Spatiotemporal Dynamics of Air Pollution on Main Streets

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Abstract. Following the continuous field studies, daily cyclograms have been obtained for carbon oxide concentration in the air, wind velocity, and traffic intensity on main streets of a big city. It was stated that the morning and evening maximums in the air pollution are determined by the quantity adjustment of the incoming exhausts, by temperature and aeration regimes in the street environment. The following factors influence the spatiotemporal change of the pollution level: direction of roads and streets, number of floors and density of buildings, planning and tree planting techniques. It is shown that during designing and exploitation of transportation infrastructure, leveling of daily “peaks” in the air pollution can be provided by optimum geometric parameters of the cross section of main streets of various categories, removal of the transit traffic to alternate routes as well as individual transportation restriction in city centers.

1. Introduction

The problem of reducing the air pollution in residential areas by vehicle exhausts acquires an acute character in big, large and metropolitan cities with historically established street and road network (SRN) with a high density of narrow streets. The discrepancy of the planning structure of these cities for passing of transportation flows of high intensity with a deficit of space for parking results in a sharp reduction of traffic speed and the increase of pollutant emissions.

The nature of spatial distribution and impact on the environmental conditions from the focus of the increased ingredient chemical pollution is reflected above all in the structure and the level of ecologically determined (sustainable) morbidity of population living within the residential areas in the corresponding zones of discomfort. The ground mapping by the results of calculation of the urban environment pollution and by data from social and hygienic monitoring shows that as a rule, most anomalies of the higher morbidity of population lie in the city downtown along the streets with heavy traffic [1, 2].

The spatiotemporal variability of zones with higher concentration of traffic emissions has a number of specific features determined by a complex structure of transportation flows – linear sources of pollution, the evident nonstationarity (instability) of their functioning, the unstable regime of traffic, as well as the impact of the city development and the elements of beautification on the impurity transfer and the atmospheric dispersion [3]. The higher gas pollution has been observed at the still values of wind velocity, temperature inversions and is intensified by the “urban heat island” [4], when the industrial emissions from industrial districts are propagated in the direction to the city center replacing the rising air currents and forming a background for the air pollution fields by vehicle emissions. In the given case detailed
records and ranging by the importance of factors determining the level of pollution in the residential area are of key value with separation according to deadlines of measures for reducing the air pollution.

The economic efficiency of the environmental protection measures is determined by comparison of the acquired level of impact of transportation infrastructure on the protection objects with the already existing one. Within the corresponding calculations, there is assessment of damages in specific periods with the deduction of total expenditure for implementation the environmental protection measures [5]:

\[ E = \sum D_t - \sum D_H - \sum C, \]

where \( \sum D_t \) and \( \sum D_H \) – respectively total damages from the urban environment pollution by vehicle emissions in the branches under study before and after the environmental protection measures; \( \sum C \) – cost of measures for the environmental protection.

When choosing air protection measures, the recommendations to use standard practice are taken into account to calculate one-time concentrations of hazardous substances (excluding benzapyrene and heavy metals) [6]. However, when determining damages in such branches as health protection and urban economy, it is necessary to use indexes of air pollution intending a longer impact of pollutants on population, green plantations, buildings, structures, cultural and architectural landmarks, etc. Therefore, in the corresponding estimates, the level of air pollution in the residential areas and public centers of cities is brought to the annual average values.

If we take into account the indexes of specific damage for the health protection per 1 person depending on the annual average concentration of carbon dioxide (CO) [7], then the corresponding damage from air pollution in the residential area of the city by the given contaminant in composition of the exhaust gases (EG) can be determined by the formula:

\[ D = H_d \cdot d_{hc} \cdot P, \]

where \( H_d \) – number of population living in a discomfort zone; \( d_{hc} \) – specific damage for public health per 1 person (in rubles/year) done under the impact of the annual average concentration of CO; \( P \) – duration of the considered period in years.

Annual average concentrations of EG in some spots of the street-road network (SRN) in the city can be stated by one time concentrations with consequent average-out per day, for each of the 12 months and per year.

The target of this work is to study temporal dynamics of air pollution by vehicle exhausts (emissions) in spots of the city SRN per scheduled time of day, week days and year months taking into account the influence of traffic flow parameters, meteorological conditions and planning and development techniques for main streets.

2. Methods used in the experiment

The study has been made in the summertime in a large city of the III -rd climatic zone characterized by a moderate continental climate with a big annual range of air temperature variation [8]. Average wind speeds are within 3…5 m/s. Frequency of the wind speeds 0…1 m/s amounts to 20…40 % annually.

From the analysis of reports made by enterprises polluting the air basin and the calculation of the gross emissions of toxins by the city motor car parks, it follows that the share of vehicles in CO emissions, hydrocarbons (\( \text{C}_x\text{H}_m \)), and nitrogen oxides (\( \text{N}_2\text{O}_x \)) amounts to 85…90 %.

A selective monitoring of air pollution has been made on two sections of the urban main streets during one week. The clear weather served the observations with a mild atmospheric circulation.

The street development is done by 5-storeyed buildings of frontal planning with minimum breaks. The street width along the development lines is 34 and 60 m. The streets have inter-perpendicular orientation of the longitudinal axis by rhumb lines respectively NS and EW. The greeneries of the street oriented in meridian consists of two rows of trees 15 m high. On a street with a latitudinal orientation, the greener is represented by 3–4-row tree lanes 10 m high. The carriageway and street pavements have asphalt covering.

As a model component, CO has been chosen – one of the most toxic gases presented in HG to a maximum (86…90 %). A close correlation has been stated between the content of CO and other
The air sampling and micro-climate parameters measurement have been performed at the height of 1.5 m at the carriageway edge during the day with intervals of 20 minutes, and during the 2…3 hour periods of peak traffic flow it was done every 20 minutes. The traffic intensity, type of traffic and the speed were registered at the same time.

The measurements of wind speed have been done by the cup anemometers МС-13 with the sensitive part at the level of 75 mm fixed at the most characteristic points at the street cross section. According to the given accuracy of the experiment 5 %, the measurements at the observation points were repeated 7 times.

In more details, the methodology of field observations and chemical air sample analysis is described in the previous work [10].

Moreover, the results of systematic observations performed in the city were studied on the organized fixed and mobile stations.

### 3. Results and discussion

Table 1 gives a comparative characteristics of geometric parameters for the cross section, amount of traffic and the maximum onetime concentrations of CO established on the two main streets as a result of simultaneous observation. To compare versions by the air quality, the traffic intensity in physical units (vehicles per hour) is shown here as the intensity of emission of CO (units per hour) according to coefficients presented in the study by Stavnichiy Yu.A. and Ryabikov N.A. [11].

| Width of street, m | Height of trees, m | Traffic intensity, vehicles/hour | Intensity of emission of CO, units/hour | Wind speed, m/s | Concentration of CO, mg/m³ |
|-------------------|--------------------|----------------------------------|----------------------------------------|----------------|--------------------------|
|                   |                    | light trucks buses               |                                        |                |                          |
| 60                | 0.25               | 10                               | 705 117 42                             | 1602           | 0.9 12.2                 |
| 34                | 0.44               | 15                               | 1155 62 25                             | 1901           | 0.46 21.0                |

*height of buildings.

*width of street (canyon).

Comparing the table lines, we can see that having a non-significant difference in the CO emission (15.7 %) in the street with the width of 60 mat \( H/B = 0.25 \), we have the most favorable conditions for aeration and impurity dispersion. The wind speed here is higher more than 2 times, and the CO concentration is lower by 42 %, than we have on a street with the width of 34 m at \( H/B = 0.44 \). This corroborates the results of continuous field studies in the SRN of large cities where it was stated that the optimum size of the cross section for street canyons corresponds to the value of the \( H/B \) parameter not more than 0.3 in terms of impurity dispersion [10].

The height of trees 15 m draws attention on the cross section of the street with a meridian orientation having the width of 34 m, built up by 5-storeyed buildings. The excessively high trees in narrow streets considerably reduce the dispersion effect of the emission of HG. In accordance with the recommended height of green planting zone at the level of middle stories [12], their optimum height in the second version of the cross section of the canyon should not exceed 7…8 m.

By the results of continuous observations, the cyclograms of the traffic intensity have been drawn, the general one and by the types of vehicles (Figure 1), maximum onetime concentration of CO (Figure 2) and the wind speed (Figure 3) in the street with a meridian orientation. The study results show that the air pollution dynamics in the daily cycle is determined by the fluctuations in the traffic intensity, speed and type of vehicles, on the one hand, and by the wind regime, on the other hand. The
role of the wind in dispersion of this impurity is most distinct during daytime hours when the atmospheric stability is broken due to the warm-up of the earth surface and the lower layer of the air.

Figure 1. Change in the traffic intensity in a main street during the daytime: 1 – total traffic intensity; 2 – personal cars (light vehicles); 3 – public transportation (buses and public minibuses); 4 – trucks.

Figure 2. Daytime variation of maximum onetime concentrations of CO normalized for average daily one in the main street air.

Figure 3. Change in the wind speed above the carriageway at the height of 1.5 m by the hour.

It is seen along the curves in Figure 1 and Figure 2 that the maximum gas pollution in the street basin corresponds to the peaks of the daytime variation of the traffic intensity from 8 to 10 am and from 4 to 6 pm observed at 9…10 am and 5…6 pm, the morning maximum of the CO concentration is more distinct.

In the early morning hours (from 7 to 9), there is a sharp increase in the traffic (all types) frequency which reflects the general rhythm of labor and cultural (community) movements of population and carriage of goods. Some declination in light vehicles intensity from 10 to 12 am is explained by the reduction of working population movement who use personal cars. Herewith, a respective stability at noon and increase of personal cars frequency in the afternoon is preserved, which characterizes a transportation and social activity of resting citizens (city dwellers), motoring tourists, and rural population arriving in the city (Figure 1).

Along with forming a traffic flow, there happens a gradual occupation of the street space with vehicle emissions. By 8 am the general traffic intensity reaches 1000 vehicles/h, that is nearly 80 % from the maximum, fixed in the morning hours, however, we cannot observe a proportionate rise in the air pollution level at this time (Figure 2). The distinct increase of the CO concentration is observed from 8 to 9 am – only after the gas will be distributed throughout the street.
With the absence of the large-scale circulation, the increase of the air mobility from 7 to 10 am in the street space preventing the CO concentration rise is insignificant (Figure 3). The rise of the wind speed at the carriageway in this period from 0.25 to 0.4 m/s parallel to the rise in the traffic intensity is determined mostly by the increase in the air turbulence by moving vehicles. In this period in the street canyon, there are no temperature contrasts and air movement connected with the convective heat exchange since the sun rays do not come to the earth surface. Herewith, the vertical temperature gradient before noon in the streets with meridian orientation has a minimal value because the air at the carriageway is heated to a lesser degree than in the upper layer due to the obstruction for sun rays represented by the development and the trees. Moreover, due to the stronger warm-up of building roofs and dense tree crowns in the morning hours, here appears a warm inversion air layer. With the still-air conditions, the inversion layer hinders the vertical air mixing, impeding thus the impurity dispersion in the atmosphere which contributes to the “phenomenon of air stagnation” [4]. As such, the morning maximum of the city street pollution exceeds the evening one in the spring-summer period.

Approximately since 10 am sun rays penetrate directly to the carriageway in the streets with meridian orientation through longitudinal gaps between the green belts and the buildings. In the streets oriented by the longitudinal axis in latitude, this occurs 1…2 hours earlier. In clear weather, low wind speed or still-air in this time, there is a sharp increase of the equivalent temperature of the road surface due to the high heat sink ability [13]. As a result, the convective heat exchange above the carriageway is increased, the temperature gradient grows too and the vertical component of the wind speed in the surface layer of the atmosphere does the same. Then happens a fast purification of the street air basin from the CO, having reached a maximum at 10 am, the CO concentration curve sharply drops to the local minimum (Figure 2).

The maximum effect of the solar radiation on the rise in the equivalent temperature of the road surface accounts for midday (1…2 pm) [13]. In the afternoon, due to the same reason and also because of the drop in the traffic intensity in the inter-peak period, the CO concentration continues to decrease and by 3 pm it reaches minimal values (Figure 2).

The wind speed above the carriageway acquires a maximum value at noon (1…1.1 m/s), and then it drops continuously due to gradual reduction of the heat ingress to the surfaces. Along the curves in Figure 2 and Figure 3, it is seen that the air motion in the streets within 0.5…0.6 m/s in the sunny weather moderates the formation of the CO maximum concentration at the afternoon “peak hour” (4–6 pm). However, the further reduction of the wind speed to 0.2…0.3 m/s in the period from 7 to 8 pm is accompanied by the rise in the air pollution level due to the high traffic intensity of light motor cars in the evening.

In the air pollution dynamics within a week, a minimal onetime concentrations are observed in the weekend, and the maximum ones fall on Friday and exceed the average pollution level per week by 1.2…1.4 times. This accounts for the rhythm of work at the enterprises and the change in the gross emission of toxins by the individual transportation.

The irregularity in the HG concentration distribution by months is determined by seasonal changes in meteorological conditions and the amount of traffic in the SRN. These peculiar features of changes in maximum and average CO concentrations by months are shown in diagrams drawn according to the observations at a fixed station located near a main street (Figure 4).

The minimum content of the CO in the air in the springtime is explained by a number of meteorological factors enabling a more intensive impurity dispersion (the non-significant amount of surface inversions, higher turbulence, precipitation, etc.).

Along with this, there is a gradual increase of the maximum and average CO concentrations in the warm period from May to August. This is connected with the traffic intensity rise for private cars and more active use of vehicles in the economic activities (transfer of building materials, harvesting period, etc), as well as the period of popular vacations and motor tourism. The most concentrated flows of light vehicles are observed in central planning zones of cities.
Figure 4. Annual course of the average monthly and the maximum per month CO concentrations on a main street.

The similar distribution of air pollution is typical for St. Petersburg and is explained by regularities of changing weather patterns and meteorological conditions characteristic for them. In the spring-summer period, the frequency (more than 50%) of anticyclones and flat pressure gradients rises here [4]. As a rule, for the anticyclone to happen, there are atmospheric phenomena hindering the impurity dispersion: subsiding of the wind speed, growth of inversion frequency, temperature rise, which contributes to the accumulation of pollutants in the air basin. A complex of the above-given meteorological parameters has an especially adverse impact on the impurity dispersion from the sources with low non-organized (fugitive) emissions to which automobile transport belongs.

By the results of the observations, a mean daily CO concentration is calculated as an average value of maximum onetime concentrations determined at regular intervals, that is:

\[ q_{cc} = \frac{1}{n} \sum_{i=1}^{n} q_{pi} \]  

where \( q_{pi} \) – maximum onetime concentration of the ingredient at \( i \)-th interval; \( n \) – number of equal intervals per day.

The calculations by formula (3) for 45 intervals found that the maximum onetime CO concentration corresponding to the morning maximum of the city street pollution exceeds the daily average in the mean by 2.38 times, that is \( q_{a,p,max} = 2.38q_{cc} \) or \( q_{cc} = 0.42q_{a,p,max} \). The given correlation is in good agreement with the results of studying a temporal dynamics for the air pollution acquired on the basis of systematic observations in the big and biggest cities (Astrakhan, Volgograd, Voronezh, Kazan, Vladivostok, Krasnodar, Kemerovo, Moscow, St. Petersburg et al.) [14]. Here it was stated that, as a rule, the maximum onetime, mean daily, mean monthly, and mean year concentrations correspond as 10:4:1.5:1, that is, the mean daily concentration amounts to 0.4 from the maximum onetime one, and the mean year one is single-order lesser. It is obvious, this correlation of concentrations is representative of the cities located in the III-nd climate zone and can be used here in the approximate estimates of damage caused by air pollution in residential areas.

4. Summary and conclusions
The daily course of the maximum onetime CO concentration in the air of urban main streets in the summertime is characterized by the two maximums – the morning one at 9…10 am and the evening one at 5…6 pm corresponding to the “peak” hours in the traffic activities. In the morning hours, the impurity dispersion in the streets of meridian orientation with a dense development is restricted due to little air motion and the air inversion restraining layer at the surface layer. Around midday, between the hours of the maximal saturation by automobile transport, there is a more intensive dispersion of
vehicles emissions. It is due to the growth of wind velocity because of the atmospheric instability under the air temperature rise in the surface layer. In the evening hours, the level of air pollution is sustained at the high level due to the wind velocity fall and the high light traffic intensity.

The behavior of the air pollution level at the transportation facilities by week days, with the non-significant change of weather factors, is connected with the variations in the traffic volume and the pollutants emission. The maximum pollution has been observed is noted on Friday in the afternoon because of the rise in the citizens’ activities due to travels out of town to the spots of weekly rest and to their summer cottages. Hence, the most concentrated light cars flows are observed on the outbound routes. The minimum pollution is stated on weekends characterized by the least traffic intensity among the other weekdays.

In the dynamics of the air pollution of sections of the city transportation network per months, an important role is played by the change of gross pollutant emission and the considerable change in the combination of meteorological factors in different seasons. The no-wind weather, presence of surface inversions, and the growth of foggy days are the most typical meteorological conditions accompanying the impurity accumulation in the surface layer.

In cities with low wind speeds and prevailing no-wind weather, the most rational orientation of main streets should be considered a latitudinal one providing the wind velocity gain and more intensive vehicle emission dispersion before noon due to the warm-up of the earth surface and the lower atmosphere. In the streets with meridian orientation, one should restrict using multi-sectional buildings and apply the techniques of free development planning with a variable number of floors and a setback from the carriageway.

The most efficient dispersion of vehicle emissions on urban streets with a dense frontal development is provided with the ratio of the building height $H$ to the street width $B$ along the development lines not more than $0.25 \ldots 0.3$. This can serve as a basis for assigning the minimum width of main streets of various categories within three-four building heights by the criteria of their aeration regime and the air quality. In the street canyons, the tree height should be maintained at the level of middle floors of buildings, and to prevent growth of their crowns (tops) toward the carriageway using their felling.

To reduce the damage caused by the air pollution in big and largest cities, one should restrict the street traffic for the transit freight and individual vehicles by way of by-passes (detour roads) away from the populated areas. Simultaneously, urban transportation systems should be modernized enhancing safety and comfort for the urban mass passenger transport and forming a system of commuting hubs with intercepting parking at the entrance points to the city and to the downtown (municipal center).

As a result of the implementation of this complex of measures, conditions to organize the multi-purpose (combined, shuttle) rides for car owners using rapid transit transportation which results in the reduction of traffic intensity in the SRN and the gross emissions of pollutants into the atmosphere, curbing the tempos of vehicle-to-population (car ownership) ratio, and city health promotion.

5. References

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