Motor transport related harmful PM2.5 and PM10: from on-road measurements to the modelling of air pollution by neural network approach on street and urban level

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Abstract. The level of PM10 and PM2.5 concentrations in the air on seven roads in St. Petersburg, Russia, were investigated using gravimetry and nephelometry measurement techniques in 2013-2015. The effects of meteorological conditions (temperature, relative humidity, wind direction, and speed) and the intensity of traffic flows on the results of the measurements were also evaluated. On the base of the measurements, there was developed a neural network modelling approach that allowed to quantify exhaust / non-exhaust PM10 and PM2.5 emissions and carry out numerical investigations of air pollution by transport related PM2.5 and PM10 on street and urban level in St. Petersburg.

1. Introduction
PM10 are the particulate matter with a diameter of 10 µm (or less) and PM2.5 are the particulate matter with a diameter of 2.5 µm (or less) suspended in the atmosphere. PM10 are also known as “inhalable coarse particles” able to penetrate into the human lungs. PM2.5 (“fine particles”) can pass not only into the respiratory system but also in the blood. Numerous scientific studies [1, 2] have linked particle pollution exposure to a variety of health problems, including premature death in people with heart or lung disease, nonfatal heart attacks, aggravated asthma, etc.

Road traffic is one of the most important sources of PM10 and PM2.5 emissions. Road traffic emissions include not only PM released from motor exhausts, but also “non-exhaust” particles derived from the brake wear, tire wear, road surface wear, and from the resuspension due to the turbulence generated by vehicle wheels [3-5].

The usage and the comparison of direct gravimetry and indirect nephelometry methods for the estimation of harmful PM10 and PM2.5 in the air near roads and highways allow to improve the quality and the accuracy of the experimental measurements and to develop mathematical models, allowing to carry out numerical investigations and monitoring of air pollution, on their base [6, 7]. A neural network approach is a highly attractive technique to build multi-level models of air pollution in megacities [8-11].
2. Measurement techniques and modelling methodology

2.1. PM10 and PM2.5 on-road concentration measurements

The results of proper measurements of PM concentrations as well as the data of measurements from mobile and stationary monitoring stations, kindly provided by the Committee on Environment Management, Environmental Protection and Ecological Safety of the Government of St. Petersburg (hear and after the Committee), were analyzed in the present investigations. PM10 and PM2.5 on-road concentrations were determined using two main measurement techniques – gravimetry and nephelometry. Gravimetry is a direct analytical approach used for the routine estimation of PM mass concentrations. Its main advantage is that the results of measurements are not influenced by the chemical and physical properties of particles, but it is a highly laborious method. Moreover, it generally requires long averaging times (> 12h) to collect enough amount of the analyte on the filters. So, it can’t show short-term temporal variations in PM concentrations. Nephelometry techniques based on the light scattering, on the contrary, allow real-time estimation of PM concentrations. However, light scattering is sensitive to particle size distribution, shape, and composition (refractive index and absorption) [12-14].

Nephelometry measurements. Proper simultaneous measurements of PM10 and PM2.5 concentrations were carried out in 2015 on four busy roads of St. Petersburg (Moskovsky pr., Mitrofan’evsky road, Koltushsky road and St. Petersburg Ring Road) using two laser DUSTTRAK 8530 spectrometers (TSI Incorporated / USA). The validation of DUSTTRAK 8530 measurements against gravimetric measurements has shown that DUSTRAK 8530 overestimated the daily mean ambient PM10 by a factor of 1.3-1.7 and PM2.5 by a factor of 1.7-2.1, like in previous investigations [12-14]. The measurements of PM2.5 and PM10 concentrations by the mobile monitoring laboratory were performed in 2012-2013 on the other busy roads (Ligovsky pr., Slavy pr. and Piskarevsky pr.) by means of an Air Pollution Monitor APM-2 nephelometer (Comde-Derenda GmbH / Germany).

The data of gravimetric measurements of PM10 (from the monitoring station № 3 in Karbysheva str.) and PM2.5 (from the station № 18 in Olga Forsh str.) for the March 2015 were provided by the Committee. A PNS16/18MT-3.1/6.1 (Comde-Derenda GmbH / Germany), equipped with a magazine with 15 filter cassettes, is used for the automatic continuous sampling of PM10 and PM2.5 on glass fiber filters, 47 mm in diameter. The filters are weighed before and after the sampling at ambient temperature 20 ± 1°C and relative humidity 50±3 %. We didn’t validate APM-2 nephelometric measurements against gravimetric measurements in this study, but according to the information of the Committee, the gravimetric and real-time nephelometric measurements are reasonably well correlated [15].

2.2. Investigation of traffic flows on St. Petersburg roads

We examined traffic situation on seven roads in St. Petersburg with intensive traffic at the morning and evening rush hours. Such parameters as the average speed of traffic flows, location geometry (average height of buildings and width of the street), meteorological parameters (temperature, relative humidity, wind direction, and velocity) were also considered.

2.3. Neural network approach

On the base of the measurements, there was developed a neural network model with parameters (weights) tuned via optimization methods [9, 10] (the RProp method and the combination of cloud and RProp methods were in use). The neural network model of the complex system can gather pieces of heterogeneous information – differential equations, conservation laws, equations of state, symmetry conditions, etc. The information exchange via neural network parameters between different levels of hierarchy makes computing less resource consuming. A neural network approach is an attractive technique to build multi-level models of air pollution in mega-cities. There was developed a neural network model for the estimation of air pollution in St. Petersburg by PM10 and PM2.5 on the city- and street-level. The modelling technique allowed also to estimate the impact of different PM sources related to road transport: exhaust PM, non-exhaust PM (including brake wear, tire wear, road surface).
3. Results and discussion

The results of on-road measurements of PM concentrations are presented in Table 1.

Table 1. Average PM concentrations, µg/m³, on roads of St. Petersburg.

| Road               | Rainy days, slow/moderate wind | Sunny/drizzly days, slow/moderate wind | Sunny dry days in spring, moderate wind |
|--------------------|--------------------------------|----------------------------------------|----------------------------------------|
|                    | PM10  | PM2.5  | PM10  | PM2.5  | PM10  | PM2.5  |
| St. Petersburg Ring Road | 27.3±2.2 | 21.8±1.5 | 63.4±8.1 | 30.0±6.3 | 230.8±31.4 | 116.7±15.8 |
| Moskovsky pr.      | 8.0±3.6 | 4.4±0.6 | 34.2±3.4 | 17.3±2.5 | 57.6±4.1 | 19.1±3.9 |
| Ligovsky pr.       | 7.8±1.3 | 3.8±1.4 | 20.1±6.1 | 11.4±4.3 | 88.2±7.2 | 48.5±6.0 |
| Pr. Slavy          | 9.9±3.1 | 5.0±1.9 | 28.7±5.6 | 14.3±4.9 | 72.4±7.1 | 46.4±8.1 |
| Piskarevsky pr.    | 10.9±1.1 | 4.2±1.3 | 30.5±5.8 | 12.3±3.4 | 124.5±7.2 | 64.2±8.3 |
| Koltushsky road    | 18.8±5.2 | 14.1±2.9 | 53.4±7.3 | 21.7±3.4 | 187.5±9.1 | 54.8±7.3 |
| Mitrofan'evsky road| 17.0±2.5 | 8.9±2.4 | 49.2±8.1 | 26.3±3.1 | 255.6±13.9 | 50.9±7.5 |

The results of on-road measurements have shown that weather conditions in St. Petersburg are mostly favorable for the precipitation of PM pollutants and usually the concentrations of PM10 and PM2.5 are below national 24h Limit Values (60 µg/m³ for PM10 and 35 µg/m³ for PM2.5). Average PM10 and PM2.5 concentrations are about 7-20 µg/m³ and 3-15 µg/m³, respectively, at rainy/drizzly days on the roads with moderate traffic volume (2500-4500 vehicle per hour) free from heavy duty vehicles (Moskovsky and Ligovsky prospects) and on the roads with the share of HDV ranging within 1-10 % (Prospect Slavy, Piskarevsky prospect, Koltushsky road, Mitrofan'evsky road). PM10 and PM2.5 concentrations on the St. Petersburg Ring Road (SPbRR) with traffic volume 7500-12000 vehicle per hour and the share of HDV ranging within 10-25% mostly suit national annual Limit Values (35 µg/m³ for PM10 and 25 µg/m³ for PM2.5) but exceed the European annual Limit Values (25 µg/m³ for PM10 and 12 µg/m³ for PM2.5).

The problem of excess PM10 and PM2.5 air pollution become significant in early spring when the roads are covered with huge dust-deposits accumulated through the winter. The investigations carried out on the SPbRR at different weather conditions in March, April and May 2015, namely, (1) Dry sunny day after 8 dry days in March (high visible level of dusting), (2) Dry sunny day after night drizzle in March (high visible level of dusting), (3) Dry sunny day after some rainy days and road washing in April, (4) Rainy day after road washing in April, (5) Dry sunny day after some rainy days and road washing in May, showed that the measured PM10 concentrations exceeded 24 hours Limit Value by 2.8-3.9 times and PM2.5 – by 2.4-3.3 times in March 2015. After some rainy days and washing, the PM concentrations have fallen below LV (Table 2). At the same time, the share of PM2.5 has increased from 49.6 % in March to 77.7 % in May, indirectly indicating the trend of the increasing share of exhaust PM.

Table 2. Average PM at different weather conditions on the St. Petersburg Ring Road

| Average PM, µg/m³ | Conditions of PM monitoring / date |
|-------------------|-----------------------------------|
|                   | 1/19.03.15 | 2/20.03.15 | 3/06.04.15 | 4/14.04.15 | 5/24.05.15 |
| PM10              | 230.8±31.4 | 167.3±34.2 | 63.4±8.1   | 38.3±9.5   | 27.3±2.2   |
| PM2.5             | 116.7±15.8 | 84.6±21.7  | 30.0±6.3   | 25.5±7.6   | 21.8±1.5   |
| PM2.5/PM10        | 0.496      | 0.503      | 0.525      | 0.657      | 0.777      |
The results of PM10 and PM2.5 gravimetric measurements from the monitoring stations №3 and №18, respectively, for the period from 12 to 19 March 2015 confirmed that the average measured PM10 and PM2.5 concentrations exceeded National 24-hour Limit Values, by a factor of 1.2 and 1.6, respectively.

On the basis of the measurements, there was developed a city- and a street-level neural network model for the estimation of air pollution in St. Petersburg by PM10. The street model was developed on the base of the Gaussian dispersion \[16, 17\]. Taking into account the principle of superposition and replacing the integral by a cubature formula, we receive the formula:

\[
q_i(t; x_0, y_0, z_0; u_x, u_y) = \sum_{i=0}^{n} K_i \left( \sqrt{2\pi t} \right)^3 \exp \left( \frac{(x_i - x_0 - u_x t)^2}{2(\sigma_x^2 t)} - \frac{(y_i - y_0 - u_y t)^2}{2(\sigma_y^2 t)} - \frac{(z_i - z_0)^2}{2(\sigma_z^2 t)} \right),
\]

where \(q\) is the concentration of pollutant (g/m\(^3\)); \(Q\) is the emission of pollutant (g m\(^{-1}\) s\(^{-1}\)); \(t\) is time (s), \((x_0, y_0, z_0)\) are the coordinates of the emission source (m); \(K_i\) are numerical coefficients; \((x_i, y_i, z_i)\) are the integration points (m); \((u_x, u_y)\) are the components of wind speed and direction (m/s); \(\sigma_x, \sigma_y, \sigma_z\) are the Gaussian horizontal and vertical dispersion parameters. It is evident that this model corresponds to the artificial neural network with Gaussians as radial basis functions.

The calculations on city-level allow to identify the districts of St. Petersburg mostly affected by PM10 air pollution (taking into account the dependence of air pollution on wind direction and speed) and receive air pollution diagrams on city-level (Fig. 1).

Figure 1 demonstrates that moderate south-western winds contribute to the accumulation of PM10 in the central and, mostly, in the eastern parts of the city, and can lead to increased concentrations of PM10 exceeding the National Limit Value by 1.1-3.5 times at adverse weather conditions. The on-street model was developed on the base of the Russian normative document for the calculation of the dispersion of harmful substances in the atmospheric air - OND-86 [18, 19].
OND-86 is based on the analytical approximation of the results of joint numerical integration of the equation of atmospheric diffusion and the system of equations of hydro thermodynamics for the atmospheric boundary layer [18, 19].

Using this approach, also known as K-theory, together with some approximations and assumptions [6, 18, 19], there was established that the concentration of a pollutant emitted from an unregulated line source, such as a traffic flow, is as follow [6]:

$$C_m = \frac{AMFm \eta}{H^{7/3}},$$

where $C_m$ is the concentration of pollutant (g/m$^3$); $A$ is the coefficient considering the temperature stratification of the atmosphere; $M$ is the joint emission of pollutant from traffic flow (g/s), $F$ is the dimensionless coefficient considering the velocity of gravitational sedimentation of particulate matter; $m' = 0.9$; $\eta$ is the dimensionless coefficient considering the influence of the terrain relief; $H$ is the source height (m).

The calculations on street-level predict that the adjacent area of the St. Petersburg Ring Road may be exposed to the enhanced levels of PM$_{10}$ exceeding National Limit Value by 1.1-3.0 times at intensive traffic and unfavorable weather conditions (Fig. 2).

Figure 2. Visualization of the air pollution by exhaust and non-exhaust PM$_{10}$ at adverse weather conditions on the busiest segment of the St. Petersburg Ring Road (near the prospect of Obukhovskoy Oborony).

Conclusions
The results of the measurements have shown that the roadside concentrations of PM$_{10}$ and PM$_{2.5}$ in St. Petersburg are mostly within the National and the European Limit Values. Short-term exceedances may occur in early spring when road dust resuspension contributes considerably to particle concentrations in the air. Vehicle-related PM air pollution in St. Petersburg is, generally, lower than in the European capitals and big cities because of the lower share of diesel passenger vehicle fleet (5.4% in St. Petersburg against 70.4% in Paris). Direct-reading nephelometric instruments are suitable for the real-time monitoring of daily variation of the roadside PM$_{10}$ and PM$_{2.5}$ concentrations, however, this method is sensitive to particle shape and composition. Recalibration for the specific aerosol, considering also seasonal variations, is necessary to produce valid measures of airborne particulate matter.

The validation of the results of the numerical investigations on street-level showed the underestimation of PM concentrations in comparison with the measurements. The underestimation of the modelled PM concentrations by 5-15% may result from the neglect of dust resuspension on roads. Hence, there is a need to develop a model forecasting road resuspension emissions in order to contribute to the optimization of environment quality management in the Russian Federation.
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