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Milevich, D.; Melnikov, V.; Karbovskii, V.; Krzhizhanovskaya, V.

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Simulating an impact of road network improvements on the performance of transportation systems under critical load: agent-based approach

Dmitrii Milevich¹, Valentin Melnikov^{1,2},
Vladislav Karbovskii¹, Valeria Krzhizhanovskaya^{1,2}

¹*ITMO University, Saint-Petersburg, Russia*

²*University of Amsterdam, the Netherlands*

*viuvirully@gmail.com, mail@valmelnikov.ru, vladislav.k.work@gmail.com,
V.Krzhizhanovskaya@uva.nl*

Abstract

In this paper, we analyze the impact of planned road network development on the dynamics of the automobile transportation system during the departure of visitors after the semifinal match of the 2018 FIFA World Cup, which will take place in the newly built stadium on Krestovsky Island. To perform such an analysis, we utilize an agent-based traffic flow simulation, which requires the construction of several models. This paper covers the following progress: (1) modeling the road network in Saint Petersburg, Russia (2) a population synthesis based on data provided by the Russian Federal Migration Service (FMS) (3) a comparative analysis of the simulated system behavior using the current and improved road network and (4) a sustainability analysis of the transportation system of the studied area. We estimate the impact of road improvements on traffic flow by simulating various scenarios and determining changes in distribution of agents travel time and load redistribution among exits from the area of interest. This paper is part of the project which aims to develop a large-scale agent-based traffic flow model of Saint Petersburg urban area applicable for a wide range of research tasks from transportation planning to disaster management.

Keywords: transportation systems, agent-based modelling, travel demand, traffic flow

1 Introduction

Mass public events such as sport games, festivals, concerts and demonstrations, are attracting thousands or even millions of people [1] to the relatively small area. This raises various issues from people safety and security to efficient management of crowd flows and transportation. These are the issues which have to be carefully considered and handled well before event occurs. This determines the

necessity of building computer models which will be able to reproduce (realistically to a certain extent) an event and to provide a framework for testing different scenarios and policies, analyzing and comparing them, and finally for supporting authorities in their decision making.

This paper covers results of our case study made during our work on a global project of construction of large scale agent based traffic flow model of Saint Petersburg, Russia. The purpose of the study was to analyze and to obtain a numeric measure of impact of the improvements of road network aimed to optimize automobile transportation system during the FIFA World Cup 2018 in Russia. As the match with the most extreme load semifinal match in Saint Petersburg has been considered. Departure of spectators from it is a process which includes multiple scales or levels: crowd behavior in the stadium, pedestrian flows from the stadium to the parking areas and traffic flow when people finally get into their cars. This paper reports results of the modeling of the latter layer. Models of the first two layers have been already designed specifically for the case of Saint Petersburg and utilized to simulate evacuation of people from the Vasilievsky Island due to the flood [2] and from the stadium after match [3]. Coupling all these models into one multiscale model is the subject of our future work. Input spatial and temporal distributions of agent departures in our model are supposed to be later provided as output of higher levels, and therefore to serve as coupling mechanism.

For simulation of people departure from parking areas and heading to their homes in personal automobiles MATSim [4] has been used. It is an agent-based traffic flow simulation package which utilizes simple queue-based principle of agents microsimulation, which omits interaction between vehicles, but nevertheless reproduces the most important properties of traffic flow [4, pp. 353-358]. For the case study, covered by this paper, simulation packages implementing car following microsimulation of agents (such as SUMO [5], which was used to simulate scenarios of Pope's visit in 2005 and FIFA World Cup 2006 in 2006 in Cologne, Germany, or TRANSIMS [6]) could look more appropriate. However the final aim of the project is the simulation of similar scenarios not only for the area nearest to the location of event, but on the scale of the whole city, which for the Saint Petersburg scenario means number of agents exceeding 1.5 million. This is a scale which, even with today available computational power, is hardly feasible for simulation with car-following micromodels in reasonable time (see [7] for a comparison of simulation times).

This paper is organized in the following way: general description and characteristics of the considered event and planned transportation management measures related to it are the subject of the Section 2. Section 3 is devoted to description of the models built to provide an input data for simulation runs: road network, spatial distribution of living places of agents, model of departure times distribution. Results of these simulations are reported and analyzed in Section 4. Finally in Section five we discuss methods and results and try to give insights into our future plans on improvements of this particular study and the project of traffic flow model of Saint Petersburg in a whole.

2 FIFA World Cup: event and new road scenarios

According to the preliminary calendar of the 2018 FIFA World Cup, 7 matches are planned to be held in St. Petersburg, including one semifinal and the third place playoff matches [8]. These matches will certainly attract full stadium of spectators. While the capacity of the stadium is 67.8 thousand of visitors the number of those who will come to stadium by personal automobile is estimated to be between 5 and 7 thousand [9].

One of the FIFA security requirements is that there should be no private parking in a 1.5 km radius from the stadium, so parking for private cars is planned on the territory of the Primorsky District [9]. The scheme of parking locations is shown in Figure 1.

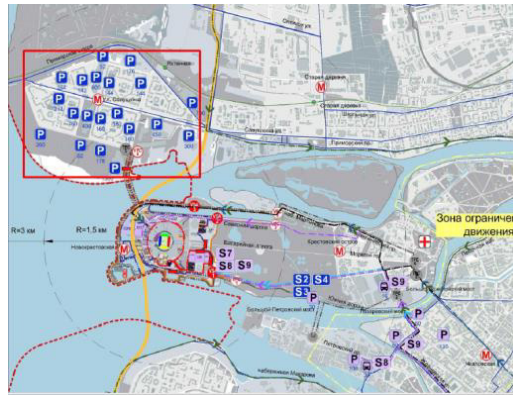


Figure 1. Preliminary scheme of the transport infrastructure positioning approved by transport authorities [9].

Four major improvements of the current road network are planned to be implemented by 2018 in order to decrease the load on existing roads during World Cup. The most important of them is the completion of the Western High-Speed Diameter (WHSD) which when finished will provide a high-speed automobile connection between northern part (which is mostly residential area) and a center of the city. However intersections design of WHSD has a critical drawback: the nearest entrance to it (in direction to the city center) is situated in 1.5 kilometers north from the area of interest and is separated from this area by a railroad. The way from the closest point of the area to the entrance to the WHSD is 5 kilometers long and a travel during the evening rush hour can take up to 20 minutes (according to Google Maps service), meaning average speed equal to 15 km/hour which is 4 times less than the speed limit. This will force drivers (which is proved by simulations) to choose route through the city center, thus WHSD aimed to take the load from roads of city center will in fact be more likely ignored. The second planned road network reconstruction is aimed to tackle this issue: building a bridge connecting two parts of Turistskaya street over the railroad could provide a quick access from the area of parking to the entrance to the WHSD. Two other improvements are not directly related to the parking area and are not considered in simulations. All improvements are demonstrated in Figure 2.

Thereby the main goal of our study was to simulate the dynamics of traffic flow inside the area, marked with red stroke in Figure 2, without and with road network changes, compare results and describe consequences these changes could have.



Figure 2. Planned road network improvements near the stadium.

3 Input models of traffic flow simulation

To perform traffic flow simulations in MATSim certain input data is required: the minimum set consists of road network and agent plans. Model of road network determines the ways agents can use to reach their destinations. Agent plans is a way to describe travel demand in agent-based simulation and in case of our study contain single trips from parking location near stadium to the place of living. Despite the simplicity of agent plans, it requires the development of models of parking places and living places density, departure times distribution. Approaches we used to build these models are similar to those used to develop model of traffic flows of Amsterdam urban area [10].

3.1. Road network model

In this section, we describe the approach we used to generate the road network file representing the road network of St. Petersburg. OpenStreetMap (OSM) has been chosen as a source of GIS data to generate road network since it continuously improves and is freely available. Although we were interested in the traffic situation within St. Petersburg, it would be incorrect to consider the city as an isolated system. To construct a road network that reflects the real one, but also is not overloaded with minor roads in the Leningrad region (region surrounding Saint Petersburg), we merged the full OSM map of St. Petersburg with the major roads of the Leningrad region using Osmosis software. This is the common practice aimed reduce the computational costs of simulations but in the same time take into account flows into and from the main simulation area [11]. After merged road network has been converted to MATSim format, which further simplifies road network by reducing simple chains of nodes into one link with length and capacity attributes equal to sum of these attributes of reduced links. Since MATSim needs to calculate distances between points many times during simulation, it is inefficient to use a spherical coordinate system WGS84 in which OSM data is stored, because distance calculation in such a system is computationally expensive. Instead of this, the Pulkovo 1995 (EPSG-2465) has been chosen, which is a local Cartesian system developed specifically for the region of interest. Then, we modified the XML file with the existing road network to add the improvements planned to be implemented by 2018. Thus, we obtained two road networks: the existing network and the planned network to be finished by 2018. Figure 3 shows the existing road network of St. Petersburg generated from OSM data.

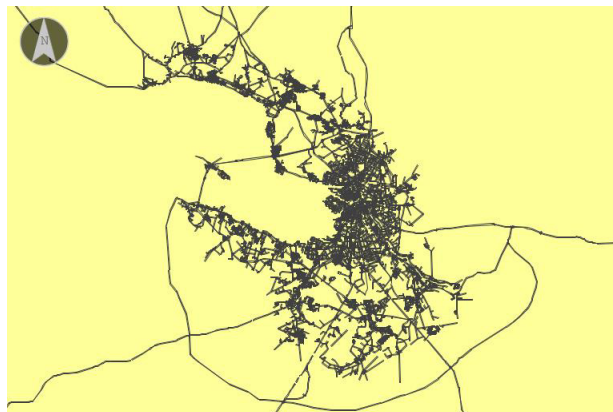


Figure 3. Road network of Saint Petersburg and major roads of Leningrad region.

3.2. Travel demand model

This section describes the model of travel demand composition we used to generate scenarios of guest departure after the semifinal of the 2018 FIFA World Cup. We simulated people's trips from the moment they get in the car until the moment they get home. In order to construct agent plans with such trips, the following models are required:

- Temporal distribution of departure time from parking places;
- Spatial distribution of parking places;
- Spatial distribution of living places.

A detailed description of the development of these models is presented below.

3.3. Population synthesis

This section describes the principles that are used to generate agents' plans. Population synthesis in this considered scenario requires the synthesis of the spatial distribution of car owners' living places. Based on available data sources, we decided to use the database of the Russian Federal Migration Service, which contains the addresses of all houses in St. Petersburg and the number of people registered at these addresses. This database is stored in several tables, which contain data about specific districts. We suppose that the overwhelming majority of cars belong to people living in St. Petersburg, while guests from other cities and countries would rather use public transport and taxis, instead of renting a car. We obtained coordinates in WGS84 for each address in the database using Yandex Geocoder and then transformed them into Pulkovo 1995 coordinate system. The heat map demonstrating the population density distribution in St. Petersburg is shown in Figure 4. This distribution has been used as the model of agent living places distribution.

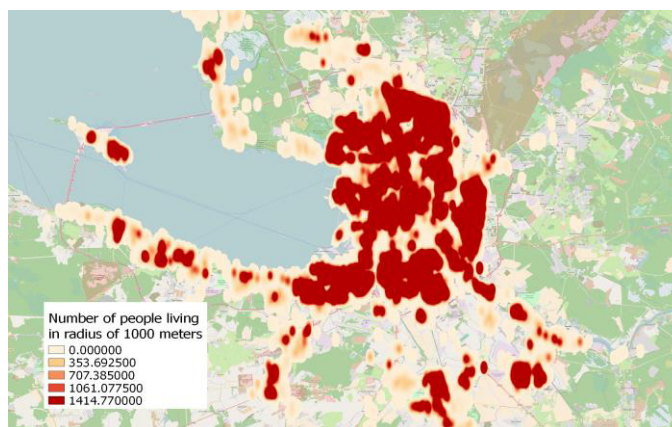


Figure 4. Population density of Saint Petersburg obtained from FMS data used to generate destinations of agents (location of their homes).

Besides the generation of living place coordinates, we should generate the locations of agent departure. Paying attention to the relatively close locations of parking places and the small size of studied area, we decided to generate parking places uniformly distributed in the highlighted area. As simulations show, traffic congestions emerge only on the boundary of this area, so that our approach of parking places generation does not distort the results.

After the generation of start and end locations of agent trips, it is necessary to generate departure times. Since no official data on intensity in time of people leaving stadium was found in open sources and the mentioned document, we decided to use the Gaussian distribution as an approximation of the

distribution of departure times. Another distributions such as Poisson or lognorm are also possible options, which however have not been tested in this study yet.

4 Results

We ran simulations in MATsim for 7 thousand agents (upper boundary of an estimated number of vehicles) on both road network without and with the bridge connecting Turistskaya street. Just from visual analysis of snapshots made at peak time for both scenarios (see Figure 5) we can already conclude that adding the bridge decreases significantly congestion of agents on the existing exits from the area: entrance to the Primorskoe shosse from Shkolnaya and Yachtennaya street and Savushkina street eastern exit. Moreover it is clear that number of agents choosing WHSD to get to the south of the city is also much greater for the second scenario, which even leads to a congestion on the entrance to WHSD.

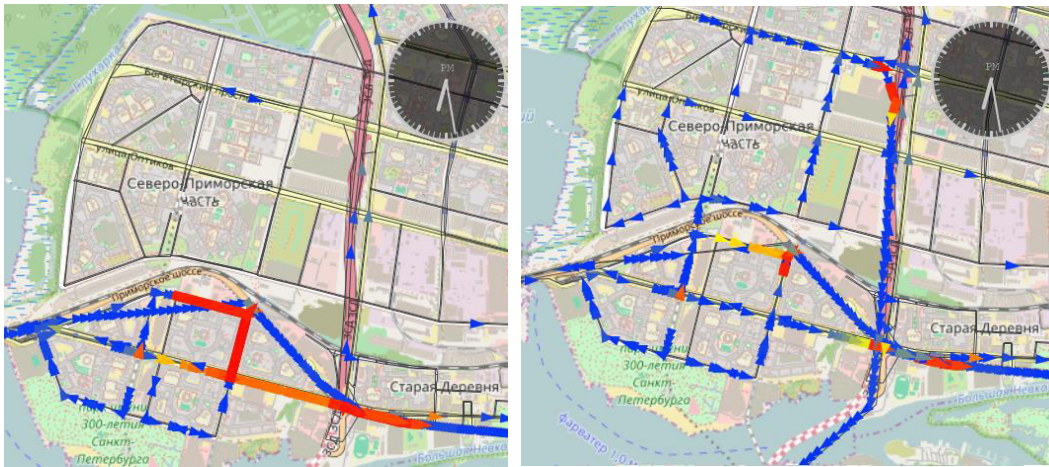


Figure 5. Traffic flows during peak load for scenario without bridge connecting Turistskaya street (left) and with it (right).

We analyzed files of the simulation results in order to define observed changes in transportation system with numbers. Figure 6 shows the dependence of the number of agents who are currently en route on the time for the existing and improved road networks. From it we can see that the peak load dropped from 3.3 thousand agents to 2.7 thousand or by 18%. The evidence of decreased average travel time is also supported by the displaced to the left (by 4 minutes) bell of a normal distribution, variance of which has decreased also. The form of these plots is determined by the chosen distribution of departure times.

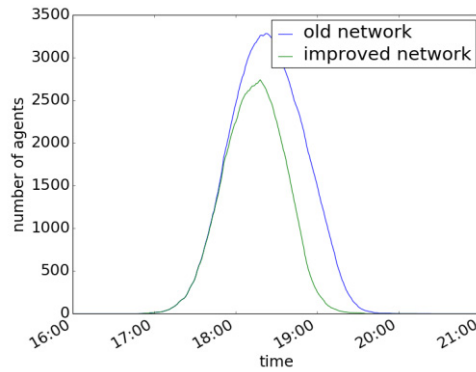


Figure 6. Comparison of number of agents en route over time for two scenarios.

4.1. Capacity and sustainability of transportation system of the studied area

We performed series of simulations aimed to determine the sustainability of transportation system inside the studied area. Increasing the number of agents from 100 to 15 thousand we measured an average trip time in the area of parking. Thus plotting dependency of average trip time on number of agents we could be able to find a law of system response on the increasing load. Plot presented in Figure 7 demonstrates this dependency. Constant average travel time from 100 to 5 thousand agent implies that common throughput of all exits from area is greater than 5 thousand in 18 minutes. From 5 thousand of agents dependency starts to follow approximately $y=x$ function, meaning, that the system is absolutely sustainable and handles any load linearly: average travel time is proportional to the load. It is obvious that this is a result which does not correspond to reality which can be explained by the fact that only agents departing from football match were simulated and density of vehicles outside area of interest (as well as inside) is not realistic. From this we can conclude that simulation of isolated systems, which are not isolated in real life, is not suitable (predictably) for some research questions such as, for example, our case of studying system sustainability.

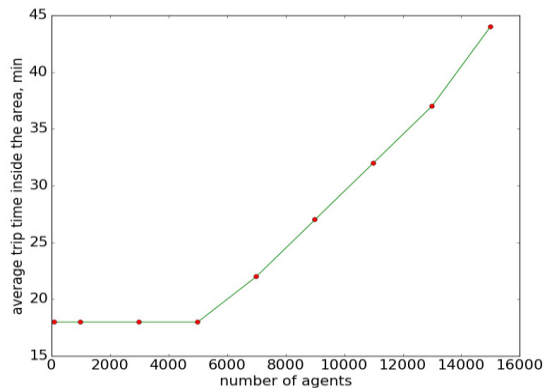


Figure 7. Dependency of average trip time inside study area on number of agents.

4.2. System load redistribution

Agents are leaving the studied area along 3 traffic arteries in the case of the old network: Primorskoe Highway (eastward), Savushkina Street and Primorskoe Highway (westward). In the case

of the improved network, a new destination appears – Turistskaya Street. These roads are shown in Figure 8. It was interesting for us to evaluate how the addition of the new destination influences the intensity of traffic on existing ones.

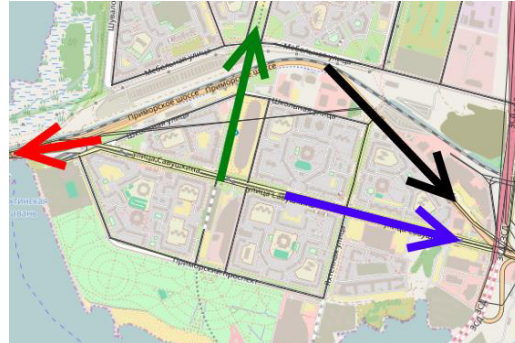


Figure 8. Four exit directions from studied area (road network with improvements).

For this purpose, we calculated the number of cars leaving the studied area along a particular destination every 10 minutes. Plots of these curves for the old and improved road network for each destination are shown in Figure 9. These graphs reflect the drop of traffic intensity after the construction of Turistskaya Street. There is a considerable drop only along the eastern destination of Primorskoe Highway. After analyzing the behavior of agents in Senozon Via, we came to the conclusion that this drop is due to the construction of the WHSD. The overwhelming majority of people leaving the studied area along Turistskaya Street then use WHSD in order to get to remote districts. Therefore, the magnitude of this drop can be considered as a measure of the road improvements in general.

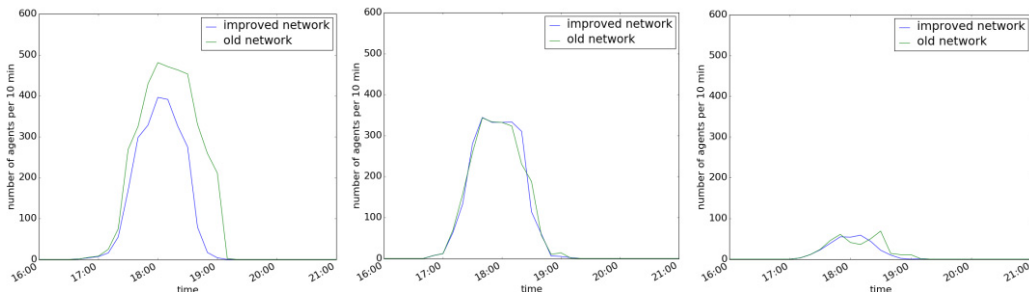


Figure 9. Change in intensities on existing exit directions: Primorskoe Highway eastward (left), Savushkina eastward (middle), Primorskoe Highway westward (right).

5 Conclusions and future work

In this work, we described the approaches we utilized to perform agent-based traffic flow simulations in St. Petersburg in the context of the 2018 FIFA World Cup. This included: a road network model, population synthesis, and a travel demand model. Based on this, we took first steps in the analysis of road network improvements planned to implement before 2018. We estimated the impact of the addition of specific road on traffic intensity on the boundary of the studied area. However, we did not take into account background automobile traffic, so the values we obtained during the simulations cannot be considered as the estimates of parameters of the real network. Nevertheless, they allow us to compare the two road graphs and calculate relative indexes.

Multiple improvements of models described in this paper are planned, most important of them are:

- Addition of regular traffic (agents travelling with no relation to the match);
- Addition of the toll points on the entrance to the WHSD (since it is a toll road) which affects significantly traffic flow characteristics on the entrance;
- Addition of payment for the travel through WHSD as a factor influencing route choice by agents;
- Coupling this traffic flow model with higher levels: crowd dynamics and pedestrian flow models.

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