by 50 %, just two of four lines is scheduled for passenger vehicles
- SCEN5: light vehicle traffic is allowed only on holidays during winter, spring and autumn season, while during summer time no any restrictions are introduced

3. Results

Overall, modelling results were obtained for different traffic flows in typical cases; according to OSPM model guidelines, a total of 8 day-type cases were used where daily traffic flow hour-by-hour was described during working days and holidays in January-June and August-December, additionally, 4 different cases were created for July as the most popular summer holiday month.

The most effective scenario for PM_{10} and NO_x concentration decrease was identified as the second scenario (SCEN2: restrictions for old cars, movement is allowed for EURO5 or higher standard light cars), and according to results it could be expected that exhaust concentrations could decrease by 9 µg/m^3 for PM_{10} and 90 µg/m^3 for NO_x in average. Comparative representation of scenario results is shown in Fig. 3. and Fig. 4.

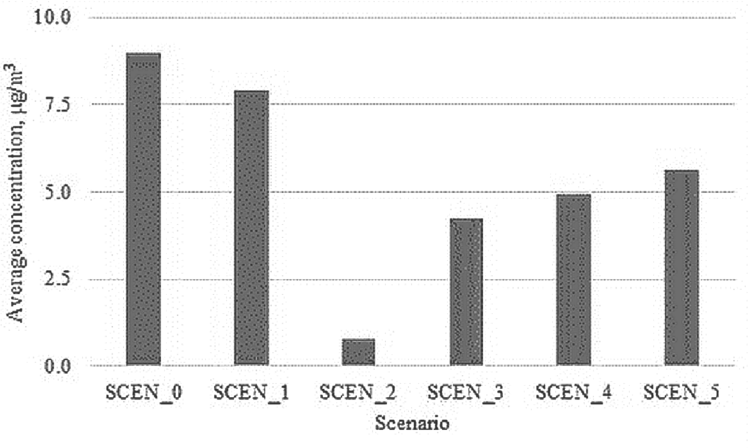

Fig. 3. Average modelled PM_{10} concentration at receptor height (2 m) in street canyon.

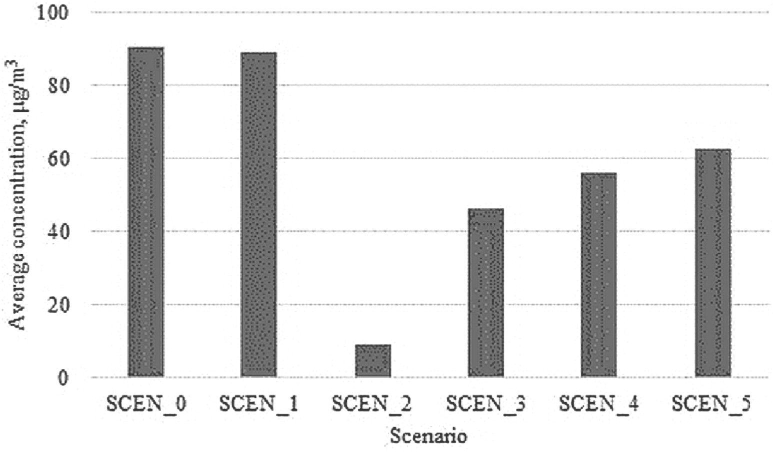

Fig. 4. Average modelled NO_x concentration at receptor height (2 m) in street canyon.

4. Conclusion

In this study, the OSPM scenario analysis methodology was used to predict pollutant levels in Riga city, thereby NO_x and PM_{10} concentration levels in the street canyon were calculated for the zero scenario (real situation) and for five different possible development scenarios in order to introduce restrictions for traffic flow regimes. Main conclusions are:

- Traffic flow structural analysis show prevalence of light vehicles reaching at least 96-98 % of total flow and 72 % of these vehicles are 11 years old corresponding to EURO3 class
- Analysis of PM_{10} and NO_x concentration variations show substantial weekly differences; as most polluted days were identified Wednesdays and Thursdays, while during holidays pollution levels are much lower; in case of PM_{10} concentration differences reach 12 $\mu g/m^3$, but in case of NO_x even 48 $\mu g/m^3$ in average
- Modelling results show that one of the most effective scenarios could be the scenario with restrictions for old cars when movement is allowed for EURO5 or higher standard light (passenger) cars; in this case effect for several cases could reach 9 $\mu g/m^3$ for PM_{10} and 90 $\mu g/m^3$ for NO_x in average. As a less effective was identified the scenario with restrictions for a light vehicle (private car) flow during working days from 7:00 AM to 7:00 PM

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