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ORIGINAL ARTICLE

Development of micromodels of traffic flows, taking into account environmental factors

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ABSTRACT

The article considers an actual problem of organizing a safe and sustainable urban transport system. We have examined the existing positive global experience in both infrastructural and managerial decisions. Then to assess possible solutions at the stage of infrastructure design, we have developed the simulation micromodels of transport network sections of the medium-sized city (Naberezhnye Chelny) with a rectangular building type. The models make it possible to determine the optimal parameters of the traffic flow, under which pollutant emissions from cars would not lead to high concentrations of pollutants. Also, the model allows to obtain the calculated values of the volume of emissions of pollutants and the parameters of the traffic flow (speed, time of passage of the section, etc.). On specific examples, the proposed method's effectiveness is shown. Case studies of cities of different sizes and layouts are implementation examples and possible uses proposed by the models. This study has shown the rationality of the suggested solution at the stage of assessing infrastructure projects and choosing the best option for sustainable transport development. The proposed research method is universal and can be applied in any city.

KEYWORDS

traffic flows; environmental safety; sustainable development; simulation modelling

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1. Introduction

The transport network is a necessary connecting element of the economic system. It unites settlements and regions into a single ecosystem, on the one hand ensures the territorial connectivity of the state, and on the other hand, allows it to fully function in the context of global world trade with other countries. Transport processes directly affect the spatial efficiency and development of the country (Polyakov, 2010). Depletion of an extensive development path potential due to the intensive increase in exports of fuels and raw materials, strengthening the priority of innovative measures and measures to ensure the deep processing of raw materials require a higher degree of population, goods, services and capital mobility (Kazakova and Pospelova, 2017). The contribution to meeting the transport needs of the population of urban transport systems is constantly increasing. This process is taking place in the context of the ongoing urbanization and motorization of society and an increase in the load on the transport infrastructure and road network.

According to the sustainable development goals of the United Nations by 2030, it is necessary to provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities, and older persons. The solution to the transport and environmental problems of the largest cities can be the consistent implementation of the concept of sustainable urban transport policy, linking the transport systems' developing and operating with urban planning, environmental protection and public health issues. The basis for efficient traffic management, which is an integral part of the sustainable development of urban transport systems, is transport planning (United Nations, 2020).

A modern city is a complex construction, engineering and infrastructure complex. Efficiently functioning transport infrastructure contributes to the optimal location of enterprises and meeting the needs of the population, which affects the city's overall development. The most important tasks for authorities at the city level are attracting investment in the development of transport infrastructure, increasing transport capacity through the expansion of roads, the construction of interchanges, etc. (Beljakova and Ryzhaja, 2017). However, poor planning of transport infrastructure also leads to negative consequences such as environmental problems, increased traffic accidents, climate change, carbon dioxide emissions and reduced transport efficiency. Therefore, an urgent task is to identify the transport infrastructure's multiple effects based on existing research (Berman, 2020).

Experience shows that motorization, besides positive consequences for the economy and social development, also has negative ones, including a significant number of traffic accidents, accompanied by material damage, as well as harming people's health, including dead and wounded. Motor transport negatively affects the ecological status of the urban environment in the form of noise pollution and air pollution with exhaust gases. Car exhaust emissions contain carcinogenic components—carbon and nitrogen oxides, hydrocarbons, aldehydes, sulfur dioxide, lead, etc. These substances have a negative impact on human health and harm the environment. The speed of traffic on the roads of cities is reduced due to congestion during peak hours, making the use of road transport as a means of transportation ineffective. Modern scientific research and practical experience make it possible to explain the causes of all these negative phenomena and give recommendations for reducing and eliminating the negative consequences of motorization.

This article focuses on the analysis of the main areas in which scientific and practical developments are being carried out, and to develop a solution that will help to ensure a safe and sustainable transport system in the urbanized area and the quality of its residents' life.

2. Review of literature

Motor transport is a major source of air pollution. According to observations, the contribution of motor transport to air pollution is 20%–30% of the total emissions in developed countries (Eurostat, 2020; Ministry of Natural Resources and Environment of the Russian Federation, 2021) (**Figure 1**).

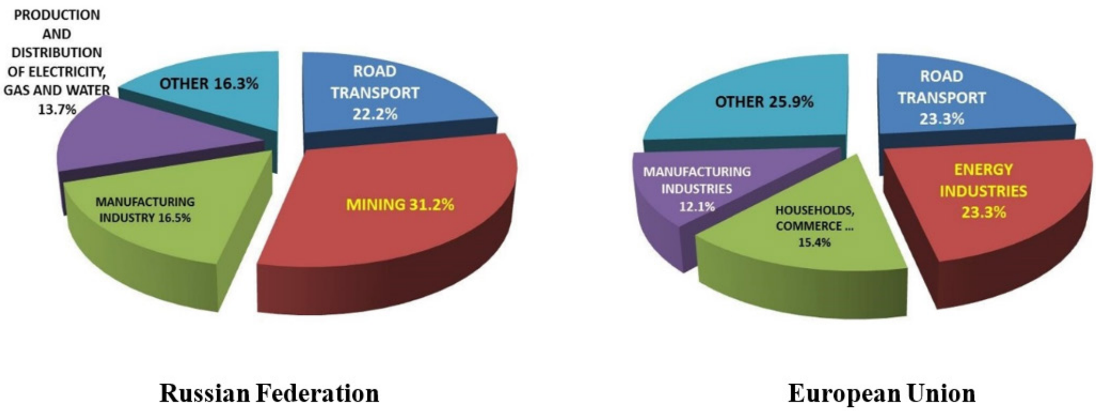


Figure 1. Emissions from various sources, 2021.

One effective way of reducing the environmental impact of road transport is to improve the environmental friendliness of a vehicle. Permyakova et al. (2020) propose to improve the environmental friendliness of transport through the use of hybrid and electric vehicles. It should be noted that at present, the share of electric cars is not large, but high rate of research and development allows making optimistic predictions to that effect. An instrument has been developed that allows identifying the main stages and means of fulfilling innovative goals of the object that require drafting text and graphic documents, and introduction of the information required to make managerial decisions thereto.

The issues of ensuring the sustainability of transport development are increasingly becoming key issues in discussions at global international platforms. At the United Nations World Conference on Environment & Development in 1992 in Rio de Janeiro, Brazil, the critical role of transport in achieving the strategic goal of sustainable development was announced. This was also reflected in the final document “Agenda for the 21st century” (United Nations Sustainable Development, 1992). A similar announcement was made later at the 2002 World Summit on Sustainable Development in Johannesburg, South Africa (Plan of Implementation of the World Summit on Sustainable Development, 2002). The Johannesburg Plan of Implementation outcome document also outlined the importance of transport functions and tasks. The organizers and participants of the 2012 United Nations Conference on Sustainable Development (Rio +20) expressed a similar position in the document “The Future We Want” (Sustainable Development Knowledge Platform, 2012): in sustainable development, the mobility provided by transport is extremely important. In 2015, the 2030 Agenda for Sustainable Development (United Nations, 2021) was adopted by world leaders in New York. It contains 17 sustainable development goals (SDGs). According to this list of goals, nonstandard and innovative ideas and actions are expected to build a sustainable future for the planet and its people. It should be noted that there is no separate SDG for transport, but “sustainable transport” is a sub-goal of Goal 11 “make cities and human settlements inclusive, safe, resilient and sustainable”. This sub-goal targets “by 2030, ensure access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, in particular through the expansion of public transport, paying particular attention to the needs of people in vulnerable situations, women, children, the disabled and the elderly” (The Global Goals, n.d.). In addition, transport stands out as an influencing factor in achieving a number of other SDGs. Thus, the search for ways and methods to develop sustainable transport and involve the population in it is a recognized global agenda. Obviously, this list of events will expand.

In urban areas, public transport has been the focus of much attention as a driver of sustainability and quality of urban life. Effectively connecting resources to destinations and making it easier for people to move around will improve urban economic and environmental performance. Public transport networks are an important part of the urban system and are a key enabler for the development of other elements of urban interaction and circulation. The level of public transport's accessibility can be characterized by the time it takes to get on any type of transport (bus or metro). Bok and Kwon (2016) propose a way for assessing and comparing public transport accessibility in different urban areas on the base of GTFS feeds and demographic data.

The article states (Korkmaza et al., 2022) that autonomous public transport systems (APTS) should provide the advantages of traditional public transportation and eliminate the disadvantages in order to be accepted and used by passengers. The study investigated the factors affecting the acceptance and use of autonomous public transport systems by potential users. According to the research results, social influence, performance expectancy, habit, and trust and safety constructs have a positive and significant effect on behavioral intention to use APTS.

Most of the subsidy-based basic bus services have been unfortunately suffering from a ridership decline over the past years. As new transport technologies emerge, more bus riders switch to other transport modes. The most attractive mode is private automobiles. Compared to city buses, private autos provide people with enhanced comfort, privacy, and convenience, which leads to a reduction in the willingness of using bus transportation. Public bus services can be viewed as quasi-public goods as they are subject to partial excludability and partial rivalry. From the perspective of the entire society, the provision of such quasi-public goods in an efficient way would rely on collaboration and coordination between the public and private sectors. In particular, bus services exclusively operated by private companies may not adequately accommodate the demand of low-income people or other socially disadvantaged populations at an affordable price. To fix this market failure, the government always steps in and supports low-priced public bus services through subsidies. However, if bus services are exclusively provided by operators fully endorsed by local governments, the model of uniform service provision and heavy subsidies becomes increasingly unsustainable. As cities grow and new technologies emerge, the public bus system can gradually lose its advantage in the passenger transportation market (Denga et al., 2023).

In the preparation and evaluation of transport investment plans and projects, social and environmental aspects are given greater weight than other evaluation criteria. In the modern context, individual and public demands for quality of life determine the tasks of transport systems and infrastructure. In the meantime, sustainable development has become the most important motivating factor in the formulation and planning of transport policy. The authors of the article (Griškevičiūtė-Gečienė and Griškevičienė, 2016) addresses the issue of the impact of transport infrastructure on sustainable living conditions. The results obtained are used in the process of determining the development strategy, investment directions and selection of priority projects. However, there are often uncertainties in the socio-economic assessment as well. This paper aims at defining the fundamental parameters that influence the living environment and the sustainability of this environment, at establishing the principles of using them in the development process, and at applying them in a way that enhances the attractivity of individual city areas.

But poorly planned transport infrastructure has negative consequences, including environmental degradation, increased road accidents, climate change, harmful emissions and reduced transport efficiency. Thus, it is necessary to identify the multiple impacts of transport system infrastructure (Wang et al., 2018).

Sustainable transport means meeting society's mobility needs with minimum environmental impact without compromising future generations' mobility needs. Promoting the balance between environmental safety, economic development and social comfort is essential for sustainable development applied to transport systems. Simultaneously improving the performance of these three areas is one of the expected results of sustainable transport. The goal of the environmental dimension is to ensure that all aspects of the transport industry address environmental issues by understanding the interactions between the physical environment and industry practices (Rodrigue, 2020).

A critical element in the ongoing traffic congestion is the current poor transport infrastructure in many cities. An ominous sign of the evolution of transport planning is the rapid increase in private car ownership combined with poor management of the transport system. A radical overhaul of all urban practices and urban form development processes is required to improve the environmental conditions necessary for urban sustainability. It is well known that well-designed cities are more social, more multicultural, happier, healthier and safer, and that they meet people's needs for leisure and urban space. Cities are, after all, dynamic organizations. They can absorb a certain number of cars without any consequences (capacity) and manage to enrich their urban environment in some way. In order to maintain its vitality and spatial distribution, the car should be replaced by other forms of sustainable transport (Bakogiannis et al., 2016).

3. Methodology

Management measures to reduce the negative vehicles impact on the environment involves identifying the causes of critical situations and taking measures to their emergence probability reducing. For these purposes, simulation's micro-models were used.

Traffic flow modeling is the creation of a working traffic model that corresponds to real-life traffic on highways and streets. This model is necessary for the development and justification of decision-making in the field of organization and optimization of traffic (Storani et al., 2021).

Modeling of traffic flows, as a rule, consists of the next steps:

- Visual analysis of the effectiveness of the functioning of the design and existing schemes for organizing traffic in different road network sections, as well as determining the traffic flows parameters of the current road network configuration;
- Developing a simulation model of road network section;
- Carrying out a simulation experiment on the developed model of traffic flows;
- Detailed analysis of simulation results for several parameters of the selected section of the road network.

When collecting traffic information, traffic flow data is central. With the help of many years of scientific research and practical observations, the main most objective indicators have been formed. Including the intensity of the traffic flow, its composition by vehicle types, traffic density, traffic speed, and traffic delays (Volkova and Stepanenko, 2021).

Traffic intensity is the number of vehicles per unit of time traveling along a road section. Traffic intensity is measured on annual, monthly, daily, hourly, and shorter timescales (minutes, seconds), according to observation and measurement equipment. Traffic flow density, measured as the number of vehicles per kilometer of road, is a spatial characteristic that determines the degree of congestion on a road. The lower the traffic density, the freer the roads and the higher the speed that drivers can develop. On the contrary, the greater the density, the greater the demands on the attentiveness and accuracy of the actions of drivers, the more their mental tension increases. As a result, the likelihood of traffic accidents due to a mistake made by one of the drivers or a vehicle failure increases. As it represents the objective function of transport, speed is the most important indicator. The graph of the vehicle's speed change along the entire route is the most objective characteristic of the vehicle's movement along the road. But such spatial characteristics are difficult to obtain for many moving vehicles because they require continuous automated velocity measurements. The transport speed is a measure of the speed at which passengers and goods are delivered. It is defined as the ratio of the distance between message points to the time the vehicle spends on the journey (message time). To characterize the vehicles' speed on specific road sections, the same indicator is used.

When assessing the traffic situation, traffic delays are an indicator to which particular attention should be given. The time lost should include the time lost for all compulsory stops, not only at junctions, level crossings, and during congestion on sections of the route, but also because of the reduction in the speed of the flow of traffic compared with the average speed of traffic on the road section. The most important criterion characterizing the functioning of communication lines is their capacity. Throughput—the maximum possible number of cars that can pass through the section of the road per unit of time. The state of the environment can have a big impact on its actual throughput value. Actual throughput drops in heavy rain, fog, heavy snow, and sleet. Also, the throughput is affected by the provision of a certain conveyance speed. This is most important for high-speed roads, where safety conditions must be maintained at higher speeds.

There are various methods for assessing the impact of traffic flows on the environment. They are calculated (calculation using mathematical formulas of the volume of emissions or concentrations of pollutants in the atmosphere) and empirical (sampling and analysis using special equipment). We will use calculation methods (Research Institute "Atmosphere", 2019).

Total emissions, *M*, g/km, are calculated using the formula.

$$M = \sum_1^n\left(M_{P_1} + M_{P_2}\right) + \sum_1^{n_1}\left(M_{L_3} + M_{L_4}\right) + \sum_1^m\left(M_{P_3} + M_{P_4}\right) + \sum_1^{m_1}\left(M_{L_1} + M_{L_2}\right),$$

where,

M_{P_1}, M_{P_2}, M_{P_3}, M_{P_4}—pollutant emissions from vehicles queuing at intersections, g/km;

M_{L_1}, M_{L_2}, M_{L_3}, M_{L_4}—pollutant emissions from vehicles travelling on the considered road during a given period, g/km.

Indexes 1 and 2 correspond to each of the two traffic directions along a higher intensity road section, 3 and 4 to a lower intensity section;

n, *m*—the number of stops of the vehicle flow in front of the junction on the roads that make it up for a period of 20 min; n_1, m_1—number of periods in which vehicles co-exist for 20 min.

The emission of the i-th pollutant by the moving stream of motor vehicles on a motorway of fixed length M_{L_i}, in grams per kilometre, shall be calculated by the following formula:

$$M_{L_i} = \frac{L}{1200} \sum_1^k M_{k,i}^L \times G_k \times r_{v_{k,i}},$$

where,

L—road length, excluding the length of vehicle queue waiting to be red-lighted, km;

$M_{k,i}^L$—specific release of the i-th pollutant by vehicles of the k-th group, g/km;

k—number of vehicle groups, pcs.;

G_k—the actual maximum traffic intensity, i.e., the number of vehicles of each k categories that pass through a fixed cross-section of the selected road section of the chosen roadway on each of the two directions;

$r_{v_{k,i}}$—a correction coefficient taking into account the average flow velocity $v_{k,i}$ (km/h). We will use the data obtained from the results of the experiment on the model to determine the correction coefficient $r_{v_{k,i}}$, taking into account the average movement speed.

The emission of the i-th pollutant from the cars in the queue in the area of the junction during the 20-min period, M_{P_i}, g/km, shall be calculated using the following formula:

$$M_{P_i} = \frac{P}{60} \sum_1^N \sum_1^k \left(M'_{P_i,k} \times G'_k \right),$$

where,

P—average stop time for 20 min, seconds;

N—number of vehicle stops for a 20-min time period;

$M'_{P_i,k}$—specific emission of the i-th pollutant by vehicles in the k-th group queuing at the junction;

G'_k—number of vehicles in group k queuing at intersection (Makarova et al., 2016).

4. Results

In our earlier scientific work (Makarova et al., 2019), we developed pollutant dispersion maps obtained from the results of field studies (**Figure 2a**). This made it possible to identify problem areas, one of which is a complex interchange formed by the intersection of three busy city avenues (**Figure 2b**). This intersection was a place with a high concentration of traffic accidents, which led to environmental problems.

Figure 2. **a)** CO dispersion map; **b)** Scheme of the simulated section of road network.

For more analysis of the intersection and development of recommendations for its reconstruction, a simulation model was built using the AnyLogic 8 program (**Figure 3**). When developing the model, the following parameters were taken into account:

- intersection geometry;
- operating modes of traffic lights;
- volumes and composition of pollutant emissions from vehicles;
- parameters of pedestrian traffic;
- traffic density.

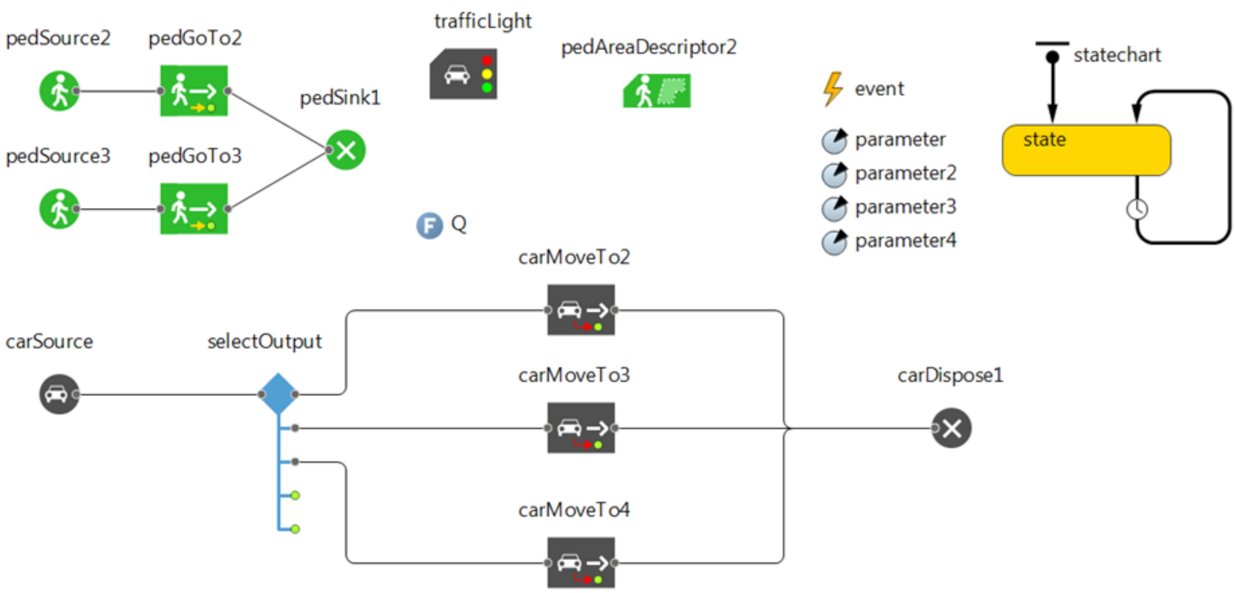


Figure 3. The structure of the developed simulation model.

The emission allowance that cannot be exceeded is a limitation of the model:

$$Q_v = \frac{M_{Li} + M_{Pi} + M_{Pr}}{M_q} \leq 1$$

Simulation experiments on the model with different characteristics of the traffic flow, determined as a result of field studies, showed that the considered intersection is a source of exceeding the maximum permissible concentrations of CO and NO_X (**Figure 4**). The first stage of the optimization experiment made it possible to determine the optimal parameters of the traffic flow, under which pollutant emissions from cars would not lead to high concentrations of pollutants.

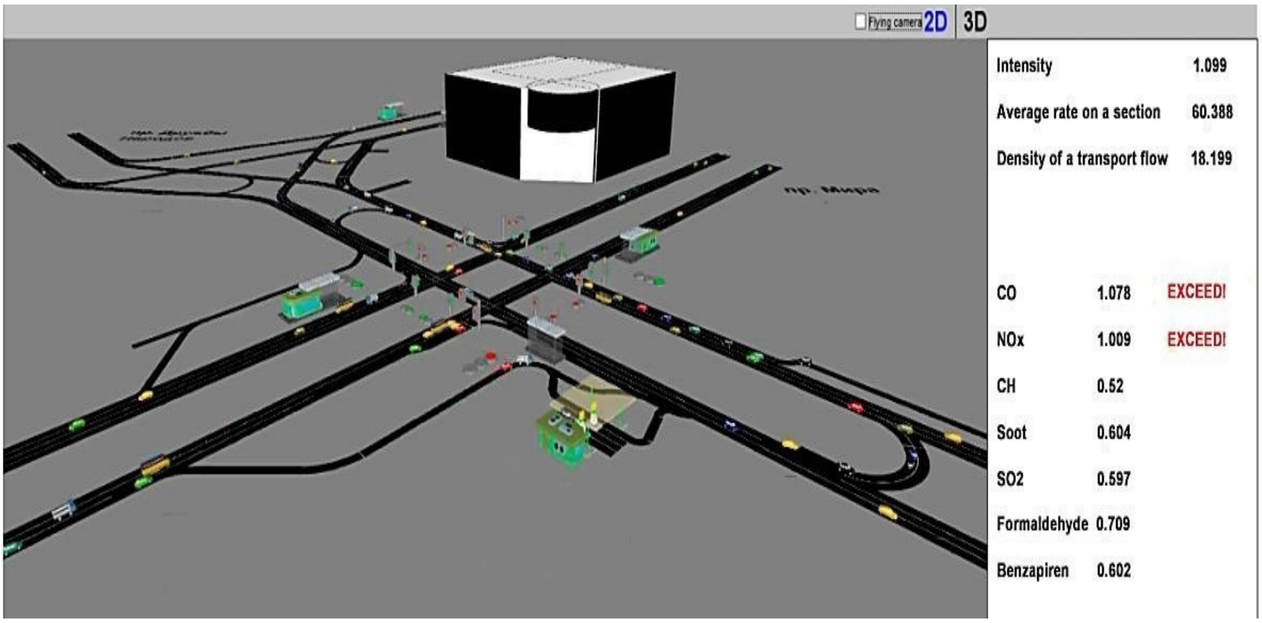


Figure 4. Road network intersection model.

5. Discussion

The road section under the study is the confluence of two transport arteries of the city, so it forms a significant number of bus routes connecting different parts of the city. One of the ways to improve the parameters of the traffic flow of this intersection is to improve the route network. The second way is the use of bus routes with a larger capacity, which will reduce the number of buses on the road section and reduce emissions of pollutants.

One of the ways to reduce the negative impact on the environment of the traffic flow is to change public transport with more environmentally friendly transport. According to the simulation experiment on the model, such a replacement will lead to a significant reduction in pollutant emissions (**Table 1**).

Table 1. Public transport emissions.

The share of emissions from the maximum allowable emissions	Pollutants						
	CO	NO_X	C_XH_Y	Soot	SO_2	Formaldehyde	Benz(α)piren
100% diesel vehicles	1.04	0.97	0.5	0.58	0.58	0.681	0.579
50% gas motor vehicles	0.87	0.91	0.44	0.47	0.58	0.69	0.587
100% gas motor vehicles	0.69	0.83	0.39	0.34	0.59	0.692	0.589

During the hours of mass traffic of road transport, this intersection could not cope with the traffic flow, which caused traffic jams. Drivers spent a lot of time on this section of the road due to the huge flow of cars. These problems arose due to the sub-optimal configuration of the road section. The situation has become even more critical due to the commissioning of the construction of a section of the tram route network passing through this intersection.

The results of simulation experiments showed that the geometry of the studied section of the road does not correspond to the parameters of the traffic flow; therefore, it negatively affects the transport characteristics. We proposed to change the configuration of the intersection. Thus, it was suggested that the roundabout would reduce the number of conflict points on this section of the road (**Figure 5**).

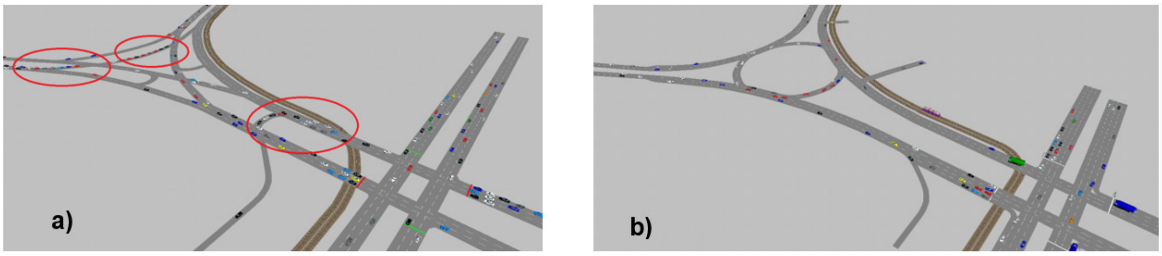


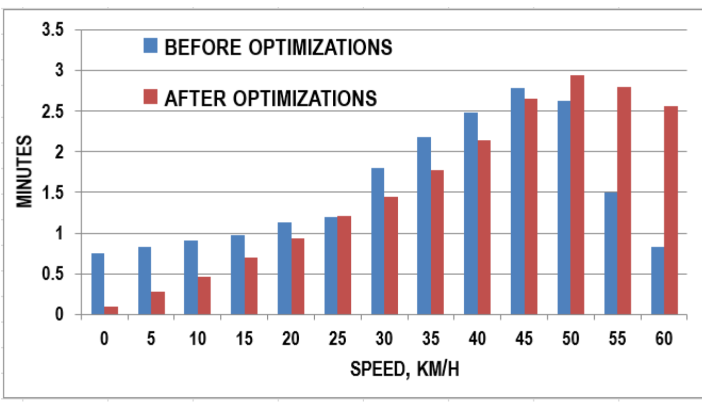
Figure 5. The view of the simulation model **a)** prior any changes; **b)** after changes.

According to the results of the study, it was found that the roundabout is preferable. The values of the parameters obtained from the simulation results of the studied intersection are presented in **Table 2**. According to these data, the parameters of the traffic flow of the studied road section can be significantly improved. Also, pollutant emissions from road transport will decrease.

Table 2. Parameters of explored section of road network.

Parameters	Values	
	Prior any changes	After changes
Average speed along explored section of the road, km/h	35	42
The number of vehicle stops per unit time, number.	6	2
Density of traffic flow, % of road area	92	67
Average duration of the movement on the section of the road, min.	4	1.4

On the model developed by us, a simulation experiment was carried out, which showed that changing the configuration of the road section led to a decrease in carbon monoxide emissions by 18.6%, nitrogen oxides by 8.2%, C_XH_Y by 17.9%, and sulfur dioxide by 15.4 %. In addition, the travel time for the road section will be significantly reduced; it will also increase the total time for cars to drive through the intersection at the maximum allowed speed (**Figure 6**).



a)

Configuration of the site	Volume of emissions, t/year			
	CO	NO_x	C_xH_Y	SO_2
Value prior to any changes	31.24	2.67	3.92	0.13
Value after changes	25.42	2.45	3.22	0.11

b)

Figure 6. **a)** Average duration of travel at different speeds (in terms of 20 min interval); **b)** Pollutant emissions.

6. Conclusion

The negative impact of the motorization process is occurring at an alarming rate, especially in small and medium-sized cities, since the solution to this problem is complicated by the lower availability of funds for the development and implementation of various methods to reduce the negative impact compared to large cities and capitals of the constituent entities of the Russian Federation. Therefore, for small and medium-sized cities, the most relevant are more accessible methods and solutions, such as the development of simulation models of road network sections and implementation experiments on it.

The article presents the development of a simulation micromodel that allows calculating the optimal parameters of the traffic flow, under which pollutant emissions from cars will not lead to high concentrations of pollutants.

The simulation experiments carried out on the developed models of a medium-sized city (the city of Naberezhnye Chelny) showed that the average time for cars to pass a problematic section of the road decreased by 65%, and the volume of pollutant emissions decreased by 17.8%.

Author contributions

Conceptualization, IM and VM; methodology, IM and VM; software, VM; validation, VM; formal analysis, IM and VM; investigation, IM, VM and PB; resources, IM, VM and PB; data curation, IM and VM; writing—original draft preparation, IM and VM; writing—review and editing, IM, VM and PB; visualization, IM, VM and PB; supervision, IM; project administration, PB. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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