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Estimated atmospheric emission from motor transport in Moscow based on transport model of the city

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Abstract

Motor transport is a main contributor to atmospheric air pollution in big cities. Estimation and forecast of harmful substances emission from motor transport is an important task in the framework of development of sustainable urban transport policy in big cities. Calculation method for motor transport emission inventory was developed by NIIAT taking into account of existing approaches (CORINAIR) and specific features of national motor fleet and traffic conditions. On the base of transport model of the city (Moscow), traffic data, data on congestions received from GPS tracks and data of traffic investigations there were made calculations of existing motor transport emission. In calculation there were also used the existing data on motor fuels environmental quality. The results of calculations gave the existing picture of distribution of motor transport emission in Moscow by vehicle types, by their environmental classes, by harmful substances (20 substances including such as benzpyrene, aldehyde), by territory (central part, motorways, residential areas) and by time of day.

On the base of developed calculation method and the use of modified transport model of the city there was made estimation of motor transport emission in Moscow in the period from 2011 to 2014 taking into account change of motor fleet, changes in town-planning, in urban road infrastructure, in public transport system. These calculations gives the base for City Government policy decisions assessment.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: Transport; pollutant emissions; calculation; transport model; population mobility; vehicle fleet; road traffic

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1. Main text

Air pollution in cities is one of the serious problems associated with the operation of transport. Motor transport in Russian cities accounts for 40 to 70% of the overall pollutant emissions. Therefore, estimated impact of vehicles on air quality is an important aspect of the urban transport management systems.

The most accurate estimates of emissions for the major cities with well-developed road network (RN) and multi-modal transport system can be made based on the verified transport model of the city, specially prepared initial data on the structure of traffic flows, as well as on the actual database of specific emissions of pollutants for various traffic conditions.

To make such estimates, a special calculation method is developed where the basic provisions are harmonized with the European emission inventory procedure EMEP/CORINAIR/COPERT (Donchenko (2014), Gkatzoflias (2011), Ntziachristos (2013)). The algorithm of calculations using this method is shown in Figure 1.

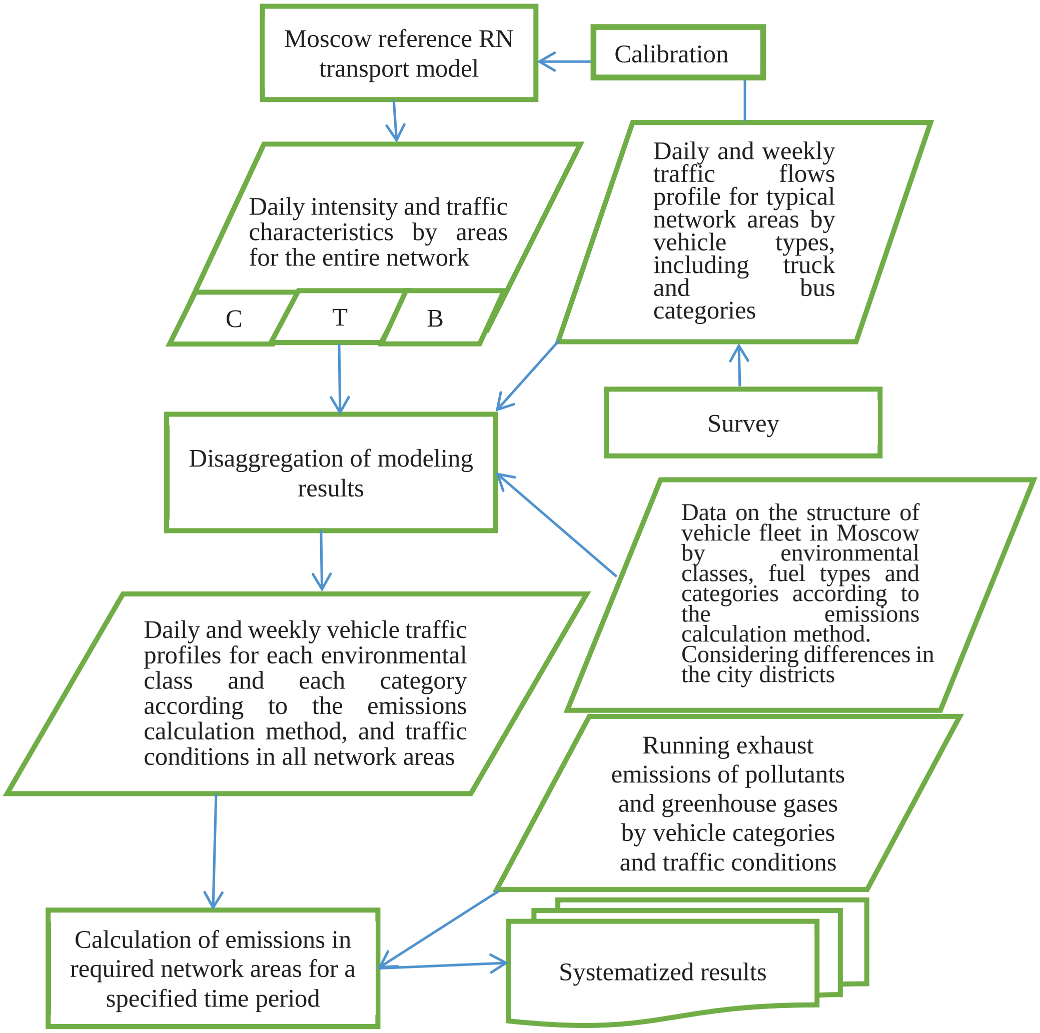


Fig. 1. Algorithm for calculating mass emissions of pollutants and greenhouse gases.

Under this method, emission of the *i-th* pollutant by the vehicles of all calculation types within 24 hours is generally calculated according to the formula:

$$M_i = \sum_j (M_{1ij} + M_{2ij} + M_{3ij}), \tag{1}$$

where:

M_{1ij} – emission of the *i-th* pollutant when driving the *j-th* type vehicles, t;

M_{2ij} – emission of the *i-th* pollutant when starting up and warming engines of the *j-th* type vehicles, t;

M_{3ij} – emission of the *i-th* pollutant due to fuel evaporation (only for vehicles with petrol engine type), t.

Emission of the *i-th* pollutant by vehicles of the *j-th* calculation type M_{1ij} taking into account traffic load in the city streets and roads areas during peak and inter-peak periods is calculated by the formula (2):

$$M_{1ij} = \sum_k \sum_l (m_{ijk}^{\text{Ï}} \cdot N_{jkl}^{\text{Ï}} + m_{ijk}^{\text{ÌÏ}} \cdot N_{jkl}^{\text{ÌÏ}}) \cdot l_{kl} \cdot 10^{-3}, \text{ t/day} \tag{2}$$

where:

$m_{ijk}^{\text{Ï}}$ – running (specific) emission of the *i-th* pollutant by vehicles of the *j-th* calculation type when driving in the streets and roads of the *k-th* category during peak period, g/km;

$m_{ijk}^{\text{ÌÏ}}$ – running emission during inter-peak period, g/km;

$N_{jkl}^{\text{Ï}}$ – traffic density of the vehicles of the *j-th* calculation-type in the *l-th* streets and roads area of the *k-th* category (*k*=1...4) during peak period, thousand vehicles/day;

$N_{jkl}^{\text{ÌÏ}}$ – traffic density during inter-peak period, thousand vehicles/day;

l_{kl} – length of the *l-th* streets and roads area of the *k-th* category, km.

Figure 2 schematically shows vehicle categories, environmental classes and types of the fuel used determining the vehicle calculation types, for which the specific (running) pollutant emissions are established.

Emissions were calculated for the following substances: CO; VOC; NOx; PM; SO_2; Pb; CO_2; CH_4; NMVOC; NH_3; N_2O; acrolein; 1,3-butadiene; toluene; xylenes; styrene; acetaldehyde; benzene; formaldehyde; benz(a)pyrene.

To facilitate preparation of initial data in taking inventory of pollutants, the RN of the city of Moscow was divided into separate streets and roads areas with the same type of driving conditions. The areas beginning and end was usually taken at the RN junctions (intersections of streets and roads). In some cases, taken as a separate area were the segments of streets and roads with special stable driving conditions (for example, regularly appearing lengthy jams) significantly different from those in the adjacent linear sections.

Transport flow characteristics were assessed dividing the daily traffic volume into two periods: peak load (traffic speed of less than 15 km/h) and inter-peak load (traffic speed of more than 15 km/h).

According to the scheme shown in Fig. 1, calculation of pollutant emissions in the city RN was based on:

- use of transport model of the city of Moscow, which allows obtaining based on the data of instrumental monitoring of flows in some RN areas the basic characteristics of traffic flows (density and driving speed, composition of the flow) in the entire network;
- study of the composition of the vehicle fleet in the city of Moscow by ecological characteristics, which allows conducting proper decomposition of the traffic flows and beginning calculation of emissions;
- field surveys of traffic in the RN of the city of Moscow in order to calibrate the transport model.

Transport model of the city of Moscow is based on the population mobility data (Table 1), i.e. on the average number of travels (trips) made with different purposes during a day by an average resident, and on the data on location on the city and region plan of the facilities generating travels (residence and work places, trade and service facilities, etc.).

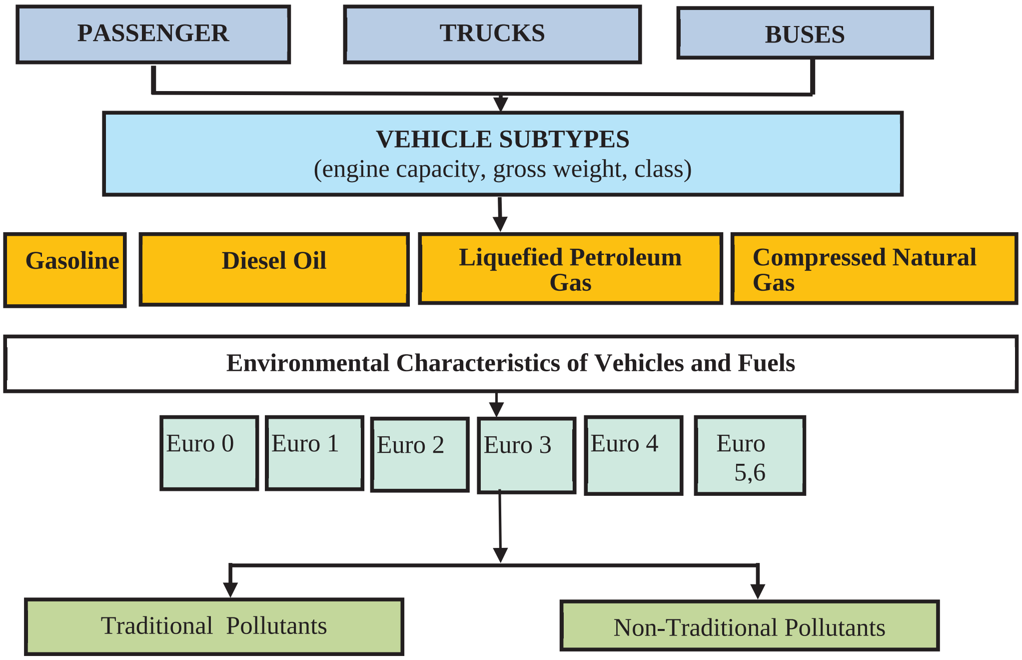


Fig. 2. Structure of specific pollutant emissions for estimated vehicle types.

Table 1. Population mobility in the city of Moscow by demand tiers on the average working day (travels / 1,000 residents).

Name of Attraction Point	Home	Work	School	NA	RA	Medicine	Leisure	Stations	Total Departures
Home		570	250	180	85	20	70	15	1,190
Work	470	160	15	70	20	10	10	0	755
School	230	15	0	15	0	0	20	0	280
NA (nearby amenities)	270	10	15	150	20	0	20	0	485
RA (remote amenities)	95	0	0	20	10	10	0	0	135
Medicine	30	0	0	10	0	0	0	0	40
Leisure	80	0	0	40	0	0	10	0	130
Stations	15	0	0	0	0	0	0	0	15
Total Arrivals	1,190	755	280	485	135	40	130	15	

Mobility of population on weekends was described in a similar way. In addition, trucks mobility was taken into account on both working days and weekends.

To determine the number of travels, a set of correspondence matrices was calculated between the estimated transport areas of the city for different types of travel (by foot, car, public transport). Also, it was taken into account that trips are made with different purposes and at any time of a day. To take into account non-uniformity of daily trips, calculations were made separately for the morning and evening peak hours and for the average daytime and nighttime hours. Correspondence matrix was calculated using the gravity model (Formula 3) for each demand tier separately, since all of the demand tiers have a different distribution of trips by their distance:

$$F_{i,j} = A_i O_i B_j D_j exp(-\lambda C_{i,j}),\ i,j \in R\ - \quad (3)$$

where:

$F_{i,j}$	–	number of trips from area i to area j;
O_i	–	number of departures from area i;
D_j	–	number of arrivals to area j;
R	–	number of transport areas;
$C_{i,j}$	–	transport distance between areas i and j

In Formula (2), coefficients A_i and B_j are calculated based on the condition that:

$$\sum_i^R Fi,j = O_i \ and \sum_j^R Fi,j = D_j; \quad (4)$$

and coefficient λ is selected empirically using the data of experimental studies and characterizes the distribution of trips by their distance depending on the demand tier.

Used as the transport distance $C_{i,j}$ were the consolidated "costs" depending on the time of travel between a pair of areas using the shortest way, taking into account traffic load, paid travel in some parts of the route and other factors. Correspondence matrices for different types of travel ("transport modes") (by individual transport, public transport, or by foot) are split individually for each pair of transport areas by comparing the values of the "consolidated costs". This allows not only calculating the share of the public transport use but also doing it for each pair of areas separately.

To determine traffic load of the Moscow agglomeration road network, the obtained correspondence matrices were distributed by specific ways in the network, i.e. by the areas of the RN with the configuration shown in Figure 3.

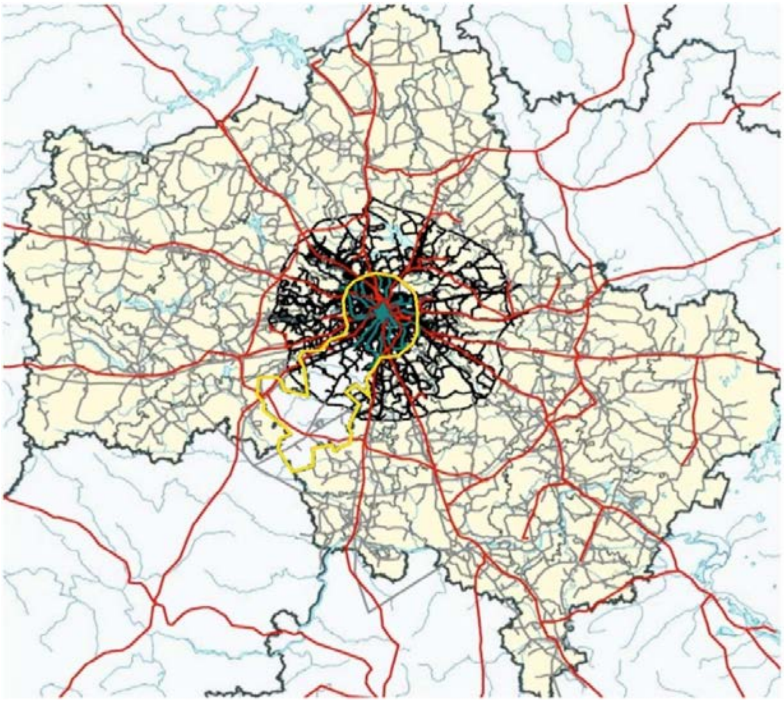


Fig. 3. Configuration of the road network in Moscow and the Moscow Region in the used transport model.

Overall, the transport model considered 3,800 elements of the Moscow RN and 3,700 elements of the Moscow Region RN determining for each of them traffic density, driving speed, composition of the traffic flow taking into account the daily, weekly and seasonal fluctuations, including in the context of different types of streets and roads. Transport graph contains more than 23,000 arcs and 7,500 junctions. Considered were more than 1,000 transport areas in Moscow and 300 areas in the Moscow Region.

It is assumed initially in the calculations that trials and errors of the road users in the network result in establishing the balance where all routes between the transport areas i and j used for travel by the correspondence members $F_{i,j}$ have equal transport distance Sij. This balance is determined for each class of users based on their contribution to the streets and roads traffic load. For example, distribution of individual vehicles takes into account creating traffic load in the RN elements not only by them but also by the public transport facilities and trucks.

Figure 4 shows spatial distribution of the entries / exits for 24 hours (diameter of the circle) and the average distance of one trip (color of the circle). Knowing these values, one can calculate the system-wide transport operation (Formula 5):

$$P_{\text{общ.сис.}} = \sum_{i}^{R} \frac{F_{i,j}L_{i,j} + F_{j,i}L_{j,i}}{2}; \quad i,j \in R \qquad (5)$$

where:

$P_{\text{общ.сис.}}$	–	system-wide transport operation;
$F_{i,j}$	–	number of trips from area i to area j;
$L_{i,j}$	–	length of way from area i to area j;
R	–	number of transport areas.

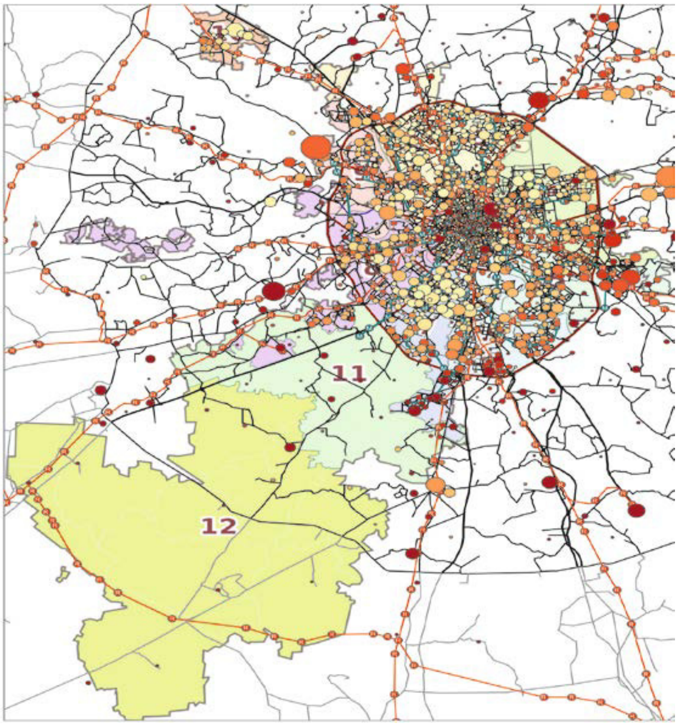


Fig. 4. Distribution of the number of trips and the average distance of one trip for the average working day of the week resulting from calculations based on the city transport model (11 and 12 - newly-annexed territories of New Moscow).

Using the described transport model of the city of Moscow, assessed were the structure and characteristics of traffic flows for the period from 2011 to 2014 (Table 2), which formed the basis for subsequent calculations of pollutant emissions. This time period was selected due to the need to assess dynamics of changes in the city's situation with air pollution by vehicles.

Table 2 shows the system-wide characteristics of the transport system in the city of Moscow in 2011 and 2014.

Table 2. Final values of the system parameters for 2011-2014 (working days, territory within the city of Moscow).

Parameter	**Value for 1 Hour**	
	2011 wd	2014 wd
Morning		
Work (vehicles*km)	6,896,135	6,666,225
Total time spent (vehicles*hour)	277,093	283,203
Number of trips	566,157	556,648
Work reduced (vehicles*km)*	6,896,135	6,780,107
Time reduced (vehicles*hour)*	277,093	288,041
Average travel length (km)**	12.18	11.98
Average travel time (min)**	29.37	30.53
Speed (network-wide, km/h)	24.89	23.54
Day		
Work (vehicles*km)	5,949,433	5,820,689
Total time spent (vehicles*hour)	185,604	189,603
Number of trips	513,099	509,145
Work reduced (vehicles*km)*	5,949,433	5,865,893
Time reduced (vehicles*hour)*	185,604	191,075
Average travel length (km)**	11.60	11.43
Average travel time (min)**	21.70	22.34
Speed (network-wide, km/h)	32.05	30.70
Evening		
Work (vehicles*km)	6,462,775	6,269,171
Total time spent (vehicles*hour)	259,735	266,127
Number of trips	551,820	543,291
Work reduced (vehicles*km)*	6,462,775	6,367,594
Time reduced (vehicles*hour)*	259,735	270,305
Average travel length (km)	11.71	11.54
Average travel time (min)	28.24	29.39
Speed (network-wide, km/h)	24.88	23.56
Night		
Work (vehicles*km)	1,788,057	1,755,482
Total time spent (vehicles*hour)	39,386	38,679
Number of trips	151,157	150,451
Work reduced (vehicles*km)*	1,788,057	1,763,712
Time reduced (vehicles*hour)*	39,386	38,860
Average travel length (km)	11.83	11.67
Average travel time (min)	15.63	15.43
Speed (network-wide, km/h)	45.40	45.39

Note: **Work and time reduced - total values reduced to the same base number of trips.*

Calculation of emissions also requires determining environmental characteristics of the vehicles involved in road traffic. For this purpose, structure of the Moscow vehicle fleet was analyzed.

According to the Traffic Police of the RF Interior Ministry, the total vehicle fleet of Moscow in 2014 was 4,285 thousand units. Changes in the vehicle fleet of Moscow in 2011-2014 are shown in Figure 5.

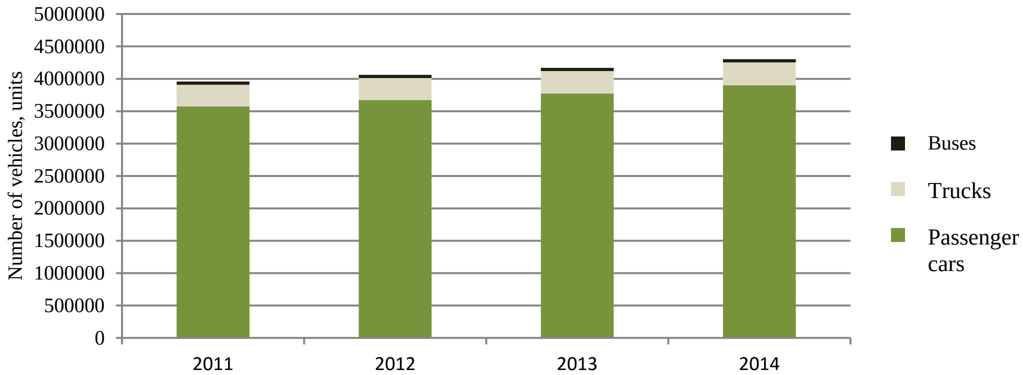
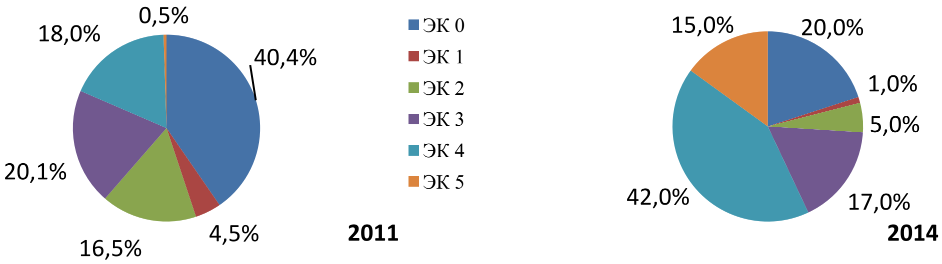
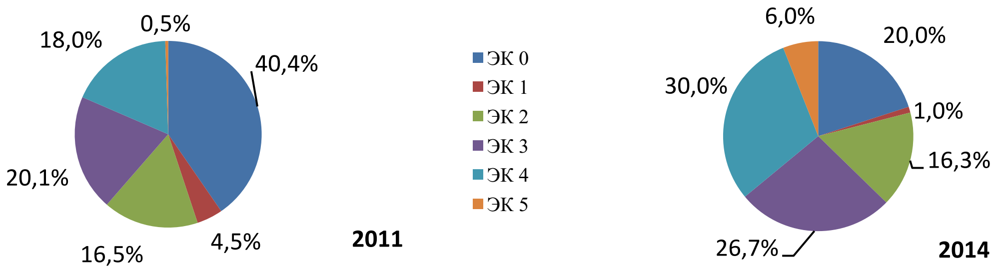


Fig. 5 - Changes in the vehicle fleet of Moscow in 2011-2014, units (as of December 31 of each year)

Data on the vehicle fleet structure of Moscow by environmental classes in 2011 and 2014 are shown in Figure 6.



a)



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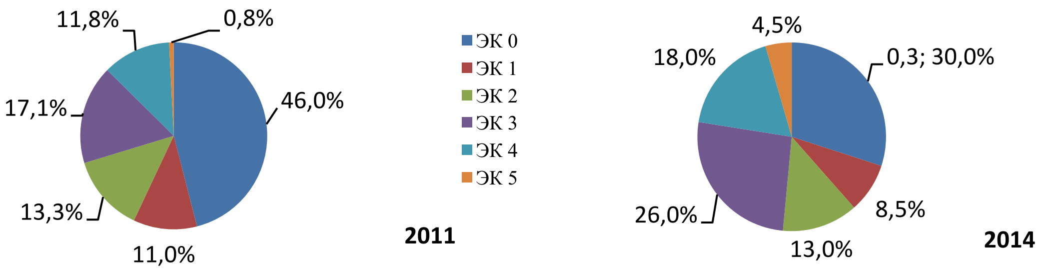

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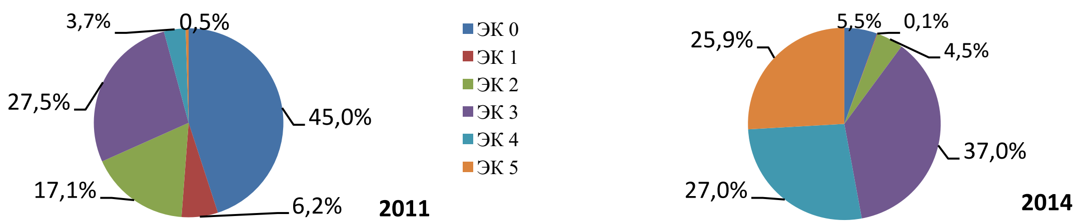

d)

Fig. 6. Distribution of the vehicle fleet structure of Moscow by environmental classes in 2011 and 2014 (%): a) passenger cars; b) trucks with gross weight up to 3.5 t; c) trucks with gross weight more than 3.5 t; d) buses.

These data show that in the considered period (4 years) structure of the vehicle fleet in Moscow by environmental classes changed significantly: actively withdrawn from service are the vehicles of low environmental classes (Euro 0 and Euro 1), it is especially true for trucks and buses. At the same time, significantly increased the number of vehicles of high environmental classes (Euro 4 and above), it is especially true for passenger cars and buses. Thus, the number of passenger cars of Euro 5 level increased more than 5 times.

Based on the data of the road traffic modeling in the road network of Moscow and on assessment of the structure of the vehicles involved in the traffic by environmental classes, gross emissions were calculated for the major pollutants from vehicles in the city of Moscow in 2011 and 2014 (Table 3).

Table 3. Gross emission of pollutants by vehicles and the share of various vehicle types in the total emissions in 2011 and 2014.

Vehicle Type	Gross Pollutant Emissions, t/year					
	CO	**VOC**	**NO_x**	**SO_2**	**CO_2**	**PM**
			2011			
Passenger cars	179,827	38,302	22,237	170	4,587,117	93.9
	78.5	78.4	36.9	56.1	58.8	5.72
Trucks and buses with gross weight up to 3.5 t	27,389	4,700	5,916	34,8	900,753	164
	12	9.62	9.82	11.5	11.5	10
Trucks with gross weight more than 3.5 t	18,190	4,319	25,649	79,1	1,745,723	978
	7.94	8.84	42.6	26.1	22.4	59.5
Buses	3,669	1,522	6,435	19,2	568,678	407
	1.6	3.12	10.7	6.33	7.29	24.8
Total	**229,075**	**48,843**	**60,237**	**303**	**7,802,271**	**1,643**
	100.0	100.0	100.0	100.0	100.0	100.0
			2014			
Passenger cars	116,771	25,980	16,368	168	4,511,682	196
	76.9	79.7	39.1	57.7	59.9	18.2
Trucks and buses with gross weight up to 3.5 t	15,830	2,472	3,196	31.6	810,331	93.5
	10.4	7.58	7.64	10.8	10.8	8.7
Trucks with gross weight more than 3.5 t	18,123	3,707	19,094	72.5	1,636,954	659
	11.9	11.4	45.7	24.9	21.7	61.3
Buses	1,198	440	3,152	19.3	577,659	126
	0.789	1.35	7.54	6.62	7.66	11.7
Total	**151,922**	**32,599**	**41,810**	**291**	**7,536,626**	**1,075**
	100.0	100.0	100.0	100.0	100.0	100.0

It was found that gross emissions of carbon monoxide (CO) decreased in 2014 by 33.7% compared to 2011, hydrocarbons (VOC) - by 33.3%, nitrogen oxides (NO_x) – by 30.6%, sulfur dioxide (SO_2) - by 4.0%, carbon dioxide (CO_2) - by 3.4% and emissions of particulate matter (PM) - by 34.6%.

2. Conclusions

Big cities and urban agglomerations with a well-developed RN and a high level of car ownership require high enough level of detail in the vehicles emission inventory calculation models. It is reasonable to use classic 4-stage transport models that allow calculating the traffic flow characteristics based on daily, weekly and seasonal fluctuations, as well as on detailed data on the structure of traffic flows by vehicle types, their environmental classes, gross weight (for trucks), engine capacity (for passenger cars), passenger capacity (for buses), and fuel type.

Gross vehicles emission inventory taken in Moscow in 2011 and 2014 using these data showed that due to uneven evolutionary upgrade of various groups of vehicles in the vehicle fleet of the city, increase in the share of vehicles using diesel and other motor fuels gross pollutant emissions in the period from 2011 to 2014 changed in some segments of the city's vehicle fleet unevenly.

Major share of emissions of the considered pollutants falls on petrol-running passenger cars (in 2011-2014, respectively, 78.5 and 76.9% for CO; 78.4 and 79.7% for VOC; 56.1 and 57.7% for SO_2 and 58.8 and 59.9% for CO_2). Due to the growing number of passenger cars with diesel engines in 2014 compared to 2011, their share in gross emissions of particulate matter increased (from 5.72% to 18.2%, respectively). Major contribution to air pollution by nitrogen oxides and particulate matter falls on the trucks with the gross weight of more than 3.5 tons (42.6 and 45.7% for NO_x and 59.5 and 61.3% for PM in 2011 and 2014, respectively).

Share of the trucks and buses with the gross weight of up to 3.5 tons in the gross emissions in 2011 was 9.6-12%, down to 7.6-10.8% by 2014 depending on the type of pollutant.

Contribution of buses to the total gross emissions of certain pollutants by vehicles varies from 1.6% in 2011 (0.79% in 2014) for CO to 24.8% for PM in 2011 (11.7% in 2014).

In terms of percentage, about 57-60% of pollutant emissions from motor vehicles fall on city streets, 27-30% - on highways, and the remaining 13-14% - on local streets.

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