Dispersion Modeling of the Air Pollution, Emitted by the Traffic in the Transport Tunnel under the Old Town of Plovdiv, Bulgaria

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Abstract. Air quality control and management is one of the areas in which Europe has been the most active in recent years. Air quality assessment is the process of determining the nature of ambient air pollution using monitoring and supplementary techniques such as modelling. Aim of this study was to evaluate the air pollution as a result of the traffic in the transport tunnel of "Tsar Boris III Obedinitel" Boulevard, situated under the Architectural Reserve "Old Town" in the central part of Plovdiv. Analyses included two consequent steps: (i) calculating the emissions of exhaused gases from the motor vehicles in the tunnel using the dispersion modeling software; (ii) comparing the values obtained with data from the automatic measuring station of the air quality, located in proximity of the tunnel. Our study revealed that the main air pollutant in the tunnel is the nitrogen oxides whose concentrations were 4 to 6 times higher than TLV. Carbon oxide concentrations were 5 times lower than TLV and those of the soot – two times lower. Curves of the NO_x, CO and dust concentrations changes in both cases (modelled and measured, respectively) are parallel which confirms the validity of the model used.

Key words: dispersion modelling, air pollution, traffic, street tunel, monitoring, Plovdiv

Introduction

Urban ecosystems are comprised of diverse land uses including commercial, industrial, residential, transport, recreational, agricultural and nature areas, resulting in different habitats within the urban landscape (PETROVA, 2011). Air pollution could be defined as a presence in the air of various gases, vapors, particles, solid or liquid substances, which adversely affect living organisms in the urban habitats, worsen environmental conditions or cause property damage. City of Plovdiv, Bulgaria, with a population of over 338 000 inhabitants (NSI, 2011), is subject to air pollution, often exceeding the threshold limit values (TLV) according to the current national standards (Regulation Norm 9, 2010), mainly by dust, however, by nitrogen oxides as well, caused by the transport (ATANASSOV et al., 2006).

Urban automobile transport is one of the major emitters of contaminants in the environment. Each car throws into the atmosphere large number of pollutants consisted of over 200 different compounds. These are primarily dust, carbon oxides, nitrogen and sulfur oxides, ozone, trace elements, benzene, toluene and other polycyclic aromatic hydrocarbons (PAHs). Many studies in different European cities have shown that motor vehicles are responsible for 75% of emissions of nitrogen oxides, 40% of carbon monoxide, 13% solids

and 3% of sulfur oxides (MONACI *et al.*, 2000; ALLEN *et al.*, 2001; HARRISON *et al.*, 2003; HARRISON *et al.*, 2004; WÅHLIN *et al.*, 2006).

Air quality control and management is one of the areas in which Europe has been the most active in recent years. Air quality assessment is the process of determining the nature of ambient air pollution using monitoring and supplementary techniques such as modelling. Validation of model results against local monitoring data (if available) is eligible. Mathematical modelling of air pollution effectively enlarges our information about the air pollution level. It is an efficient tool for the elaboration and control of projects for air sanitation in areas with the individual extra protection (SZABO *et al.*, 2005).

City transport tunnels represent a specific concentrator of pollutants in the air, especially in places with intensive traffic and moderate traffic speed. Transport tunnels can be compared to horizontal chimneys with two opposite emitting openings which in city conditions contribute substantially to the air pollution and in this role they focus the scientific attention of a number of authors (BELLASIO, 1997; YASSIN *et al.*, 2005; SIMMONS & SEAKINS, 2012).

Aim of this study was to evaluate the air pollution as a result of the traffic in the transport tunnel of "Tsar Boris III Obedinitel" Boulevard, situated under the Architectural Reserve "Old Town" in the central part of Plovdiv. Analyses included two consequent steps: (i) calculating the emissions of exhaused gases from the motor vehicles in the tunnel using the dispersion modeling software; (ii) comparing the values obtained with data from the automatic measuring station of the air quality, located in proximity of the tunnel.

Materials and Methods

Study area. The road tunnel on "Tsar Boris III Obedinitel" Boulevard in Plovdiv under the Architectural Reserve "Old Town" was built in the 50-ies of the past century. It is a two-way road tunnel (two lanes for each direction), with North-South orientation (N 42.148515°, E 24.750755°), 183 m above sea level. Its dimensions are as follows: Length=216 m, Width=18 m, Height=5.1 m, Cross-section=105 m² (i.e. volume of 22680 m³).

On a busy juncture nearby the tunnel – 460 m away from its northern side, operates the automatic measuring station „Banya Starinna"(AMS) for the air quality monitoring (N 42.152641°, E 24.750736°), which allowed us to compare the air pollutants' concentrations – NO_x, CO and dust particles (soot), calculated with the dispersion model to the data for the same pollutants, measured by the AMS (Fig. 1).

Selection of place and time to conduct the counting. In order to evaluate the emissions by the motor vehicles (MV) in the tunnel, an observation point for counting the vehicles was set up, located above the northern side of the tunnel which revealed a sufficiently long part of the boulevard to the observer (hundreds of meters). This viewpoint gave the counters sufficient time for unambiguous classification into 13 categories of the motor vehicles, passing through the tunnel.

Study was conducted in two successive, sunny, dry and warm for the season days, without any need of domestic heating at least, in the middle of the day.

Counting was carried out in the following one-hour time intervals:

• from 17 hour 15 minutes to 18 hour 15 minutes on March 14, 2013, Thursday. Our expectations, based on preliminary observations, were that this time interval corresponded to the evening maximum of the MV number. In the text below this interval is abbreviated as "17-18 h".

• from 8 hour 20 minutes to 9 hour 20 minutes on March 15, 2013, the interval of the expected morning maximum of the MV number, expressed in short as "8-9 h".

• from 12 hour 16 minutes to 13 hour 16 minutes on March 15, 2013 – the middle of the work day. The interval is briefly expressed as „12-13 h".

Counting of the motor vehicles. For the purposes of the study, a suitable software was developed (by Nikolay Takuchev) for traffic counting (using Visual Basic for Applications, build in MS Excel). It allowed us both to easy and quick register the MV passing through the observation point, and

to classify them into categories by the mouse click on the button in the software window, corresponding to the passing motor vehicle (Fig. 2).

Computers saved a database with the type of each MV and its moment of passing with precision of a second. Only quota of the categories 4 and 8 was calculated according to the statistical data from the Ministry of Internal Affairs of Bulgaria (2013).

Dispersion modelling procedure.

Handbook of assessment and management of ambient air quality at the local level for SO_2, PM_{10}, Pb, and NO_2 (MOEW, 2002) was elaborated on the basis of the Joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook (EEA, 2001) by the Ministry of Environment and Waters in Bulgaria.

Fig. 1. Satellite picture of the transport tunnel in the city of Plovdiv, Bulgaria (source Google Earth, 2014), location of the observation point and of the automatic measuring station (AMS)
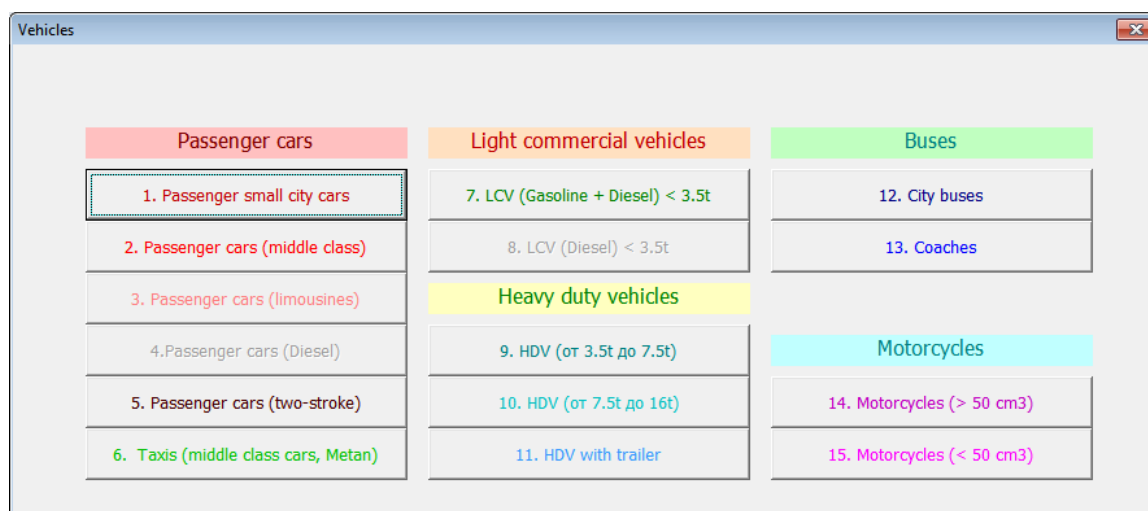

Fig. 2. Screen window of the software for counting of the 15 categories MV.

On the basis of this methodology that is intended for mathematical modelling of air pollution an user-oriented software product, named Traffic Oracle Program Software, was developed by the Geophysical Institute of the Bulgarian Academy of Sciences on 2004 (Traffic Oracle Program Software, 2002). This model for the ground surface field determines the concentrations of gaseous pollutant substances in the air and the solid particles to 20 micrometers. It makes possible to calculate short and long-term critical concentrations of pollutants and the overfull of threshold values. It was spread according to the methodology US EPA - ISC.

Given the source strength, meteorology, site geometry, and site characteristics, the model can reliably predict pollutant concentrations for receptors located at the chosen points. In this study, the model presents only pollutants such as carbon monoxide, nitrogen oxides and particular matter (PM).

In order to assess the MV emissions in the ambient air, the motor vehicles passing through the observation point, shall be distributed according to the type of their engines into 15 categories (13 counted and 2 calculated by statistical data). The MV categories were determined according to the SNAP nomenclature (Selected Nomenclature for Sources of Air Pollution) of EMEP/CORINAIR (European Monitoring and Evaluation Programme/The Core Inventory of Air Emissions in Europe) (EB.AIR/GE.1/1997/5).

Due to the dependence of the emissions on the age of the engines, the MV number in each of the 15 categories was divided into 4 subcategories according to the age of the engines, i.e. separately for each one of time intervals. Statistical data about the percent distribution of the motor vehicles according to type and age of the engines were obtained from the Ministry of Internal Affairs of Bulgaria (2013).

In order to count and classify quickly and precisely the motor vehicles in the 15 mentioned categories, the counters carried out a preliminary counting and training –

both for the quick identification of the MV categories and for handling the software, specifically developed for the counting. Counting was performed by two counters using portable computers – one for each direction in the tunnel.

In the beginning and at the end of each one-hour counting interval, the temperature, the velocity and the direction of the wind (VORTEX Hand Held Wind Meter) through the tunnel were measured. Ambient temperature plays a role in the calculation of the traffic emissions while the wind power and direction determine the calculated pollutants concentration.

Calculation of the emission factor (EF) – the mass of a specific pollutant, emitted in the air from all MV per unit time and per unit length (unit g/s/m) was performed with the Emission module of the Traffic Oracle Software. Calculation of the traffic-emitted pollutants concentrations was performed with the Diffusion module of the same software.

Statistical evaluation. Student test was used for testing of the calculated concentrations by dispersion modeling and measured concentrations by the AMS, respectively for each one of studied pollutants ($p < 0.05$). Relationships between two types of data were tested using Pearson correlation coefficients ($p < 0.05$). All statistical analyses were made with the STATISTICA 7.0 statistical package (STATSOFT, 2004).

Results and discussion

Traffic counting characteristics
Traffic past was intensive and continuous - a total of 8745 motor vehicles passed through the observation point for the three time intervals. Distribution of the MV number into the three studied one-hour intervals is presented in Table 1.

We revealed, that ¾ from all motor vehicles, passing through the tunnel, were medium class passenger cars, (2nd + 6th category). Number of some MV categories increased during the day – that of taxis, limos and small city cars. At noon, the number of middle-class cars and buses had

minimum and the number of light commercial vehicles – maximum. Total

number of vehicles was also increasing throughout the day.

Table 1. Distribution of the counted motor vehicles, passing through the tunnel under the Architectural Reserve "Old Town" in Plovdiv (Bulgaria).

	17-18 h on 14 March 2013	8-9 h on 15 March 2013	12-13 h on 15 March 2013	Proportion according to the MV type, %
1. Passenger small city cars	208	159	174	6
2. Passenger cars (middle class)	2615	1525	1477	64
3. Passenger cars (limousines)	389	107	213	8
6. Taxis (middle class passenger cars)	410	270	310	11
7. Light commercial vehicles < 3.5t	105	172	211	6
12. City buses	138	139	123	5
Total	3865	2372	2508	
Proportion, %	44	27	29	

Matrix for determination of the emissions

Categories 4 and 8 (diesel cars and light commercial vehicles) were calculated according to the total number of counted vehicles of the respective type and the statistical data (Ministry of Internal Affairs, 2013), according to which the passenger diesel cars are 20%, while the light commercial vehicles are 80% of total number of cars in the country.

According to the mentioned method, in addition to the MV type, they had to be divided according to their age into 4 categories: above 20 years; between 15 and 20 years; between 10 and 15 years; less than 10 years. Data about the age distribution of the motor vehicles were obtained by the Ministry of the Internal Affairs (as on 31.12.2010) (Table 2).

Data from Table 1 and Table 2 were set in the software re-distributing the MV number, obtained after counting, into 60 categories according both to the type and engine age.

Slope of the street has an impact on the traffic emissions as the ascending cars burn more fuel than the descending ones. Slope of the road section through the tunnel is small (about 1%), and was ignored in the calculation of the emissions. MV flows in the two opposite directions were treated as one common flow.

Average temperature values, wind power and direction through the tunnel for the three time intervals are presented in Table 3.

Emission factors of the pollutants were determined using the Emission module of the Traffic Oracle Program Software (2002).

As input parameters in the Emissions module for the calculation of the emission factors of the nitrogen oxides, the carbon monoxide and the dust particles (soot) for each of the above-mentioned time intervals, were used:

• MV distribution into 60 groups (as described above)

• Road type – the option "a town street" was chosen,

• Road slope – 0% (no slope),

• Air temperature – data from Table 2,

• Counting time – 60 minutes,

• Type of pollutant – nitrogen oxides, carbon monoxide, and soot (part of the dust particles pollution), respectively.

Three emission factors were obtained for each one of the three time intervals and were presented in Table 4.

Determination of the pollutants concentrations

In order to determine the air pollutants concentration along the tunnel length, the following three data groups were included in the Diffusion module of the Traffic Oracle Program:

Table 2. Distribution of MV according to their age.

	Proportion, %			
	above 20 years	*between 15 and 20 years*	*from 10 to 15 years*	*less than 10 years*
Passenger cars	25.46	32.63	29.17	12.74
Light commercial vehicles	20.68	25.89	26.02	27.42
Heavy duty vehicles	41.49	22.13	17.82	18.56
Buses	36.53	24.77	18.99	19.71
Motorcycles	29.74	17.17	18.62	34.47

Table 3. Temperature and wind velocity values during counting (measured at 1.8 m above the road pavement, 1 m away from the wall at the tunnel entry).

Time interval	Temperature, °C	Wind velocity magnitude, m/s	Wind velocity direction
8-9 h	13.8	3	South
12-13 h	16.5	2.5	South
17-18 h	18.6	6	South

- *Input model parameters*

This module calculates the pollutants concentrations in the nodes of a rectangular grid on the map. Density and dimensions of the grid are preset by the user who determines the number and step sizes to the East and North. As disposition of the tunnel is in North-South direction, the step size in the grid was chosen North-Southwards 10 m and the number of the steps was North-South = 24, i.e. the calculation of the concentrations was executed for length of 240 m – 10 m outside the two ends of the tunnel. Chosen number of the steps West-Eastwards were equal to two, with 10 m step size.

Mobility of the pollution depends on the type of the underground surface – in this case the "city region" option was preferred.

- *Meteorology*

In the beginning and at the end of the counting intervals the air temperature was measured at 1.8 m and at 7.8 m above the tunnel floor. Temperature difference for the three intervals was about 0.2°C, i.e. the vertical temperature gradient in the three cases was similar by magnitude and close to the neutral stability in regards to the vertical motions in the atmosphere, which was preset in the calculations. The option "one wind direction" was selected - South (Table 3).

- *Source parameters*

Ambient air pollution due to a linear source (the MV flow through the tunnel) was calculated with input parameters the coordinates of the tunnel ends – from 10 m to 230 m, and linear source width (the street) -18 m. Gravitational deposition velocity of the gas emissions was set as 0 m/s, for the soot – as 0.07 m/s (EMEP/CORINAIR Atmospheric Emission Inventory Guidebook, EEA, 2001). Input parameter of the source correlated also with the emission factor for the respective pollutant and the time interval (Table 4).

Concentrations of the Nitrogen oxides

Concentrations of nitrogen oxides along the axis line of the street in the tunnel, emitted by the traffic during the three MV counting intervals, were shown on Fig. 3. For the three measurement intervals, the NO_x concentrations have growing to the wind-blown end of the tunnel. Negative relationships were found between the NO_x concentration, and the air temperature and wind velocity – the NO_x level was about 3 times lower when the wind's speed increased two fold and the temperature

increased with 6°C (p<0.05). Threshold limit value (TLV) of 200 µg.m⁻³ (Regulation Norm 9, 2010) was exceeded in all three studied time intervals.

Next step was to compare the calculated average concentration of NO_x on the tunnel axis with the concentration, registered by AMS „Banya Starinna" at the same time interval (Fig. 4). Since the street through the tunnel passes also besides the AMS „Banya Starinna", located 460 m away, i.e. almost all cars, passing through the tunnel pass also besides the station, proportionality of the concentrations in the tunnel pollution should also be expected in the region of AMS. Statistical evaluation of two types of data found no significant difference (p<0.05). Almost parallel disposition of the lines in Fig. 4 corresponds to this conclusion; therefore, it is an indirect proof for the validity of the nitrogen oxides concentrations in the tunnel air, calculated with the dispersion model. This comparison

yields the conclusion that the nitrogen oxides concentration in the tunnel (at the level of the car exhaust-pipes, along the axis line of the street) is about 4.5 times higher than in the open air around the AMS „Banya Starinna" (30 m away from the street, at 3 m above the street pavement – the height for sample taking by the analyzers of the automatic station).

Concentrations of the Carbon oxide

Calculated carbon oxide concentrations in the tunnel are presented on Fig. 5. Pollution distribution along the tunnel axis was found to be with the same form as that of the nitrogen oxides; however, the concentrations of CO remained about 5 times lower than TLV in all studied time intervals. Dependence of the pollution level from the wind and temperature was similar to that of the nitrogen oxides – it decreased when the wind became stronger and the temperature increased (p<0.05).
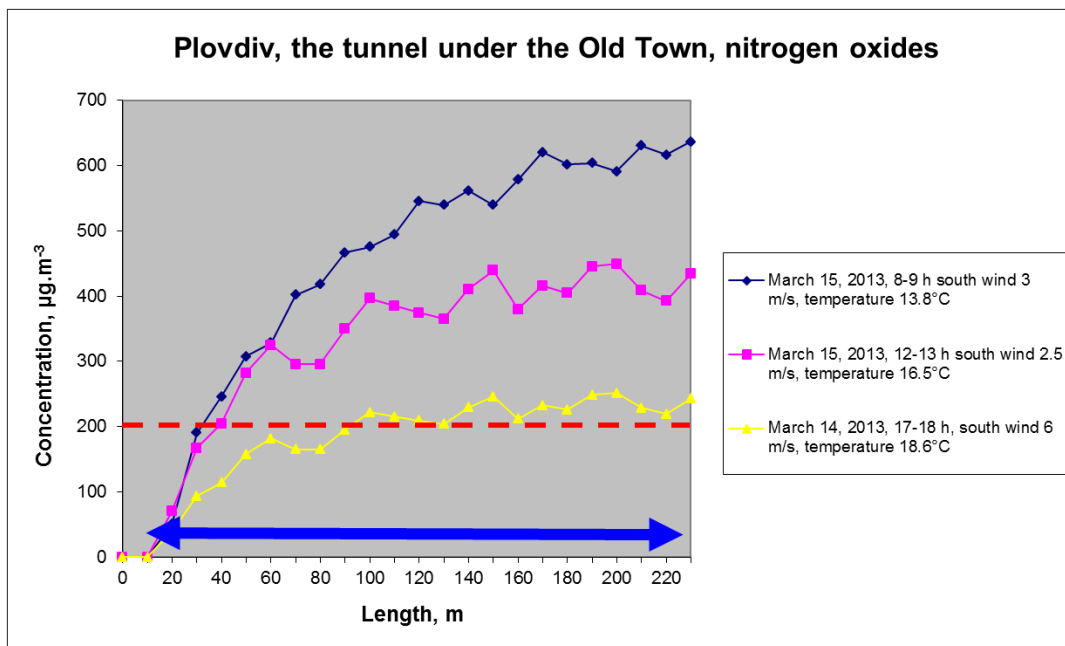

Fig. 3. Dynamic in the nitrogen oxides concentrations along the axis line of the tunnel under the Old Town in Plovdiv (Bulgaria). Double arrow showed the tunnel length; dashed line - the threshold limit value (TLV).
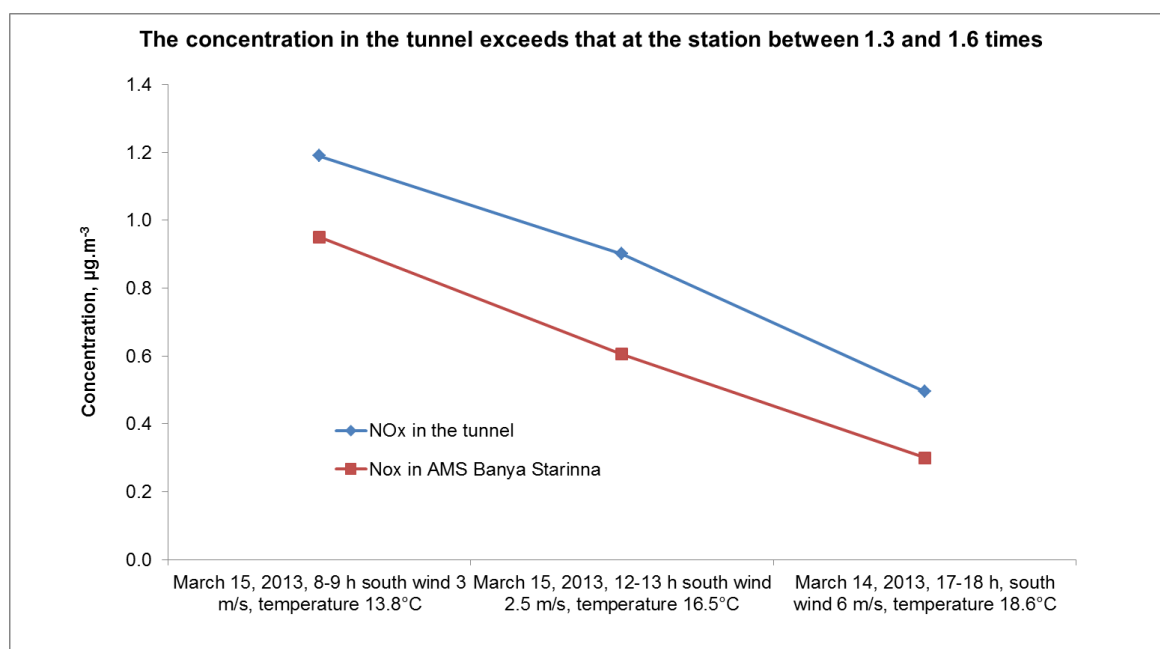
Fig. 4. Comparison between the nitrogen oxides concentrations calculated for the tunnel and registered by AMS „Banya Starinna", respectively.
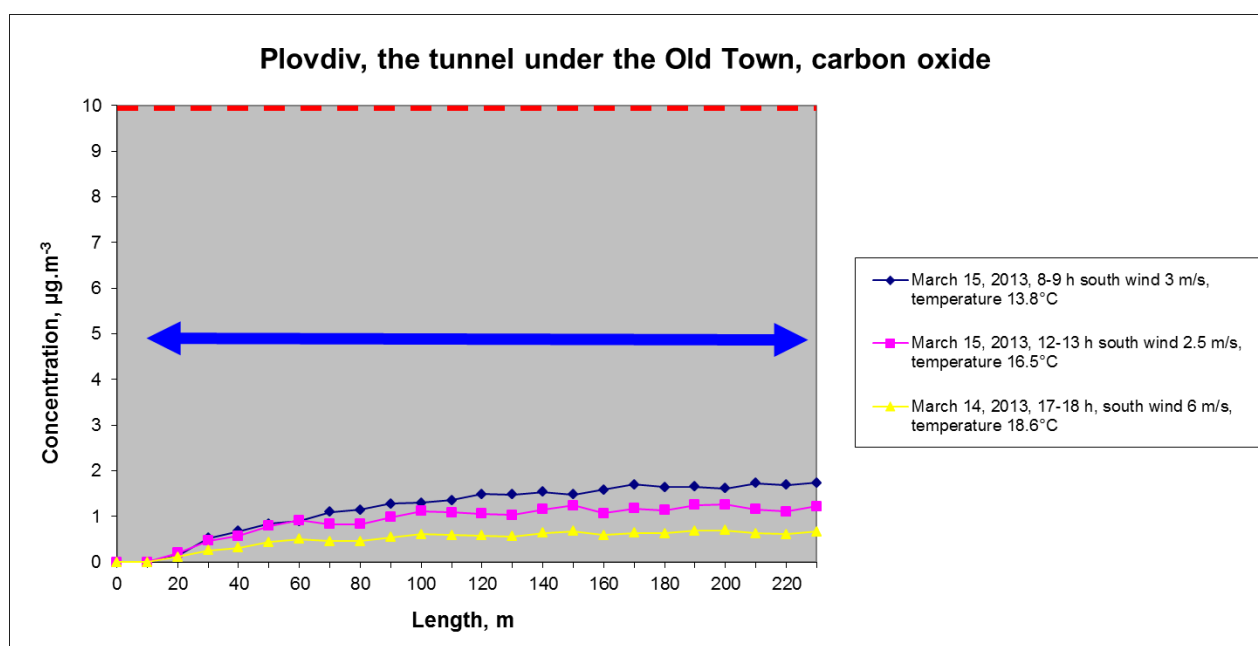

Fig. 5. Distribution of the carbon oxide concentrations along the axis line of the tunnel under the Old Town Plovdiv. A double arrow marks the tunnel length. A dashed line presents the threshold limit value (TLV).

When comparing the calculated by the Dispersion module values of CO concentration with those registered by the AMS, we found no statistical significant differences ($p < 0.05$). Fig. 6 shows the simultaneous change of the concentrations – the average one, calculated along the tunnel length and those, registered by AMS „Banya Starinna". Curves of the concentration change in two cases are parallel which confirms the validity of the model used. Comparison leads to the conclusion that the carbon oxide concentration in the tunnel (at the level of the car exhaust-pipes, along the axis line of the street) was about 1.5 times more than in the open air (30 m away from

the street, at 3 m above the ground – the height for sample taking by the analyzers of the automatic station).

Concentrations of the Soot from the burning fuel

Calculated concentrations of soot as a result of the fuel burnt by the engines in the tunnel are presented on Fig. 7. These are part of the dust particles ejected in the air by the traffic. Distribution of the pollution along the tunnel axis was quite similar to those of the nitrogen oxides and the carbon oxide; however, the concentrations of soot remained approximately two times lower than TLV. Negative relationships of the soot pollution by the wind and air temperature were found, similarly to the tendency of the nitrogen oxides level.

Fig. 8 presents the common change of the both concentrations – the average soot level, calculated for the tunnel axis, and the PM_{10} content in the ambient air, registered by AMS. Concentration of the dust particles

PM_{10} (particulate matter with aerodynamic diameter of 10 µm), registered with the automatic station and the calculated soot concentration were almost the same at noon, but significantly differed in the morning and evening when the air pollution outside the tunnel prevailed ($p<0.05$). This discrepancy between the observed and the calculated concentrations could be due to the emissions from domestic heating (during the experiment the heating season wasn't over yet) and to the increased dynamic atmosphere stability in the beginning and at the end of the day.

From the other hand, the particulate matter (PM) within the urban environment are often associated not only with exhaust emission, but also with tire, brake, vehicle and engine wear, or the re-suspension of road dusts (ALLEN *et al.*, 2001; HARRISON *et al.*, 2003; MONACI *et al.*, 2000; RIGA-KARANDINOS & SAITANIS, 2004; WÅHLIN *et al.*, 2006).
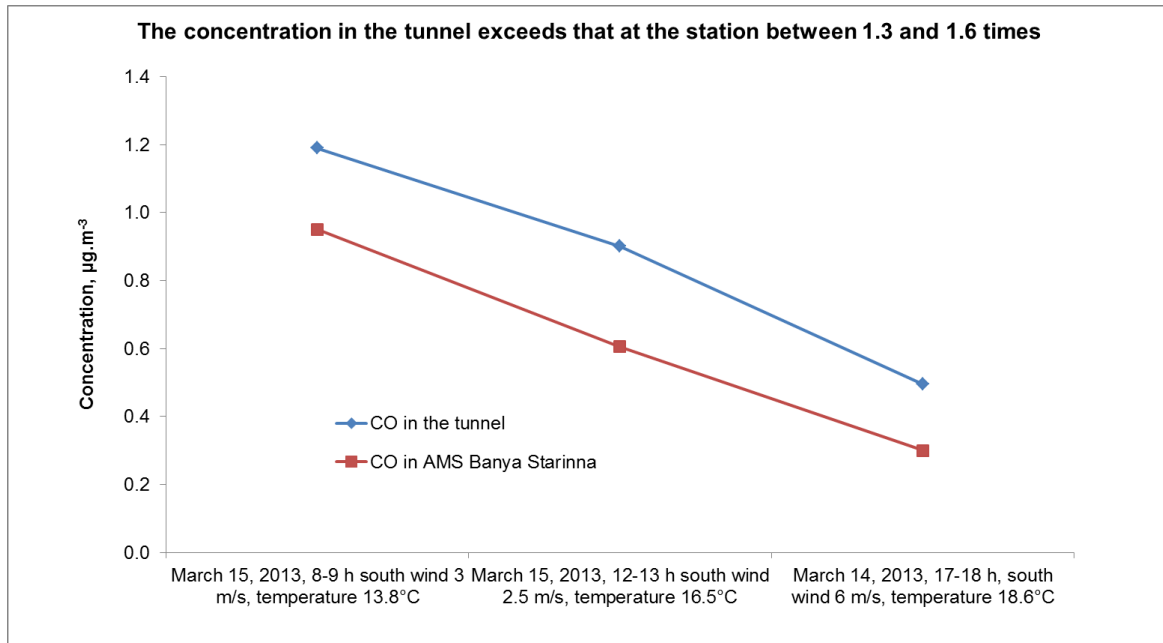

Fig. 6. Comparison between the carbon oxide concentrations – the one, calculated for the tunnel and the one, registered by AMS „Banya Starinna".
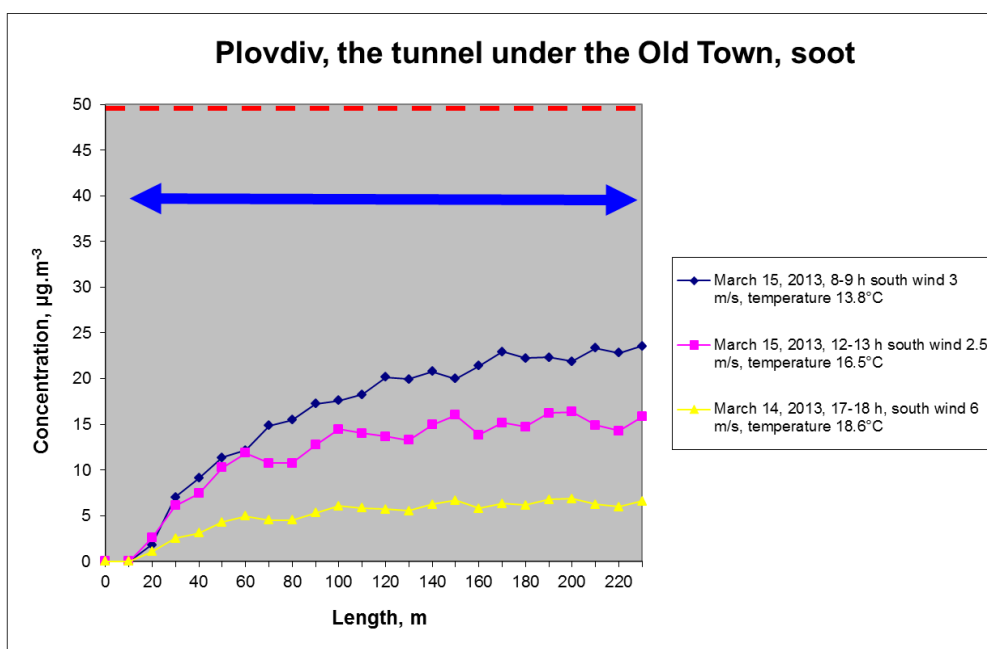
Fig. 7. Distribution of the soot concentration along the axis line of the tunnel under the Old Town Plovdiv. A double arrow marks the tunnel length. A dashed line presents the threshold limit value (TLV).
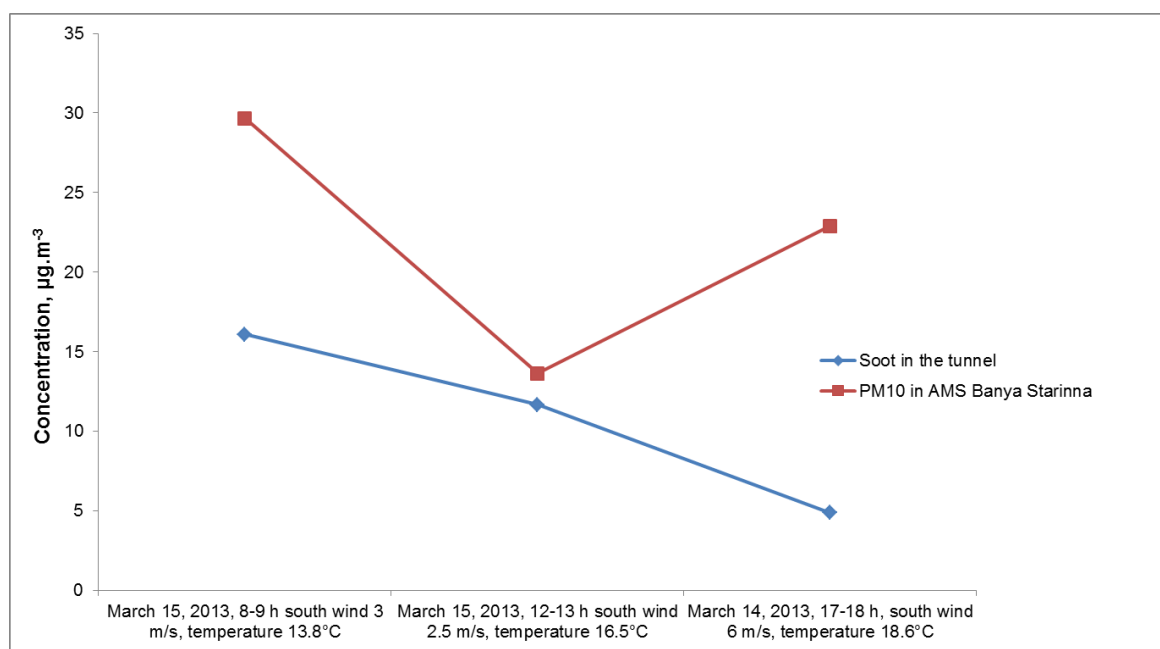

Fig. 8. Comparison between the concentrations of soot emitted in the air as a result of the engine combustion – the calculated concentration of soot by the engines in the tunnel and the concentration registered by AMS „Banya Starinna" differ in the beginning and at the end of the work day and almost coincide in the middle.

Average concentrations of NO_x, CO and Soot in the tunnel

Average concentrations of the studied air pollutants in the tunnel volume as a whole could be assessed by evaluation of the emitted pollutant mass in the tunnel, divided into its volume. Overall emitted pollutant mass of all MV in the tunnel could be calculated by multiplying the emission factor value to the time for MV passing through the tunnel. As the maximal permitted motion speed in city conditions is

50 km/h=13.9 m/s, and the tunnel length is 216 m, so the time for MV passing through the tunnel is 15.6 s.

Average pollutants concentrations in the tunnel were calculated as the emitted pollutants mass was divided to the tunnel volume (22680 m³) and were presented in Table 5. These concentrations in the tunnel volume could be used only for orientation since the wind and the atmosphere dynamic stability have not been taken into account, and the complete mixing of the emissions with the air in the tunnel was presumed.

Table 4. Emission factors of the pollutants during the experiment.

Time interval	Emission factor, g/s/m		
	NO$_x$	*CO*	*Soot*
8-9 h	0.0010138	0.0027713	0.0000375
12-13 h	0.0010128	0.0028481	0.0000369
17-18 h	0.0013583	0.0037529	0.0000370

Table 5. Average concentrations of the studied pollutants in the tunnel.

	Average concentration		
Time interval	*NO$_x$,* μg/m³	*CO,* mg/m³	*Soot,* μg/m³
8-9 h	134.2	0.37	4.96
12-13 h	134.1	0.38	4.88
17-18 h	179.8	0.50	4.90

Sources and characteristics of studied pollutants

By the recent decade we find ourselves in the middle of a period of rapid change in vehicle emissions. Improvements in vehicle and fuel technology have led to rapid reductions in the average rate of per vehicle emissions of CO and particulates. Emission modeling predicts that this reduction will continue, albeit at a reduced rate, for at least a further decade. Trends in the precursors of NO$_2$, however, are much less clear. There is emerging evidence that, in contrast to CO and PM, the trend is upwards. Whether all of this leads to improvement of the air quality depends on whether reduced emissions are offset by growth in traffic or increases in congestion.

Carbon monoxide emissions arise from incomplete or inefficient combustion. Petrol engines tend to emit greater amounts of CO than diesel. Technological advances have substantially improved CO emissions from newer vehicles, such that CO emissions from the vehicle fleet have rapidly declined over the last decade and reductions are expected to continue over the next decades.

Sources and determinants of **nitrogen oxides** in the tunnel are more complex. NO$_2$ can be emitted directly from vehicle tailpipes, but mostly indirectly via the emission of nitric oxide (NO). Diesel vehicles are the dominant source and the fraction of NO$_x$ emitted directly as NO$_2$ is also greater for diesel vehicles. The dominant source of NO$_2$ is in-situ chemical formation from the reaction of NO with ozone. Ozone is a natural component of the atmosphere. The reaction between NO and O$_3$ to form NO$_2$ is rapid, especially in the dark. For this reason, emissions of NO suppress the availability of O$_3$ in urban areas. Other factors also influence O$_3$ levels, and on a short-time basis ambient ozone can vary rapidly and unpredictably in response to meteorological conditions.

The potential for NO$_2$ formation inside tunnel is likely to depend on the external levels of ozone and how far it can penetrate into the tunnel before it is depleted. However, even if there is zero available

ozone, NO_2 can still arise in the tunnel from two less significant sources: from external (ambient) sources or from limited direct emission from the tailpipe (particularly from diesel engines). All of these factors are complex and difficult to predict. In summary, however, there is greater potential for elevated NO_2 levels, relative to CO, in rural tunnel with high proportions of diesel vehicles.

Nitrogen oxides are pollutants associated with several adverse respiratory effects, especially in children. Asthmatics have been shown to be particularly vulnerable to these effects and have an increased sensitivity to particles and allergens subsequent to NO_2 exposure. Inhalation of nitrogen dioxide in the presence of airborne particulates can lead to respiratory symptoms in asthmatics at concentrations which can occur in some road tunnels. However, this finding is based on exposures of 30 minutes or more; the effect of shorter exposures is currently unknown. Long-term repeated exposure, as may be experienced by regular commuters, has been associated with reduced lung function and other adverse effects in children.

Fine particulates are derived from both vehicle tailpipe emissions, resuspension of road dust, tire and brake wear and from material lost from truck loads. There are substantial evidences for effects on respiratory health, risk for exacerbations of cardiovascular disease (including mortality) and cancer. However, the casual pathways linking exposures to these effects are still active areas of research. Most of the evidence is focused on exposures of hours, days or years, not seconds or minutes. Although it is toxicologically plausible that very brief exposures to very high levels of vehicle-related particulates (as is the case in a road tunnel) poses a risk to health, there is currently insufficient scientific evidence to quantify any risk and there are no associated guidelines.

External air quality

A roan tunnel has an impact on external air quality because nearly all of the air pollutants emitted by vehicles within the tunnel are, at some point, vented into the ambient atmosphere, either via the portals, and/or via one or more stacks. This has the potential to lead to localized degraded air quality and the potential for exceedances of national standards.

For a tunnel without stacks, contaminated air is vented at the exit portals. Tunnel portal emissions are complex and difficult to assess. However, the extent of the affected zone is typically of the order of 100-200 m. If this localized impact is too high, the tunnel air can be vented elsewhere, at a ventilation station, and possibly via a tall stack. In some cases this stack is at some distance from the tunnel, so that tunnel air may be vented into the atmosphere in a non-residential location. Stacks are shown as remarkably efficient at dispersing pollutants (COLBERG *et al*., 2005). Concentrations at ground level are strongly reduced when stacks are used and very tall stacks can have minimal to zero impact in their local vicinity. One of the great advantages of road tunnels is the opportunity to deliberately site portals (or stacks) away from sensitive receptors so that road transport emissions may be removed from dense residential areas improving local air quality.

Conclusions

The 24-hour cyclic recurrence in the city traffic determines cyclic recurrence in the concentrations of the main pollutants – nitrogen oxides, carbon oxide and dust. During the experiment, two peaks were outlined in the traffic intensity through the observation point above the tunnel – in the time intervals 8:40 – 8:50 h and 17:15 – 17:35 h.

Comparison of the calculated concentration of nitrogen oxides and carbon oxide from the tunnel traffic to the concentration of the same air pollutants, measured by the automatic station, showed that the changes in the concentration are synchronous and proportional. This fact corresponds to our expectations upon supposition that the pollution source in the studied area is the same transport flow,

passing both through the tunnel and along the station. Changes of the both dust particles concentrations, calculated for the tunnel and measured by the station, respectively, differ in the beginning and at the end of the work day, probably due to the domestic heating.

Our study revealed that the main air pollutant in the tunnel is the nitrogen oxides whose concentrations were 4 to 6 times higher than TLV. Carbon oxide concentrations were 5 times lower than TLV and those of the soot – two times lower.

Compared to a surface road or the ambient environment, the air quality as experienced by tunnel users is relatively poor, with the concentrations of traffic-related contaminants likely to be many times higher inside as opposed to outside the tunnel. The two main determinants of in-tunnel concentrations (emissions from the tunnel openings into the external environment) are the rate of vehicle emissions and the rate of ventilation. Vehicle emission rates are related to vehicle volume, speed, the proportion of heavy duty vehicles, and road gradient. Carbon monoxide arises from tailpipe emissions, whilst nitrogen dioxide arises indirectly from the chemical oxidation of tailpipe emissions. Particulates arise from both tailpipe emissions, resuspension of road dust, tire and brake wear and from material lost from truck loads. Oxides of nitrogen arise from tailpipe emissions, with a bias towards diesel engines relative to carbon monoxide.

In recent years improvements in fuel specifications and vehicle technology has led to rapid reductions in the emission rates of CO and PM of new vehicles. NO_x emissions not arise from the reaction of the two main constituents of the atmosphere (nitrogen and oxygen) in the high temperatures of combustion, rather than any component of the fuel. NO_x emissions rates respond differently to fuel and technology change. In recent years NO_x emissions rates have reduced much more slowly than for CO and PM, a trend which is expected to continue for some years to come.

Consequently, a campaign of high quality NO_x measurements, supported by simultaneous, detailed and continuous monitoring of traffic flow, speed and composition and air flow is recommended as a first priority. An interim objective should be to evaluate or adjust a tunnel-specific emission model for prediction of future ventilation demand.

Tunnel monitoring campaigns are critical for ensuring the all air quality management/air pollution mitigation measures, such as road tunnel ventilation systems, correctly to ensure they continue to provide the designed level of mitigation in order to meet objectives set in the Bulgarian legislation.

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