ARCHIWUM MOTORYZACJI
3, pp. 127–140 (2000)

The numerical analysis of car pollutants dispersion

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It is important to know how car exhaust pollutants are formed and how they are distributed in natural environment. This paper presents a numerical model of a short-term dispersion of pollutants caused by vehicles which moves with changeable velocities. A cross-road with changing traffic lights is considered here. Each vehicle is treated as one point source of pollutants and the values of emitted pollutants, depending on vehicle speed, are described by individual characteristics of vehicle engines. The Gaussian mathematical model for instantaneous moving point source has been applied. The turbulent zone is taken into account in order to estimate the dispersion coefficients. In the model, the wind speed and its direction, which influence the concentration of pollutants in the neighbourhood of a road, have also been considered. The results of some calculations and conclusions are presented at the end of the paper.

1. Introduction

A lot of mathematical modelling techniques can be used to estimate the air state in the neighbourhood of a road. Models, which are used to estimate the distribution of pollutants concentration, differ in the level of difficulty.

The main disadvantage of using existing models [1, 2, 3, 4, 5, 6, 7] of pollutant dispersion is the assumption that the sources are stationary. However, mentioned above models are used for estimating the air pollution in longer periods of time because of the assumption of constant point sources and their linearity. So, also they are not useful in non-modified version, for solving problems dealt with in this work.

The estimation of pollutant emissions from vehicles is of importance to several institutions, that's why have been developed different methodologies to estimate road traffic emissions, mostly independent from each other [8]. A comparison of emission models can be found in report [9] that providing the main conclusions on the activities performed during COST 319 European action exactly in the area of emission models.

The model described is used to estimate the emission and dispersion of car exhaust pollutants, when the cars are going through cross-roads, controlled by traffic lights. It is based on the multiple point model. Each vehicle is treated as one, instantaneous point source with emission which depends on the vehicle speed. A cross-road controlled by lights and roads without traffic lights are taken into account and simulated in numerical calculations.

In the paper, the main assumptions and models, which were used to create the package of computer programs are described. Fig. 1 presents components of the model.

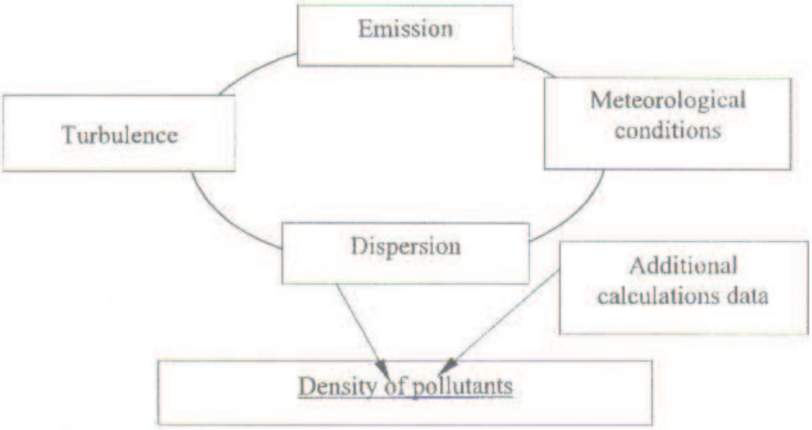


Fig. 1. Components of the model

In particular, we concentrate on:
- single emission of pollutants;
- rules, used in designing of a car motion scheme;
- mathematical model of dispersion.

The main model assumptions are:
- each vehicle is a moving point source of exhaust pollutants,
- moving of pollutant clouds has been over the flat and uninhabited areas,
- emitted pollutants don't take part in any chemical reactions,
- car velocity changes according to traffic lights.

2. Single emission characteristics

To estimate the influence of vehicle motion on instantaneous values of pollutant concentration the emission of pollutants must be calculated first. The emitted amount of pollutants depends on: the percentage participation of each kind and class of vehicles, kinds of their engines, and the scheme of vehicle motion in the modelling zone. It is not possible, to transform a real single emission precisely. Many parameters, which determine emission are not correlated in a linear way. For instance: an instantaneous acceleration considered in [10] can increases the emission of pollutants. The other factors which influence emission are: the way of driving, its dynamics, conditions of the road surface, air temperature, catalyst temperature.

Two different approaches are usually applied in order to estimate pollutant characteristics.

The instantaneous emission approach (modal method) [11] is applied when estimating micro-scale emission. The emission function for each pollutant can be defined as 2D matrix. Emission data are put into one cell of emission matrix according to the velocity and acceleration of the measured vehicle – see Fig. 2. Having 2D- emission matrix and recorded driving patterns it is possible to calculate the emission corresponding to dynamic state of vehicle. Some instantaneous characteristics can be found in Emission Factor Workbook [12]. An advantage of such approach is that emission calculation can be performed according to real-world behaviour. However, the large emission data sets are required, and some of them are hard to find.

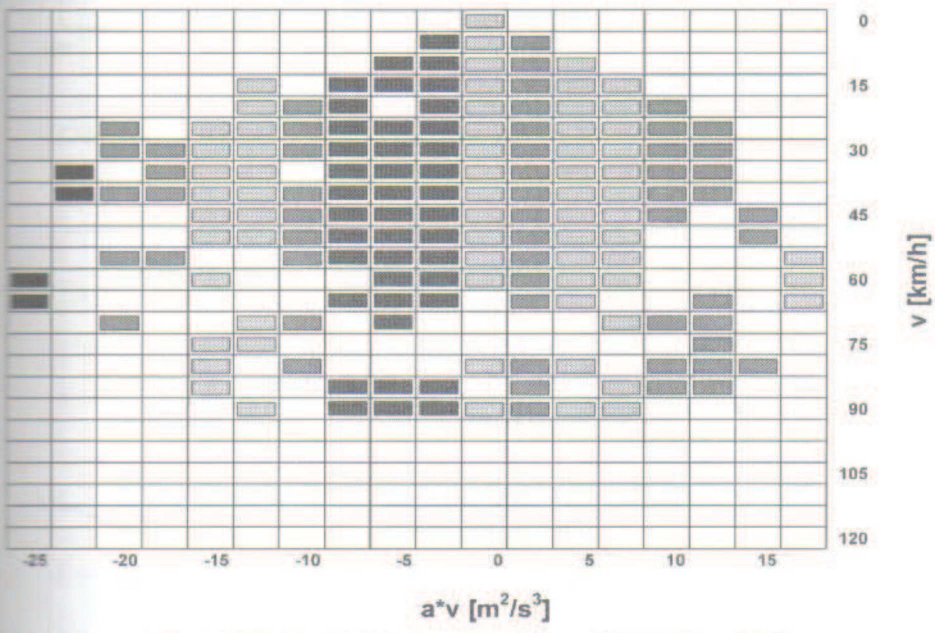


Fig. 2. Emission matrix for a typical urban driving pattern [11]

The average speed approach is the most commonly used method for estimating emission from road traffic [11, 13]. This method define a road emission [g/km] as a function of average vehicle speed [13]. An example of NO_x emission characteristics for vehicles with petrol engine (EURO 1) is shown in Fig.3a and NO_x characteristics for vehicles with Diesel engines (conventional) is presented in Fig. 3b.

In our paper the second (average speed) approach has been applied. In the model considered, the emission characteristics were created on the base of European algorithm (model) COPERT II [14]. We created the data base which includes information about: types of vehicles (passenger car, light duty vehicle, heavy duty vehicle, bus), as well as information concerning engines (petrol, diesel), their

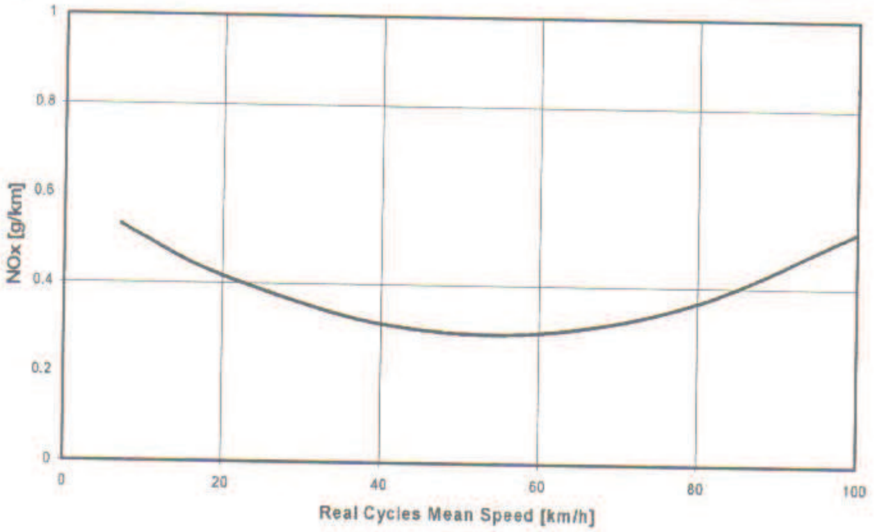


Fig. 3a. NO_x emission factor for gasoline passenger cars (class EURO1 (91/441/EEC), cylinder capacity 1.4 $dm^3 \div 2.0$ dm^3) [13]

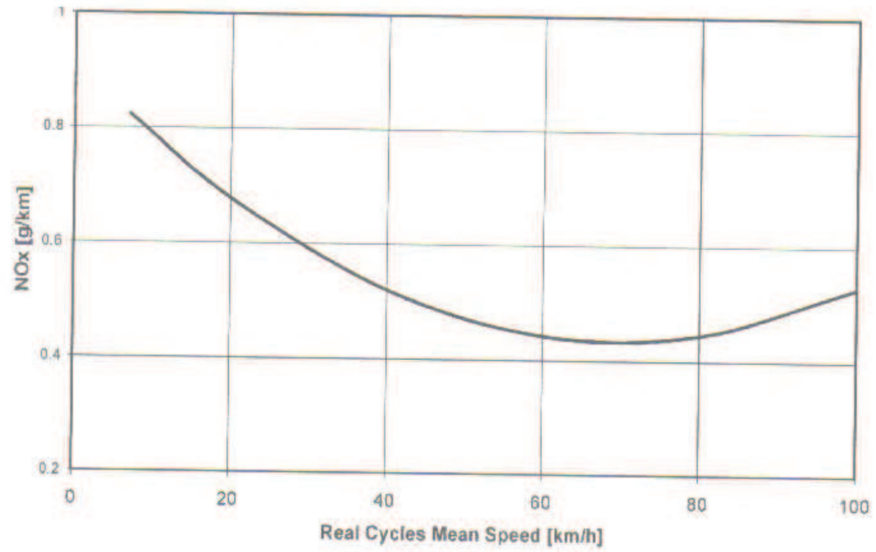


Fig. 3b. NO_x emission factor for conventional diesel vehicles (cylinder capacity <2.0 dm^3, weight kg $<2.5 \times 10^3$ kg) [13]

capacity or weight (HDV) and vehicle pollution control technology. The main part of the data are emission characteristics for the most important pollutants such as CO, NO_x, HC, and PM for vehicles with diesel engines. Scheme of data base is presented in Table 1.

Table 1. Vehicle classes and categories according to [14] taken into account in data base

Legislation	Classification												
	Passenger Cars Cylinder Capacity in dm^3					Light Duty Vehicles Weight in kg		Heavy Duty Vehicles Weight in kg				Buses	
	Gasoline			Diesel		Gasoline	Diesel	Gasoline	Diesel				
	<1.4	$1.4 \div 2.0$	>2.0	<2.0	>2.0	$<3.5\cdot10^3$	$<3.5\cdot10^3$	$>3.5\cdot10^3$	$>7.5\cdot10^3$	$7.5\cdot10^3 \div 16\cdot10^3$	$16\cdot10^3 \div 32\cdot10^3$	Urban buses	Coaches
PRE ECE	▨	▨	▨										
ECE 15/00-01	▨	▨	▨										
ECE 15/02	▨	▨	▨										
ECE 15/03	▨	▨	▨										
ECE 15/04	▨	▨	▨										
91/441/EEC (EURO 1)	▨	▨	▨	▨	▨								
94/12/EEC	▨	▨	▨	▨	▨								
Conventional				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
93/59/EEC (EURO 1)						▨	▨						
91/542/EEC Stage I									▨	▨	▨	▨	▨
91/542/EEC Stage II									▨	▨	▨	▨	▨

▨ – implemented in data base

3. Scheme of car motion

Motion scheme can be formulated according to real – life conditions, or for design, as a random scheme. Generated at random scheme should define following parameters:

- density of vehicles per hour;
- percent participation of main types (groups) of vehicles (passenger car, light duty vehicle, heavy duty vehicle, bus);
- percent participation of vehicles with diesel engines in a given group of vehicles;
- percent participation of vehicles with different vehicle pollution control technology in a given group of vehicles.

The assumed scheme of motion can be visualised in a computer simulation. Some other parameters which influence the situation on the cross-road and in its neighbourhood, must be taken into account as well. They are:

- maximal vehicle speed;
- minimal distance between vehicles;
- duration of traffic lights.

It is also necessary to define how big is the observed zone, in which we are going to estimate concentrations of pollutants.

4. Modelling of pollutants dispersion

The Gaussian formula for instantaneous point sources, which describes distribution of pollutant concentration in a given receptor for non-reactive gases has form [15]:

$$S(x, y, z, t) = \frac{Q}{(2\pi)^{3}\sigma_x\sigma_y\sigma_z} \times \exp\left[\frac{(x-x'-\bar{u}(t-t'))^2}{2\sigma_x^2} + \frac{(y-y')^2}{2\sigma_y^2}\right] \times \tag{1}$$
$$\times\left[\exp\left(-\frac{(z-z')^2}{2\sigma_z^2}\right) + \exp\left(\frac{(z+z')^2}{2\sigma_z^2}\right)\right],$$

where $S(x, y, z, t)$ is the pollutant concentration in the point with co-ordinates (x, y, z) in time t, Q is the mass of the pollutants emitted in the point (x', y', z') in time t', $0<t'<t$, σ_x, σ_y, σ_z are standard deviations of normal distribution in the x, y, z directions.

In the model, it has been assumed that the total pollution caused by petrol burning is the sum of pollutants emitted by every vehicle. Total amount of pollution in time and space point with co-ordinates x, y, z can be calculated as:

$$S = \sum_{i=1}^{n} S_i, \tag{2}$$

where S_i is density of pollutants which come from i-th vehicle, n is the number of vehicles.

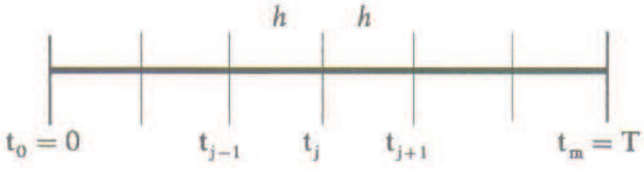


Fig. 4. The division of the time interval (0, *T*)

Let's consider a single i-th vehicle. Let T be the duration of pollutants emission, and time interval $(0, T)$ be divided into m intervals with length h – Fig. 4.

It has been assumed that the speed of i-th vehicle for $t = t_j$ is v_{ij}. The emission of pollutants in the interval $\left(t_j - \frac{h}{2}, t_j + \frac{h}{2}\right)$ for the i-th vehicle is given by:

$$Q_{ij} = e_i \cdot v_i|_{t=t_j} \cdot h, \tag{3}$$

where e_i is the average linear density of pollutants in considered interval.

This assumption is correct when h is small enough, and in this case, pollutant density caused by all vehicles in receptor with co-ordinates x, y, z is:

$$S = \sum_{i=1}^{n} \cdot \sum_{j=0}^{m} S_{ij} \tag{4}$$

S_{ij} can be calculated from (1) for $Q = Q_{ij}$.

In order to use the formula (1) the coefficients σ_x, σ_y, σ_z must be deffined.

5. Coefficients of pollutants dispersion σ_x, σ_y, σ_z

The mechanical turbulence behind a vehicle and the heat turbulence influence the initial conditions of dispersion. There are a lot of works which deal with the role of mechanical turbulence when pollutants are dispersed.

The turbulence influence is taken into account in presented model by adding the turbulence zone model (zone of mixing) [1]. The modification of the value of vertical diffusion coefficient ($\sigma_z = 1$) is applied in mixing zone when vehicles stop at the traffic lights. Outside the turbulence zone, the influence of the heat of exhaust gas is additionally considered in order to determine a modified class of atmosphere stability.

Horizontal dispersion coefficients σ_x, σ_y can be calculated thanks to Draxler method [1].

The full description of the model requires the following:

- Meteorological data:
  1. the velocity of the wind at the height of the receptor;
  2. the classes of atmosphere stability;
  3. deviation of horizontal wind angle;
  4. inclination angle of wind vector to the road.

- Additional data:
  5. position of the receptor over the surface of the zone;
  6. density of the receptors net in the modelling zone;
  7. aerodynamic roughness of the zone;
  8. width of the turbulence zone (mixing).

6. Results of the computer simulation

As it was mentioned above, the assumption (4) is right when time interval h is small enough. The discretization step h influences the accuracy of numerical calculations. So, from one point of views it should by very small. But from the other side the calculation time increases rapidly when step h is small. In order to define the acceptable length of time – discretization step h the series of calculations where carried out for the same data.

Table 2. Influence of time discretization step h on calculation time and exactness of results

Time interval [s]	Summary emission [g]	Calculation time [s]	Error [%]
0.05	7.3580	886	0
0.1	7.3582	453	0.002
0.15	7.3528	314	0.07
0.2	7.3464	234	0.16
0.25	7.3423	186	0.21
0.5	7.3217	95	0.49
0.75	7.2954	65	0.85
1	7.2463	48	1.52

In Table 2 are presented the results of calculations. The relative percentage error in last column was calculated in relation to the smallest calculation step $h = 0.05\,\text{s}$. The Fig. 5 presents influence of step h on exactness of results and on calculation time. All calculations were performed on IBM PC Pentium III/600 MHz. The discretization step $h = 0.1\,\text{s}$ has been taken as sufficient for further calculations.

The presented computer simulation was carried out for data from a real cross-road in the city of Bielsko-Biała for typical meteorological data. The cross-road is controlled by traffic lights. By numerical experiments we would like to show, how the change of vehicles speed according to traffic lights (dynamic states) influence the global emission of pollutants and their dispersion in the neighbourhood of the cross-road (see Fig. 6). As background for analysis additional calculations were carried out for the case when the vehicle motion is free from traffic-lights so, vehicle speed is constant.

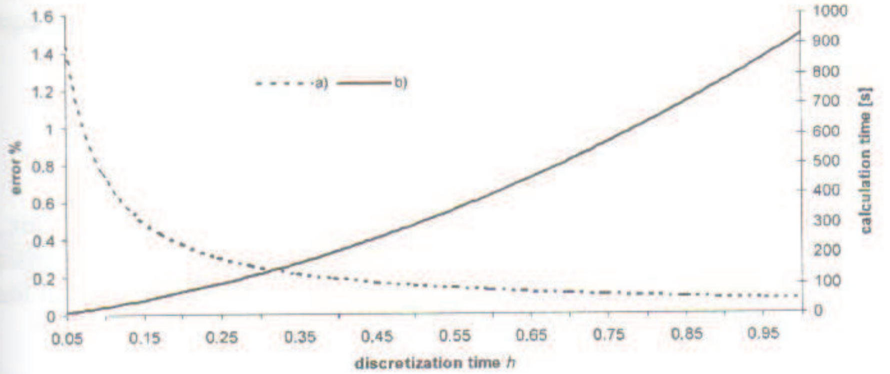


Fig. 5. Influence of time discretization step *h* on
a) calculation time, b) exactness of calculation results

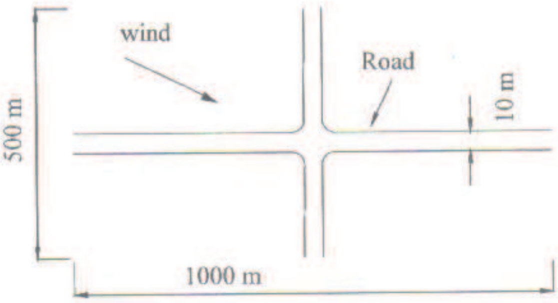


Fig. 6. Road system

Pollutant density was calculated in receptor network. Receptors were situated 10 meters from one to another on the height of 1.8 meters. The following parameters were assumed for the sake of the test:

1. the class of atmosphere stability according to formula Pasquill-C
2. the wind velocity on the height of 1.8 m over the surface – 2 m/s
3. aerodynamic roughness of the surface – 1m
4. wind angle to the road – 45 degrees
5. fluctuation of wind direction in averaging time – 0.57 degrees;
6. maximum speed limit was 60 km/h;
7. minimum distance of vehicles in the motion was 5 m.

As it was mentioned above the individual characteristics of emission were taken from European model COPERT II [14]. We assumed that vehicles decelerate and accelerate with constant acceleration, according to the speed of preceding vehicles, in order to survey the minimal distance.

In the model where change of vehicle speed occurs (a cross-road with traffic lights), a single duration of the green lights was 30 second while for yellows lights 15 second. Figure 7 presents the diagram of average vehicles speed on both roadways in this case. In background case (uniform motion) all vehicles go with speed equal to 60 km/h. The average speed of vehicles is calculated according to formula:

$$v_a(t) = \frac{1}{n_c} \sum_{i=1}^{n} v_i(t), \tag{5}$$

where $v_i(t^+)$ is speed of i – th car, n is the number of cars.

The comparison of emitted pollutants during the simulation period for both calculation cases is presented at Fig. 8. It can be observed that the emission of pollutants for assumed, particular traffic situation is 2 to 3 times higher then for case with constant vehicle speed.

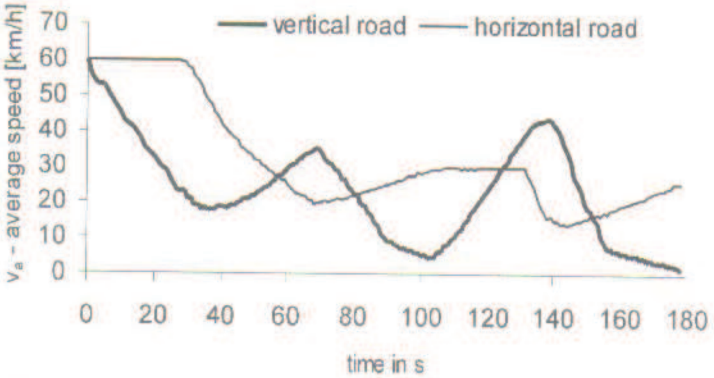


Fig. 7. Average speed of vehicles on both roadways for cross-road controlled by traffic lights.

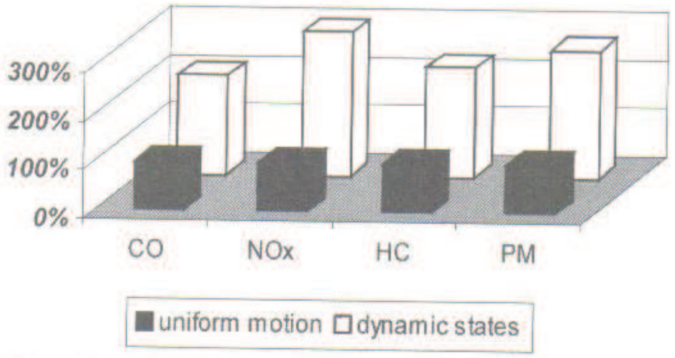
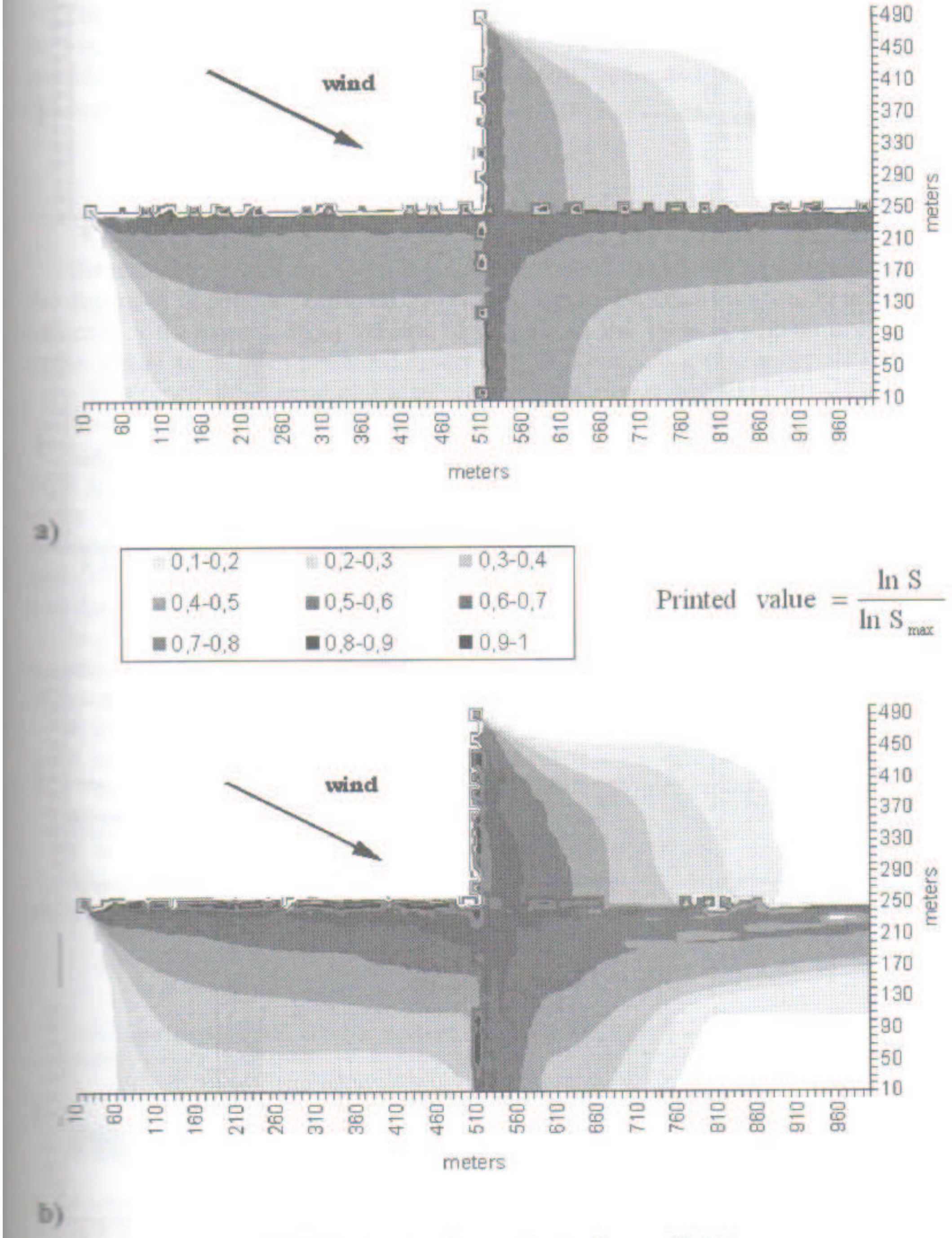


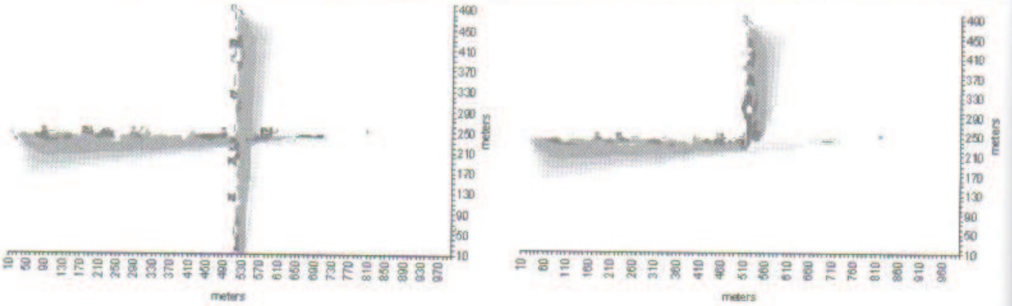
Fig. 8. Comparison of emitted pollutants in uniform motion and dynamic states

In the Fig. 9, a maximal 3-minutes distribution of carbon monoxide concentration in the modelled zone is presented, separately for the cases with uniform motion and with dynamic states. Maximal density of CO and its arithmetical average, in the case when dynamics was considered, were larger than for the case with uniform motion. This occurs because of a smaller vertical coefficient of dispersion, when vehicles are stopped by lights. That is more the average speed characteristics applied mostly show higher emission of pollutants for low speed of vehicles.

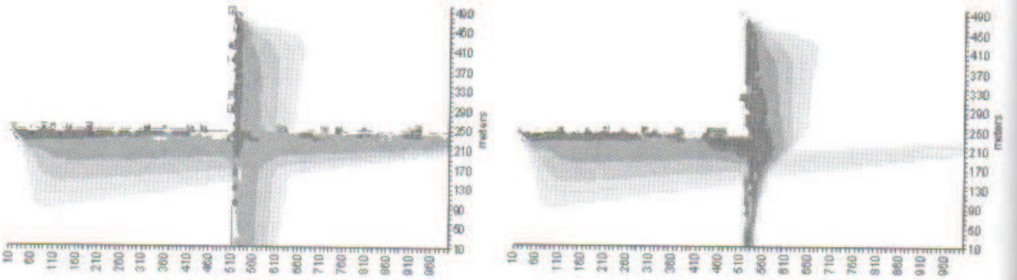


$$\text{Printed value} = \frac{\ln S}{\ln S_{max}}$$

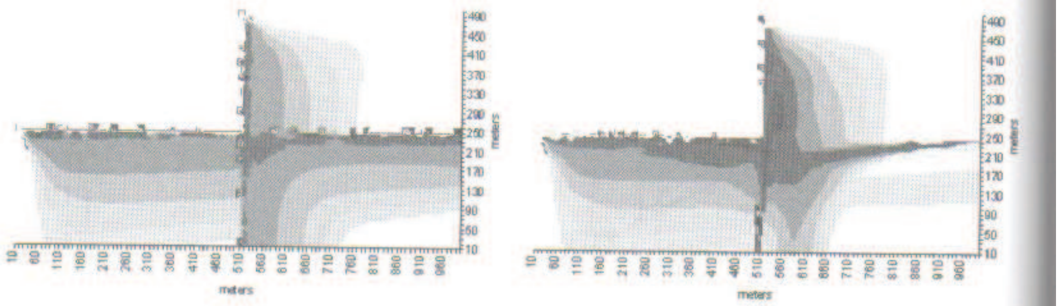
Fig. 9. CO density; a) uniform motion – without traffic lights,
b) dynamic states – with traffic lights



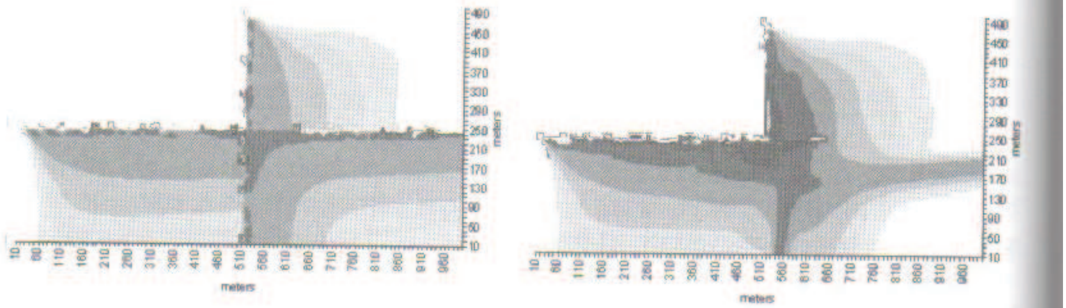
t = 54 s



t = 90 s



t = 144 s



t = 180 s

Fig. 10. CO density. Left side – uniform motion, Right side – dynamic states

The model presented allows to observe how the pollutants clouds move in time. In Fig. 10 are presented some phases of pollutants clouds. On the left side are presented results for uniform motion, while results presented on the right concern the case with dynamic states. We can see that results differ significantly.

7. Conclusion

The aim of this work was to form a numerical model, which can be used to estimate the dispersion of pollutants emitted by vehicles. The model takes into consideration the influence of the instantaneous velocity of vehicles on the value of pollutants concentration. Single emission in presented model can be formulated in two ways:

- as a function of speed and accelerate (instantaneous model);
- as a function of vehicle speed (average speed model).

The results of calculation obtained while the second model of single emission has been applied, show that the emission of pollutants can be higher when the dynamic states of vehicles occur. The model can be widened by terms which describe chemical equations of pollutant transformation (refers to nitrogen oxides and hydrocarbons) or by terms which describe the percentage of pollutant subsiding on a surface (for example solid particles).

In real conditions, the total pollution is a sum of pollutants emitted by simple systems which are similar to a system we describe in the paper. We can analyse a lot of systems by using a presented model:

- a cross-road (controlled by lights or not);
- car parking (very important because of a cold start in which pollutant emission is much larger);
- roundabouts;
- tunnels.

After that by using a superposition principle we can design a map of total pollutants, according to the number of systems in a given zone.

Acknowledgements

This paper presents result obtained thanks to grant No: 9T12C00817 founded by Polish Committee of Science.

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Numeryczna analiza dyspersji zanieczyszczeń pochodzenia motoryzacyjnego

Streszczenie

W artykule przedstawiono przykład numerycznego modelowania chwilowych (o czasie uśredniania 3 min.) stężeń zanieczyszczeń powietrza powstałych w wyniku nieustalonego ruchu pojazdów. Rozpatrzono przypadek skrzyżowania dróg z sygnalizacją świetlną o predefiniowanym natężeniu ruchu, zastępując strumień pojazdów ciągiem źródeł punktowych reprezentujących poszczególne pojazdy. Dla każdego źródła (pojazdu), na podstawie charakterystyk emisyjnych obliczono emisję w zależności od chwilowej prędkości i czasu dyskretyzacji wyrzutu gazów. Do obliczenia stężeń zanieczyszczeń posłużono się formułą Gaussa (w postaci dla poruszającego się źródła chwilowego), uwzględniając wpływ turbulencji cieplnej i mechanicznej na wartość pionowego współczynnika dyspersji.