Engineering Method for Calculating Changes in the Structure and Intensity of Traffic Flow

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Abstract. The real costs of the population caused by pollutants emitted by motor vehicles operating on the roads of cities of the Russian Federation are directly related to the intensity and structure of motor vehicle flows. The paper solves the scientific and practical problem of reformating the data of instrumental online monitoring of the intensity and structure of motor vehicle flows on the street and road network of St. Petersburg into numerical information, adapted to the program for calculating the expected air pollution with pollutants emitted by road traffic for conditions of extremely dangerous vulnerability of the urban population. The conditions of extremely dangerous vulnerability of the urban population are determined by a combination of unfavorable meteorological factors for the dispersion of pollutants with hours of maximum traffic load (rush hours of automobile traffic). An engineering technique for calculating changes in the structure and intensity of motor vehicle flow and an original program for its implementation by means of MS Excel are presented. New statistical patterns of changes in the intensity of motor vehicle flows for typical highways and streets have been obtained, which make it possible to reliably predict in real time the local situations of extremely dangerous for the urban population air pollution with pollutants emitted by road traffic. Computational study, using the developed methodology, found that on the most loaded ring line in St. Petersburg in the vicinity of the cable-stayed crossing "Obukhovsky Bridge", under unfavorable meteorological conditions during rush hours it is likely to expect a multiple excess of the maximum permissible standards for dioxide nitrogen NO₂ (up to 10 MACMOT). The calculation method efficiency has been confirmed when solving specific problems of urban motor vehicle flow management under extreme meteorological and road conditions.
1. Introduction
A sharp increase in the number of vehicles operated in densely populated districts of cities of the Russian Federation (in St. Petersburg, in comparison with 1980, more than 10 times), together with an increase in extreme manifestations of a hydro-meteorological and transport-road nature, led to an aggravation of the factors of potentially dangerous chemical impact on urban population living in the vicinity of major highways.

The main factors and conditions of the potentially dangerous impact of motor transport on the population include:
- an increase in road traffic accidents (RTA);
- excess chemical air pollution;
- growth of regularly recurring extreme climatic and hydro-meteorological conditions favorable to the aggravation of various vulnerability factors (prolonged temperature inversions and wind loads, fogs, smog, icing of the roadway, etc.).

The most dangerous is the impact of pollutants emitted by motor vehicles; therefore, there arose the scientific and applied problem of determining the intensity and structure of the motor vehicle flow on city highways to control and prevent factors of extreme and extremely dangerous technogenic vulnerability of the urban population.

2. Relevance and scientific significance of the issue with a brief review of the literature
The value of real costs caused by the manifestation of factors of complex population vulnerability by vehicles operating on the roads of the Russian Federation is directly related to the intensity and structure (type, state of constructive safety, environmental class) of the motor vehicle flow. Consequently, the organization of control and management of motor vehicle flows based on predicting the traffic intensity and the associated complex costs of the urban population caused by transport should be considered an urgent scientific and practical task.

One of the first models developed was the Graz model [1]. This model is a method for estimating emissions from road traffic in direct combination with driving pattern records. It has been used to estimate measures to reduce motor vehicle flows. In the United States a similar approach was based on measurements using FTP-75 and highway driving cycles [2]. Another model was created as part of the Drive / Modem project [3]. In this work, 14 urban driving cycles were developed from driving patterns recorded in several European cities. These cycles are used as the basis for vehicle dynamometer testing. Emissions data are recorded continuously and result in compiling matrices with velocity and acceleration parameters. Joint studies to estimate emission factors were carried out in Germany [4] and Switzerland [5]. In the course of these studies instantaneous emission data from passenger cars were used to determine emission factors. In [6], a methodology for calculating exhaust gas emissions from road transport in cities with insufficient statistical data on road traffic and an outdated vehicle register is presented. The COPERT3 model of the European Environment Agency [7] provides a set of aggregated emission factors. Average speed models, which are often used in conjunction with macroscopic transport models, relate emissions and fuel consumption to the average speed of each driving cycle for each vehicle category. The multiple linear regression models show the relationship between driving dynamics and emission rates. The dynamics of traffic is described by various parameters of the model and their derivatives. Velocity-time profiles are used as input and are generated by traffic intensity “micro-models”. In [7], a regression model was derived for the air pollutant under consideration and the vehicle category. In [8], a Passenger Car Emission System (PCEU) was developed for estimating transport emissions. The paper [9] presents results of experiments on emissions in real time, which were carried out in Bogotá for 78 light vehicles. The work [10] provides a methodology for determining vehicle emissions using the COPERT-5 tool, which includes emission factors for more than 240 individual types of vehicles. In [11], when considering the COST-319 methodology, the composition of the vehicle fleet is divided into several categories, which are determined by emission or utilization factors. The Traffic Measurement Tool
[12] is designed to collect high quality, consistent road traffic data for subsequent analysis of greenhouse gases and local pollution.

Works [13] - [18] are devoted to the study of structure and intensity of traffic under conditions of extreme and extremely dangerous complex technogenic vulnerability of the urban population. In [19], [20], methods are given for calculating exhaust gas emissions from road transport in cities, data on traffic in which require development.

3. Statement of the problem
Assessment of the intensity and structure of the motor vehicle flow will make it possible to more accurately carry out the forecast for the control and prevention of factors of extreme and extremely dangerous technogenic vulnerability of the urban population in the vicinity of highways. The objective of the study is to develop an engineering methodology for calculating changes in the structure and intensity of motor vehicle flow under conditions of extremely dangerous vulnerability of the urban population - "rush" hours of traffic load and unfavorable meteorological factors.

4. Theoretical and methodological part
The methodology is based on online information on the structure and speed of motor vehicles, obtained by sensors for automated traffic census on the road network of St. Petersburg. Online information is formed into an electronic protocol of initial data (text file [21]), an example of which for the cable-stayed transition "Obukhovsky Bridge" is shown in Fig. 1. Knowing the structure and intensity of traffic flows, it is possible to estimate the emissions of harmful (polluting) substances by motor vehicles moving along the road (or its section) of a fixed length L, km [13].

The protocols (text files) for each series of measurements included the following information for all eight traffic lanes in conventional abbreviations: overall traffic intensity (VOLUME), traffic intensity by four groups of freight vehicles: MID SIZE 1 (Freight vehicle <5 tons), MID SIZE 2 (Freight vehicle 5–12 tons), LONG VEH 1 (Freight vehicle 12–20 tons), LONG VEH 2 (Freight vehicle > 20 tons) and passenger transport. In addition, the files record the speed of movement (SIDEFRD SPD) and the number of unidentified cargo objects (XLONG VEH) [21].
Figure 1. An example of an excerpt from a text file, which is obtained using sensors of automated traffic census.

In view of the fact that the sensors of automated traffic census do not provide the required information for the environmental control of motor vehicles, the digital data of text files by means of the original program using MS "Excel" is reformatted into information corresponding to the groups which are covered by our methodology (Table 1) [21].

The calculation for each line of Table 1 (the line corresponds to the time of fixing the number of vehicles by sensors - from the protocol file in Fig. 1) of the intensities of their movement is carried out by preliminary recalculation of the data from the protocol file into the number of vehicles by groups under consideration according to the developed formulas:

- I – passenger vehicles (P): [(VOLUME+XLONG VEH) – (MID SIZE 1+MID SIZE 2+LONG VEH 1+ LONG VEH 2)];
- II – vans and minibuses up to 3.5 tons (VM): MID SIZE 1;
- III – freight vehicles from 3.5 to 12 tons (F3,12): MID SIZE 2 - 0,15 MID SIZE 2;
- IV – freight vehicles over 12 tons (F>12): LONG VEH 1 + LONG VEH 2;
- V – buses over 3.5 tons (B>3,5): 0,15 MID SIZE 2.
Table 1. The table of recalculation of the sensors readings into the intensity (vehicle / hour) of movement by the groups of vehicles under consideration.

| Date, time | Traffic intensity (vehicle / h) by groups | Total traffic intensity (vehicle / h) | Average speed of movement in the flow, km / h |
|------------|------------------------------------------|-------------------------------------|-------------------------------------------|
|            | P | VM | F_{<12} | F_{>12} | B_{>3.5} |            | Passenger vehicles | Freight vehicles | Buses |
| 20/04/2018 12:40 | 24 | 5 | 2.55 | 2 | 0.45 | 34 | 53 | 84 | 65 |
| 20/04/2018 12:45 | 21 | 5 | 0.85 | 0 | 0.15 | 27 | 56 | 79 | 70 |
| 20/04/2018 12:50 | 27 | 6 | 1.7 | 2 | 0.3 | 37 | 65 | 79 | 68 |
| 20/04/2018 12:55 | 32 | 8 | 1.7 | 2 | 0.3 | 44 | 67 | 78 | 66 |
| 20/04/2018 13:00 | 32 | 4 | 2.55 | 1 | 0.45 | 40 | 68 | 79 | 73 |

Statistical equations for the intensities of traffic flows were obtained using MS "Excel" for three typical city highways and streets: type 1 (with one or two characteristic maximums of traffic intensity, 25-30% higher than the average hourly daily value of intensity, observed in the morning (8-10) and evening (17-19) time); type 2 (with increased traffic intensity of traffic flows, with hourly deviations of up to 10-20% of the highest hourly intensity value, with traffic intensity up to 1500-2000 thousand vehicle / hour, observed in the period from 7-8 to 20-21); transit roads.

5. Results of experimental studies

Based on experimental and computational studies on predicting the quality of atmospheric air at the boundaries of established sanitary protection zones in the vicinity of sea and river ports [13, 14], it can be argued that the cable-stayed crossing “Obukhovsky Bridge” is the most loaded in St. Petersburg. The average values of traffic intensity on this crossing within the period from 20.04.2018 to 28.04.2018 are shown in Table 2.

Table 2. Average values of traffic intensity and speed obtained on the Obukhovsky bridge section in St. Petersburg within the period from 20.04.2018 to 28.04.2018.

| Date       | Traffic intensity (vehicle / h) by categories | Total traffic intensity (vehicle / h) | Flow speed, km/h |
|------------|-----------------------------------------------|-------------------------------------|------------------|
|            | P    | VM  | F_{<12} | F_{>12} | B_{>3.5} | Passenger vehicles | Freight vehicles | Buses |
| 20.04.18   | 6836 | 1366 | 356     | 299     | 63      | 8919 | 59,9 | 81,51 | 78,44 |
| 21.04.18   | 4550 | 845  | 229     | 258     | 40      | 5922 | 43,85 | 70,75 | 64,55 |
| 22.04.18   | 4186 | 932  | 249     | 272     | 44      | 5683 | 46,47 | 71,26 | 59,44 |
| 23.04.18   | 5350 | 1209 | 300     | 269     | 53      | 7181 | 50,58 | 67,69 | 59,19 |
| 24.04.18   | 5243 | 1183 | 332     | 255     | 59      | 7071 | 48,92 | 65,8  | 60,25 |
| 25.04.18   | 5367 | 1074 | 294     | 269     | 52      | 7056 | 44,87 | 70,48 | 60,12 |
| 26.04.18   | 5409 | 1096 | 310     | 281     | 55      | 7151 | 45,2  | 73,06 | 63,97 |
| 27.04.18   | 5242 | 1168 | 251     | 247     | 44      | 6952 | 49,04 | 71,79 | 68,16 |
| 28.04.18   | 3417 | 781  | 184     | 181     | 32      | 4595 | 39,47 | 67,28 | 56,65 |
Figure 2 shows the change in values of the traffic intensity of motor vehicles at the cable-stayed crossing "Obukhovsky Bridge" in St. Petersburg by groups under consideration, and Figure 3 shows this change in total for all groups of motor vehicles under consideration within the analyzed time interval from 20.04.2018 to 28.04.2018.

Computational study, using the developed methodology, the “Highway - City” software and "Ecologist", the unified program for calculating the atmospheric pollution, developed by the "Firm" Integral-Soft "LLC (St. Petersburg), made it possible to find out (Fig. 4) that on the most loaded ring road in St. Petersburg in the vicinity of the cable-stayed crossing "Obukhovsky Bridge" under unfavorable meteorological conditions during rush hours, it is likely to expect a multiple excess of the maximum permissible norms for nitrogen dioxide NO₂ (up to … MACΜΟΤ).
To predict the traffic intensity of motor vehicles while controlling its technogenic impact on the population under emergency conditions using MS Excel, the following statistical dependencies were obtained (averaged, for the streets and roads of St. Petersburg):

- for type 1 highways and streets:
  \[ y = -14.16x^2 + 1248.73x - 3662.1; \]

- for type 2 highways and streets:
  \[ y = -15.85x^2 + 1374.65x - 4031.4; \]

- for transit roads:
  \[ y = -17.28x^2 + 1524.18x - 4469.9; \]

where \( y \) – traffic intensity of motor vehicles for typical roads, vehicles/hour; \( x \) – time intervals during the day, which correspond to the values of traffic intensity of motor vehicles \( y \).

The obtained new statistical regularities of changes in the structure and intensity of traffic flows on city highways will make it possible to reliably identify in real time local situations of atmospheric pollution with harmful substances that are extremely dangerous for the population.

Figure 4. The results of calculating the maximum permissible concentrations by groups under consideration for \( \text{NO}_2 \) at the cable-stayed crossing "Obukhovsky Bridge" in St. Petersburg within the analyzed period from 20.04.2018 to 28.04.2018.

6. Findings

An engineering method has been developed for calculating changes in the structure and intensity of motor vehicles flow, as well as an original program for its numerical implementation in MS "Excel" under conditions of extremely dangerous vulnerability of the urban population.

The new statistical regularities of changes in the structure and intensity of traffic flows obtained using the described method for typical highways and streets of St. Petersburg are adequate to reliably identify in real time the local situations of air pollution with motor vehicle pollutants that are extremely dangerous for the population.

Efficiency of the calculation method was confirmed when solving a specific problem of assessing transport and environmental loads in the vicinity of the cable-stayed crossing "Obukhovsky Bridge" over the Neva River under extreme meteorological and road conditions. Under such conditions, it is likely to expect a multiple excess of the maximum permissible norms for nitrogen dioxide \( \text{NO}_2 \) (up to 10 MACMOT).

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