MODELLING OF AVERAGE EXHAUST POLLUTANT EMISSION INTENSITY ON A ROAD

Lucyna Brzozowska, Krzysztof Brzozowski

University of Bielsko-Biała
Willowa 2, 43-309 Bielsko-Biała
tel.: +48 33 8279289, fax: +48 33 8279289
e-mail: kbrzozowski@ath.eu

Abstract

Traffic is a major source of pollutant emission in cities. In order to evaluate the air quality in urban areas it is necessary to use appropriate traffic flow and exhaust emission models. In air quality studies, the common approach of constant average emission intensity is used for describing emission along a whole road i.e. one road – one linear source. This approach can not be used in case of analysing local air pollution caused by traffic on roads between intersections and on roads with input or outputs.

In the paper a method of dividing road on several segments is presented. Each segment represents linear source of emission. The method enables modelling of exhaust pollutant emission intensity taking into account its local changes. The average speed of traffic flow and density of vehicles is obtained from microscopic traffic flow model. Next, average exhaust pollutant emission intensity is calculated using the average emission factor method (European models COPERT or INFRAS can be applied). Some calculation results are presented in the paper as well. The algorithm of dividing road on segments using microscopic traffic flow model presented in the paper is a solution which enables more precisely identification of regions in which the exhaust emission is high and the permissible concentration of vehicle exhaust pollutant can be exceed.

Keywords: transport, modelling, traffic, exhaust emission, calculation of exhaust emission

1. Introduction

In many countries, in Poland too, there have been considerable problems in urban areas to maintain the air quality in a satisfactory state. The rapid development of particularly individual transport has resulted in very busy roads, with traffic intensity exceeding several thousand vehicle per hour on main roads. The increase of vehicles on the roads has caused excessive congestion and simultaneously the concentration of exhaust pollutants in many cities had exceeded permissible levels given by EU and WHO. As had been reported in [10], almost 30% urban inhabitants in Europe lives in zones where permissible levels of NO_x and ozone have been exceeded.

The total quantity of vehicle exhaust pollutants emitted in urban areas is closely connected to the density of traffic, technological efficiency of vehicles, quality of fuel, and quality of road network and road surface. Essential criteria are also the number of intersections, waiting time at traffic lights, and situation and volume of parking spaces.

Therefore, exhaust emission of harmful substances as results of combustion process and pollutants formed into atmosphere as a result of chemical reactions can be only limited by using effective organisation of road infrastructure and management of traffic in urban areas.

Calculation of exhaust emission using traffic flow and emission models makes the base of knowledge for any air quality activities. Traffic flow models are using in order to describe traffic conditions i.e. traffic density, average speed and other input parameters to the emission models. Computational simulations with traffic flow models enable testing of new traffic scenario as a result of changes in traffic organisation. In connection with computational modelling of exhaust emission, local authorities can analyse effectiveness of new solution regarding minimisation the influence of traffic on air quality in selected areas. The paper presents a method using both traffic flow and emission model for calculation of average exhaust pollutant emission intensity.

2. The emission model

In general, existing emission models can be classified according to different criteria such as: structure of the model, spatial scale in which the model is used, input data, purpose of the model etc.[1]. Emission models are generally constructed for certain categories of vehicles and not for individual vehicles; categories are made up of vehicles whose emissions are similar. The criteria for classification of vehicles in various categories in European models are the following: purpose of the vehicle (PC, LDV, HDV, Bus etc.), generally accepted vehicle size (defined by: engine capacity for PCs and LDVs, vehicle mass for HDVs and Buses), engine type (SI, CI) and technical level regarding ecological properties (ECE emission legislation) [2, 5, 12, 17].

Existing emission models according to structure of the model can be classified as follows [1]:
- aggregated models,
- average speed models,
- traffic situation models,
- regression models,
- modal models.

Analysis of the emission models leads to the conclusion that two basic methods are used. Those methods differ in relation between emission and parameters describing vehicle operation [14, 18]:
- instantaneous emission method applied in modal models,
- average emission factor method applied in other models.

Among existing emission models, those based on the average emission factor method are often used in many studies which concern modelling of exhaust emission for real traffic. The main reason of that is the database of emission factor which is available for many different vehicle categories. Therefore, also in air quality studies, models applied the average emission factor method are commonly using for predicting air quality [3].

In the method presented here the average speed model has been used. Emission factors were obtained from dynamic characteristics with the method presented in paper [4]. In this type of emission model average speed is the only decisive parameter used in estimating emission values for a given category of vehicles, i.e. average emission factor is presented as a function of average speed. The course of the average emission factor as a function of speed is quite similar for different categories of vehicles and exhaust pollutants but differs in terms of absolute values. Highest emission values are observed for both: low and high average speeds. The high emission value in the range of low average speeds results from the high dynamics of such motion. In the range of medium speed values the emission value is lowest. However, in the range of high speeds, it rises because of the large load and engine speed. More detailed analysis can be found in papers [6, 8, 11, 13, 15, 17].

3. Calculation of exhaust emission

In order to make an appropriate modelling of exhaust emission on a road using the average emission factors one should know density of vehicles, average speed in certain time period and length of queue of vehicles in front of signalised intersection. In case of modelling air quality for existing road these parameters can be measured experimentally. However, in prognostic studies these parameters can be achieved only from traffic simulation. The traffic flow models provide information about dynamic behaviour of traffic flow which is a crucial factor determining exhaust emission on road, especially on road with signalised intersections.

Dynamic behaviour of traffic flow can be taken into account directly in air quality modelling using emission models which based on instantaneous emission method or indirectly if model based on average emission factor method is applied. In the second case, it is necessary to use an

additional algorithm of dividing road on segments allowing spatial averaging of computational results. The algorithm is presented later.

Total amount of emission in time period $\langle 0, T^{max} \rangle$ on road with length X divided on n-th segments, is calculated from the form:

$$\bar{\varepsilon} = \int\limits_0^{T^{max}} \sum_{i=1}^{n} \Delta x_i \varepsilon_i(t) dt , \tag{1}$$

where:

Δx_i - length of the i-th segment,

$\varepsilon_i(t)$ - average exhaust emission intensity per distance unit for i-th segment, calculated as

$$\varepsilon_i(t) = \sum_{j=1}^{m} q_i \delta_j b_j (v_{s,i}), \tag{2}$$

where:

q_i - traffic intensity on i-th segment,

δ_j - fraction of j-th vehicle category in traffic,

$b_j(v_{s,i})$ - average emission factor for j-th vehicle category in dependency on traffic average speed

        $v_{s,i}$ on i-th segment,

m - number of vehicle categories in traffic.

In order to calculate emission from equation (2) simulation of traffic flow has to be averaged over given time period in order to calculate representative for each segment values of q_i and $v_{s,i}$. The time period depends on analysed spatial and time scale e.g. for spatial meso-scale air quality study it has to be 15 minutes [3].

3.1. Microscopic traffic flow model

There are several types of traffic flow models. The classification of the models with respect to their resolution allows to distinguish microscopic, macroscopic and mesoscopic models. Microscopic traffic flow models regard single vehicles as atomic parts in contrary to macroscopic models which are based on equations for averaged quantities like vehicle density and average flux. So, the macroscopic models describe the whole traffic flow. The third type of models - mesoscopic can be treated as a bridge between micro and macro approach i.e. in mesoscopic models individual vehicles are moved according to dynamic laws that are governed by macroscopic quantities.

In urban areas, for signalised traffic flow the microscopic traffic flow models are often used. On a microscopic scale, two types of motion of vehicles can be considered. The first type is the free motion of a vehicle, the second is the motion of a vehicle while interaction with another vehicle takes place. Such models may be discrete in time and space or only discrete in time. Because we are interested in modelling exhaust pollutant emission intensity on a road (more precisely along the road), the model can not be discrete in space. Therefore, the car-following type model is used in order to describe the dynamics of each individual vehicle as a function of the positions and velocities of the neighbouring vehicles. These models are generally quite complex and contain a number of free parameters. As was shown in [9], for emission calculation purposes the Krauss model is the optimal one.

The Krauss model allows describing main features of traffic like free and congested flow. In each time step the speed of vehicle is adapted to the speed of the leading vehicle in a way that yields to collision-free system behaviour within the following simulation steps [16]. If we consider

two vehicles, leading vehicle A and following vehicle B (Fig. 1), speed of vehicle B in time $i\Delta t$ is given as maximum from two values:

$$v_B^{(i)} = \max\{0, v_B^{(i-1)} - \eta\},$$ (3)

where:

η - perturbation of desired speed $v_B^{zad,(i-1)}$, with value from range $\langle v_B^{zad,(i-1)} - \varepsilon\,\Delta t\,a_B^{p,\max}, v_B^{zad,(i-1)} \rangle$,

$a_B^{p,\max}\left(v_B^{(i-1)}\right)$ - function of maximum acceleration of vehicle B in dependency on speed of vehicle

B $v_B^{(i-1)}$ in time step i-1,

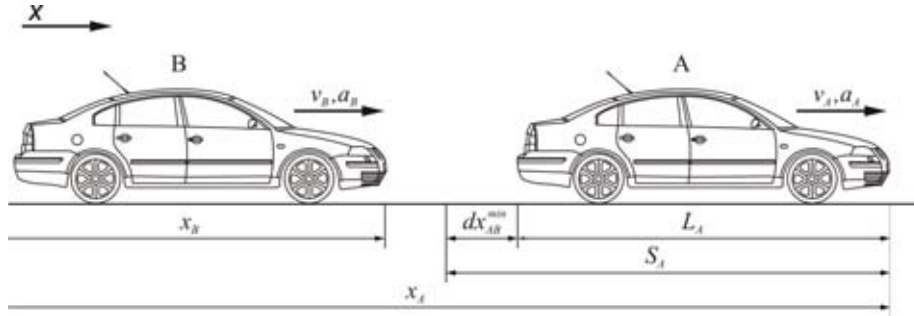ε - a random number from range $\langle 0\,;1 \rangle$.

Fig. 1. The leading vehicle A and the following vehicle B during motion

The desired speed is computed as the minimum of the vehicle's possible maximum speed, the vehicle's speed plus the maximum acceleration and the safe speed, i.e.:

$$v_B^{zad,(i-1)} = \min\{v_B^{bez,(i-1)}, v_B^{(i-1)} + a_B^{p,\max}\left(v_B^{(i-1)}\right)\Delta t, v_B^{\max}\},$$ (4)

where:

$v_B^{bez,(i-1)}$ - the safe velocity of vehicle B ,

$v_B^{\max}$ - allowing maximum speed of vehicle B.

The safe speed of vehicle B in time $(i-1)\Delta t$ of simulation is computed from equation [16]:

$$v_B^{bez,(i-1)} = v_A^{(i-1)} + \frac{dx_{AB}^{(i-1)} - d_A^{(i-1)}}{t_{AB}^{o,(i-1)} + T_B},$$ (5)

where:

$v_A^{(i-1)}$ - speed of the leading vehicle in time step i-1,

T_B - the driver reaction time of vehicle B,

$dx_{AB}^{(i-1)} = x_A^{(i-1)} - S_A - x_B^{(i-1)}$ - distance to leading vehicle A in time step i-1,

$S_A = L_A + dx_{AB}^{\min}$ - the effective length of leading vehicle A, L_A is length of leading vehicle A and

$dx_{AB}^{\min}$ is minimal distance between vehicles,

$d_A^{(i-1)} = v_A^{(i-1)} T_B$ - desired distance moved by leading vehicle A during T_B for time step i-1,

$t_{AB}^{o,(i-1)} = \bar{v}_{AB}^{(i-1)} / a_B^{o,\max}(\bar{v}_{AB}^{(i-1)})$ - the time of deceleration from $\bar{v}_{AB}^{(i-1)}$ to 0 taking into account

deceleration function $a_B^{o,\max}\left(\bar{v}_{AB}^{(i-1)}\right)$ in time step i-1,

$\bar{v}_{AB}^{(i-1)} = \left(v_A^{(i-1)} + v_B^{(i-1)}\right)/2$ - the average speed of vehicles A and B in time step i-1.

Simulation of traffic flow by using the Krauss model is possible after choosing the values of model parameters $a_B^{p,\max}$ and $v_B^{\max}$. Values of these parameters have to be properly estimated in

case of using traffic flow model in solving task of exhaust emission estimation. Beside dependency of these values for any vehicle category on engine and mass of vehicle, these values depend on: road gradient, weather conditions, additional mass or road surface.

As was shown in [3] estimation of $a_B^{p,max}$ and v_B^{max} with taking into account conditions mentioned above, provide to more realistic simulation of traffic dynamics and in consequence to better estimation of exhaust emission. A methodology which can be used for estimation the model parameters is presented in [9].

3.2. The algorithm of dividing road on segments

In this section a method of dividing road on several segments is presented. Each segment represents linear source of emission. The method enables modelling of emission intensity with taking into account its local changes due to dynamic behaviour of the traffic. The algorithm with four basic steps is presented below.

1° Let consider road with length X and its division on $i = 1,..,n$ -th segments with length Δx_i, as presented in Fig. 2.
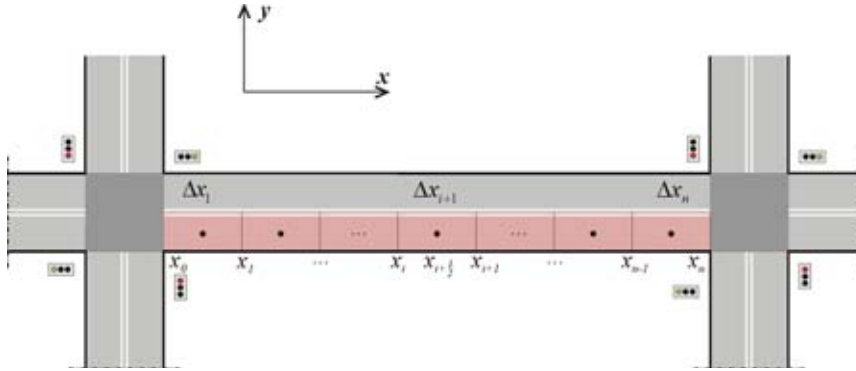

Fig. 2. Descriptions used in the algorithm of dividing road on n-th segments

2° Next, choose the length of time period $\langle \tau, T \rangle$ for averaging results from traffic flow model and simulate the traffic on considered road with 1 Hz frequency for saving changes in traffic density $\bar{k}_i(t)$ and average speed of vehicles $\bar{v}_i(t)$ for each road segment, i.e for $i = 1..n$: are calculated:

$$\bar{k}_i(t) = \frac{L_i}{\Delta x_i} , \tag{6.1}$$

$$\bar{v}_i(t) = \frac{\sum_{j=1}^{L_i} v_i^{(j)}}{L_i} , \tag{6.2}$$

where:
$\bar{k}_i$ - density of vehicles in i -th segment,

L_i - number of vehicles in i -th segment,

$\bar{v}_i$ - average speed of vehicles in i -th segment,

$v_i^{(j)}$ - speed of vehicle belonged to j category in i -th segment.

3° In this step, for each road segment time average density and time average speed are calculated for time period $\langle \tau, T \rangle$:

$$k_{s,x_{i-\frac{1}{2}}} = \frac{\int_{\tau}^{T} \overline{k}_i(t)dt}{T-\tau}, \qquad (7.1)$$

$$v_{s,x_{i-\frac{1}{2}}} = \frac{\int_{\tau}^{T} \overline{v}_i(t)dt}{T-\tau}, \qquad (7.2)$$

and, using calculated values of time average density and time average speed for all segments, the average traffic flow in each segment is calculated:

$$q_i = k_{s,x_{i-\frac{1}{2}}} \cdot v_{s,x_{i-\frac{1}{2}}}. \qquad (8)$$

4° Finally, the time average speed from (7.2) and the time average traffic flow (8) are used in equation (2) in order to calculate the average exhaust emission intensity for a linear source representing each segment during the $\langle \tau, T \rangle$ time period.

4. Results of calculations

In this chapter some results of simulations using the above algorithm of dividing road on segments are presented. In all cases considered, one way traffic flow on single-line road between two signalised intersections is modelling with the parameterised Krauss model. The traffic structure is considered as uniform i.e. only one vehicle category is used. The length of the time period for averaging results and modelling the average exhaust emission intensity is equal to 15 minutes. The dynamic behaviour of traffic is determined by traffic signals on the inlet and outlet intersections. In Tab. 1 are presented the parameters of simulations which are constant for all cases.

Tab. 1. The main parameters which are constant in all cases considered

Parameter		Value
X	Road length [m]	1000
q	Traffic flow on the inlet [veh./h]	1000
δ	Vehicle category	PC with SI engine (EURO 1)
v_{max}	Allowing maximum speed [m/s]	13.9
dx^{min}	Minimal distance between vehicles [m]	2
L	Length of each vehicle [m]	5
t_z, t_e	Duration of yellow and green signals respectively [s]	5, 50

The aim of the computation is to show results of exhaust emission modelling for different traffic situations. Because is analysed uniform structure of the traffic, the behaviour of the traffic flow depends directly on formation and dissipation of queues due to traffic signals at outlet intersection. Formation and dissipation of queues result in changeable density of vehicles along the road and then of exhaust emission distribution. In order to show this, five different simulation cases are considered which differ in duration of red signal – Tab. 2.

Tab. 2. The duration of red signal for five simulation cases

Simulation	The duration of red signal [s]
I	60
II	65
III	70
IV	75
V	80

Computational traffic flow simulations was performed for each case considered using the algorithm of dividing road on segments presented in section 3.2. The road was divided on equidistance segments, each 20 meters long. In Fig. 3 are presented results of simulations - the time average density and the time average speed of vehicles in time period of 15 minutes along the road.
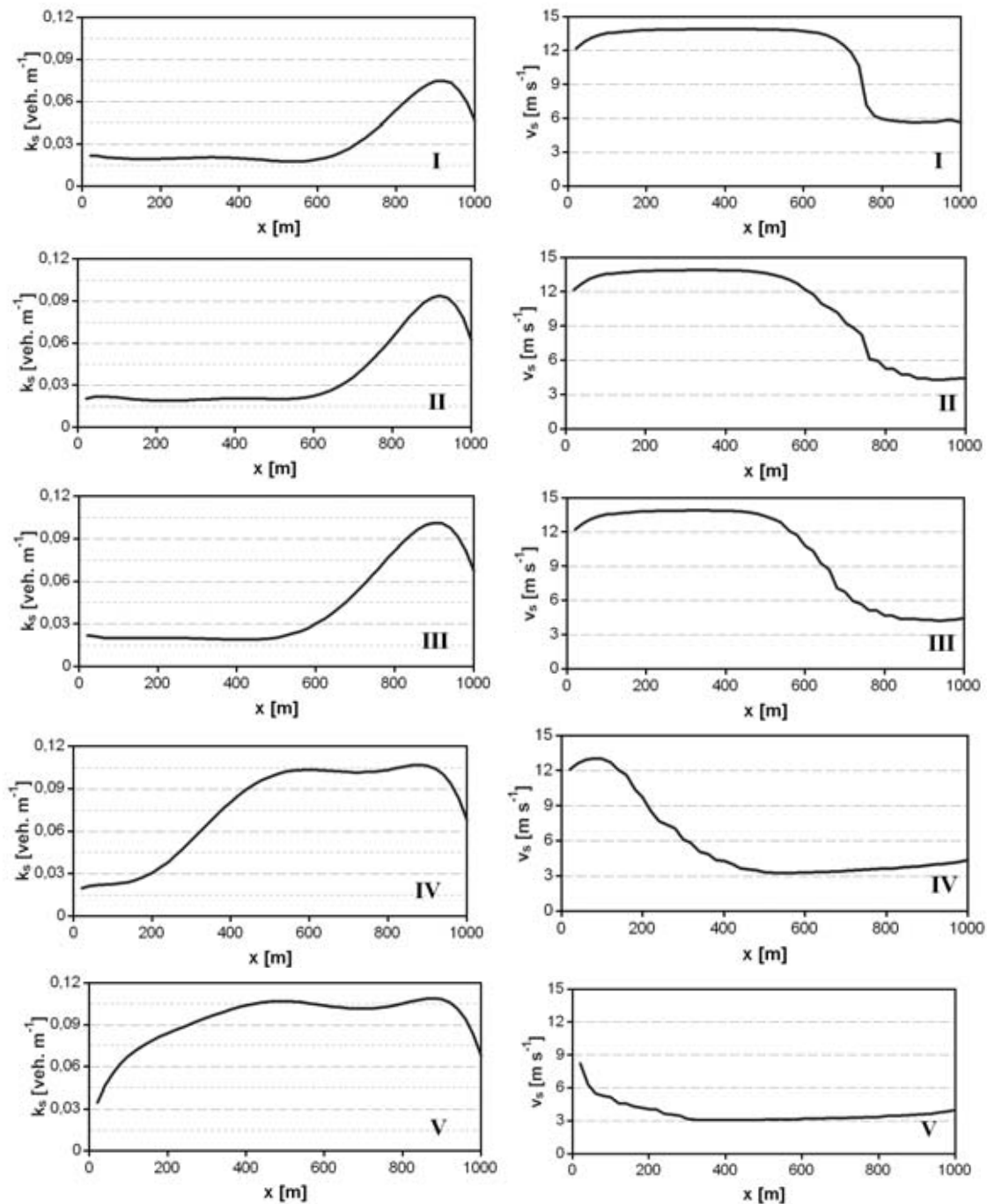

Fig. 3. The time average density and the time average speed of vehicles along the road

Analysis of the results shows significant changes in the time average density of vehicles and in the time average speed of vehicles according to the duration of red signal. Prolongation of the waiting time leads to longer queues at intersection and more congested traffic flow on the road.

The average exhaust emission intensity of CO per distance unit calculated along the road for all cases considered is presented in Fig. 4.
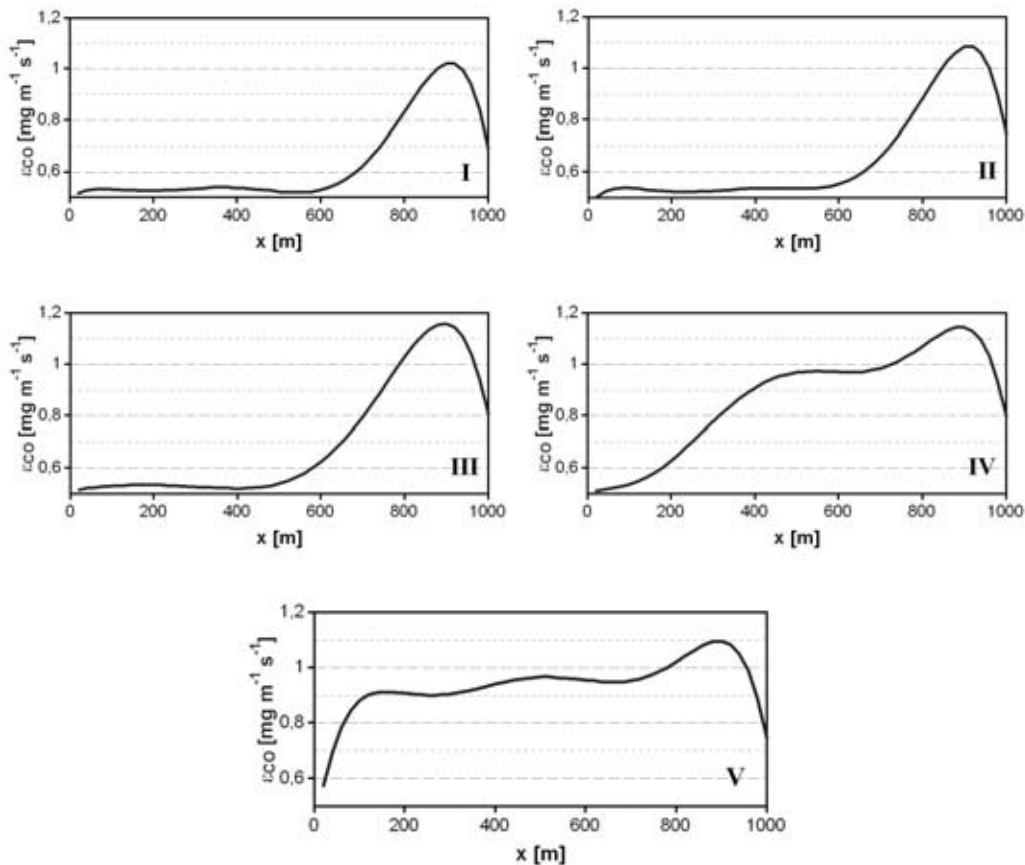

Fig. 4. The average exhausts emission intensity of CO per distance unit along the road

Simulation results presented in Fig. 4 illustrate the changes in the average exhaust emission intensity along the road as a result of vehicle queues formation and dissipation. These results clearly indicate that the algorithm of dividing road on segments presented in this work, using accessible data about average emission factors, enables modelling of local air quality for spatial scale less than the length of the road.

5. Conclusion

Modelling the average exhaust emission intensity for a communication network is a base step in evaluation of influence of traffic on air quality. Requirements for input data for emission models and applied evaluation method depend on spatial scale of air quality study. If the influence of traffic is examined for urban areas, modellers should include fundamental phenomena of traffic in those regions such as queues, traffic jams etc. The algorithm of dividing road on segments using microscopic traffic flow model presented in the paper is a solution which enables more precisely identification of regions in which the exhaust emission is high and the permissible concentration of vehicle exhaust pollutant can be exceed. It should be noticed that for modelling of the average emission intensity one can used free of charge European emission model COPERT, nowadays in the fourth version [19].

References

[1] Boulter P. G., McCrae I. S. Barlow, T. J., *A review of instantaneous emission models for road vehicles*, Transport Research Laboratory, Project report PPR 267, 2007.

[2] Brzozowska, L., Brzozowski, K., *Komputerowe modelowanie emisji i rozprzestrzeniania się zanieczyszczeń samochodowych,* WN Śląsk, Katowice-Warszawa 2003.

[3] Brzozowska, L., Brzozowski, K., Drąg, Ł., *Transport drogowy a jakość powietrza atmosferycznego. Modelowanie komputerowe w mezoskali*, WKiŁ, Warszawa 2009.

[4] Brzozowski, K., Grinke, L., *Losowe generowanie charakterystyk statycznych emisji*, Konstrukcja, badania, eksploatacja, technologia pojazdów samochodowych i silników spalinowych.- Kraków : PAN Oddz. Kraków, Ser. Teka Komisji Motoryzacji, Nr 29-30, pp. 63-70, 2005, 2005.

[5] Chłopek, Z., *Modelowanie procesów emisji spalin w warunkach eksploatacji trakcyjnej silników spalinowych*. Politechnika Warszawska, Prace Naukowe, Mechanika 173, 1999.

[6] Chłopek, Z., *Procedura wyznaczania ekologicznych charakterystyk silników trakcyjnych z zastosowaniem metody Monte Carlo,* Archiwum Motoryzacji 4, pp. 135-147, 1999.

[7] Chłopek, Z., *Ochrona środowiska naturalnego*, WKiŁ, Warszawa 2002.

[8] De Vlieger, I., De Keukeleere, D., Kretzschmar, J.G., *Environmental effects of driving behavior and congestion related to passenger cars*, Atmospheric Environment 34, pp. 4649-4655, 2000.

[9] Drąg, Ł., *Wpływ modeli ruchu pojazdów na obliczeniową emisję zanieczyszczeń*, Rozprawa doktorska, Akademia Techniczno-Humanistyczna, Bielsko-Biała 2008.

[10] EEA Report, *Air Pollution in Europe 1990–2004*, Copenhagen 2007.

[11] Hansen, J. Q., Winther, M., Sorenson, S. C., *The influence of driving patterns on petrol passenger car emissions*, The Science of the Total Environment 169, pp. 129-139, 1995.

[12] INFRAS AG, *Handbuch für Emissionsfaktoren des Strassenverkehrs*, INFRAS, Bern 1995.

[13] Jensen, S. S., *Driving patterns and emissions from different types of roads*, The Science of the Total Environment 169, pp. 123-128, 1995.

[14] Joumard, R., André, M., Vidon, R., Tassel, P., Pruvost, C., *Influence of driving cycles on unit emissions from passenger cars*, Atmospheric Environment 34, pp.4621-4628, 2000.

[15] Joumard, R., André, M., Vidon, R., Tassel, P., *Characterizing real unit emissions for light duty goods vehicles*, Atmospheric Environment 37, pp. 5217-5225, 2003.

[16] Krauss, S., *Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics*, Ph.D. Thesis, University of Cologne, Cologne 1998.

[17] Ntziachristos, L., Samaras, Z., *Speed-dependent representative emission factors for catalyst passenger cars and influencing parameters*, Atmospheric Environment 34, pp. 4611-4619, 2000.

[18] Pronello, C., André, M., *Pollutant emissions estimation in road transport models*, Report INRETS-LTE No 2007, 2000.

[19] Samaras, Z., Zierock, K-H., *Emission Inventory Guidebook*, Aristotle University, Greece 2007.