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Design and evaluation of simulation model to connect an interurban toll road to the street and road network

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Abstract

The paper is devoted to the study of the toll plaza connection at the exit of the interurban toll road to the urban street-road network as the estimated place of traffic congestion. A discrete-event simulation was used as a research method. A model of a traffic intersection on Shuvalovsky Prospect was considered on the example of the Western High-Speed Diameter toll highway project (hereinafter referred to as WHSD), implemented in St. Petersburg. A toll plaza simulation model was created at the exit from the toll road as part of the study, taking into account the specifics of traffic and user behavior on the road, as well as a signal controlled intersection that connects the road junction to the urban street-road network. The paper describes the parameters of the original object, as well as the developed simulation model, provides an assessment of possible transport situations that lead to traffic congestions. The authors analyzed the throughput capacity of the toll plaza, as well as the transport intersection in general, and determined the values of threshold traffic intensities that affect the traffic situation. Based on the data obtained, optimization experiments were carried out on the simulation model aimed at improving the parameters of the traffic light phases, which provide exit from the toll road. The obtained results allowed improving the work of the traffic intersection simulation model, reducing the risk of congestion at the study object.

Keywords: Discrete-event simulation; Toll road; Toll plaza; Toll collection system; Traffic congestion

1. Introduction

The number of ongoing projects of highways operated on a toll basis is steadily growing to date. The length and number of express roads connecting large urban agglomerations and logistics centers is increasing. There is also an increase in the number of interurban toll road projects that increase the mobility of the urban population and allow moving within the city without crossing intersections with a higher speed limit.

Connection of interurban toll roads is carried out by connecting their exits and entrances to the street-road network of the city or its highways. When connecting a toll highway to the street-road network, it is necessary to note the importance of the laid down solutions for organizing traffic in connection areas at the stages of design and implementation of projects. Insufficient quality of engineering study of these solutions may lead to the risk of traffic congestion from the side of the street-road network or toll road. In addition, it should be noted that projects for the organization of the road network can be considered optimized for solving transport problems immediately at the time of their implementation, which may require additional changes in them in the future. The purpose of the research is to develop simulation model of infrastructure facility for inter-urban toll road and traffic flow passing through the exit toll plaza to the urban street-road network, allowing to assess the risk of traffic congestion.

Experiments carried out in the course of simulation modeling can make it possible to determine the required parameters for upgrading the toll collecting system at the toll plaza, providing optimal throughput and increasing the efficiency of the toll plaza.

Section 2 of the paper provides a literature review of the studies on traffic optimization in various simulation software environments. In Section 3 the authors set the statement of the problem being solved. Section 4 describes the simulation model that has been developed, including the at the exit of the toll road and signal controlled intersection following it. Section 5 presents the results of the study. Finally, general conclusions are presented in the section 6 of the paper.

2. Literature review

The work is devoted to the study of the toll plaza at the exit of the interurban toll road to the urban street-road network. Discrete-event simulation modeling was used as a research method.

To conduct simulation experiments and solve optimization problems, researchers choose the PTV VISSIM and AnyLogic software environments, which is confirmed by the examples of the studies of the authors Gagarina S.N. et al. (Gagarina, Chausov, and Levkina, 2020), Yang, L. et al. (Y. Yang, Li, and Zhao, 2014), Pop, M et al. (Pop, 2020), Sun, L et al. (Sun et al., 2018), Karaaslan, E et al. (Karaaslan et al., 2018), Yang, J., and Li, M. (J. Yang, Zhang, and Li, 2021), Y. Zhu et al (Zhu et al., 2021), (Zhang and Wang, 2022), Arafat, M. et al. (Arafat et al., 2020), Liu, L. et al. (Liu et al., 2020), Dutta, M. et al. (Dutta and Ahmed, 2019), Fabianova, J. et al. (Fabianova et al., 2020), Vortisch, P. (Manjunatha, Vortisch, and Mathew, 2013), (Datta, 2018).

The capability to analyze complex transport systems and visualize digital twins of transport objects allows using of simulation modeling to optimize complex road junctions, as evidenced by the examples of studies conducted in China by Ma, Q. et al. (Ma et al., 2021), Xu, M. et al. (Xu et al., 2019) Russia by Shchegolova, N et al. (Shchegolova et al., 2020), Czech Republic by Plocova, K. & Fibich, D (Plocova and D.Fibich, 2020) and Thailand by Morita, H., Inenaga, S., & Takano, T. (Morita, Inenaga, and Takano, 2019). It should be noted that the capabilities of this method can also be expanded by integrating simulation environments with other software packages and Intelligent Transportation Systems. So, in the studies of Nie, C., et al. (Nie et al., 2021), Raju, N., et al. (Raju, Arkatkar, and Joshi, 2021), Liang, Y. et al. (Liang et al., 2020), Petrov, T., et al. (Petrov et al., 2021) the possibilities of integrating the PTV VISSIM software environment with the MatLab software package MatLab (Nie et al., 2021), the vehicle registration plate recognition system (Liang et al., 2020), and the OMNET ++ communication network simulator, which provides a testing ground for realistic scenarios of infrastructure interaction with connected vehicles are demonstrated (Petrov et al., 2021).

3. Problem statement

The interurban toll road Western High Speed Diameter (hereinafter referred to as WHSD), implemented in St. Petersburg, was considered as an object of simulation modelling. One of these road junctions is the intersection at the crossing with Shuvalovsky Prospect.

Now the road junction provides traffic in the following directions:

- Turning from Shuvalovsky Prospect to WHSD towards Ring Road (North);
- Turning from Shuvalovsky Prospect to WHSD towards Bogatyrsky Prospect;
- Exit from WHSD to Shuvalovsky Prospect when driving from the Southern Section.

The Shuvalovskaya intersection provides an additional connection to the toll road to the Primorsky district and removes the traffic load both from the street-road network of the district and from the toll plaza at the exit from WHSD to Bogatyrsky Prospect, which is currently operating at maximum throughput capacity. The performance of this toll plaza was estimated by the authors earlier in the study (Talavirya and Laskin, 2020) (similar results were obtained in the study (Talavirya and Laskin, 2022)).

The exit from the toll road is carried out through the toll plaza, which consists of six toll lanes, four lanes operate in automatic mode, two lanes – in manual mode, combined with the electronic toll collection.

Being in cramped urban conditions, the connection of the toll road exit to the street-road network of the district is carried out through a signal controlled intersection, located behind the toll plaza, and providing traffic exits to Shuvalovsky Prospect and Planernaya Street. The connection to the signal controlled intersection is carried out through four traffic lanes, three of which require movement in the forward direction along Shuvalovsky Prospect and one provides a right turn to Planernaya Street.

It should be noted that an additional feature of this exit is the presence of the so-called toll plaza bottlenecks and a signal controlled intersection is the presence of two-lane road sections at the exit from the main road at the approach to the toll plaza entrance area and a two-lane road section at the exit from the toll plaza area to vehicular access area to the traffic light. This feature allows us to consider this section of the road as a sequence of "obstacles" that slow down the speed of movement and affect its throughput capacity.

Since this area of the city is a bedroom community, its main transport communications are "home – work" and "work – home". Thus, the main load on the exit of the toll plaza, located on Shuvalovsky Prospect, will take place on the evening rush hours. The objective of this study is to assess the traffic environment at the toll plaza at the exit of the toll road in the conditions of its close location to the signal controlled intersection, which connects the motorway to the urban street-road network.

4. Simulation model

The simulation model was developed in AnyLogic software using traffic and process modeling libraries. A general view of the simulation model of the intersection is shown in Figure 1.

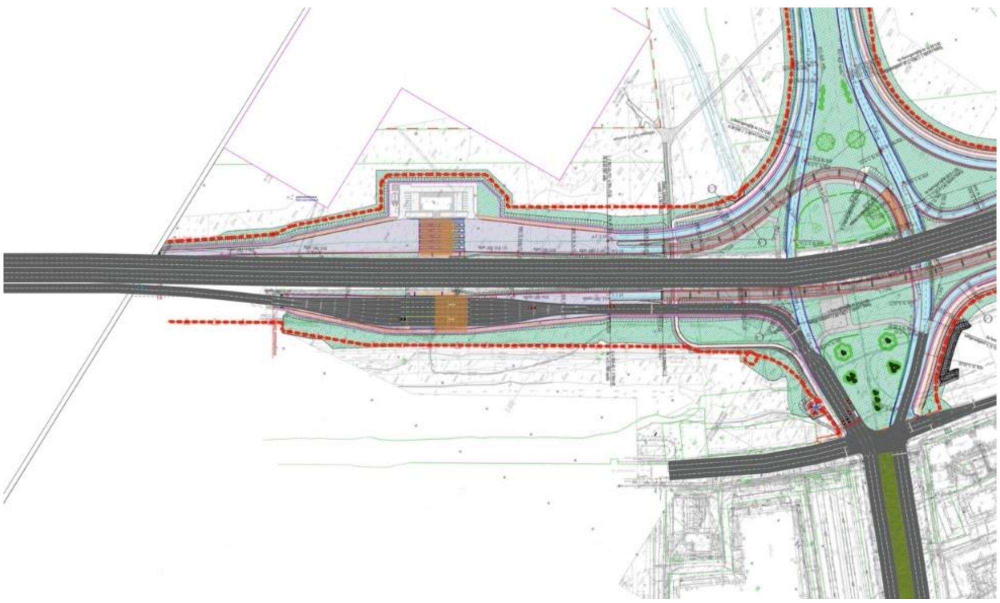

Figure 1. General view of the simulation model of the intersection at the crossing with Shuvalovsky Prospect.

The parameters of the toll plaza simulation model on Shuvalovsky Prospect fully correspond to the parameters of the original object in terms of the geometric dimensions of the toll plaza and the zones of entrance and exit from it, the number of toll lanes, as well as their modes of operation.

The developed simulation model of the toll plaza on Shuvalovsky Prospect allows to take into account the following parameters:

- Traffic intensity at the toll plaza;
- Composition of traffic;
- Distribution of vehicles by payment methods;
- Service time on the automatic lane;
- Service time on the manual payment lane;
- Operating modes of lanes;
- Additional parameters (user behavior).

A general view of the developed simulation model of the toll plaza on Shuvalovsky Prospect is shown in Figure 2.

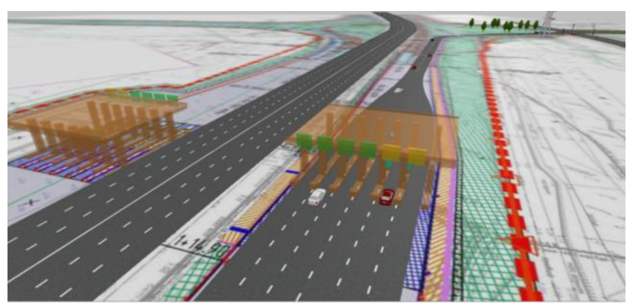

Figure 2. General view of the toll plaza simulation model at the exit to Shuvalovsky Prospect.

A general view of the simulation model for connecting the exit from the toll road to the signal controlled intersection is shown in Figure 3.

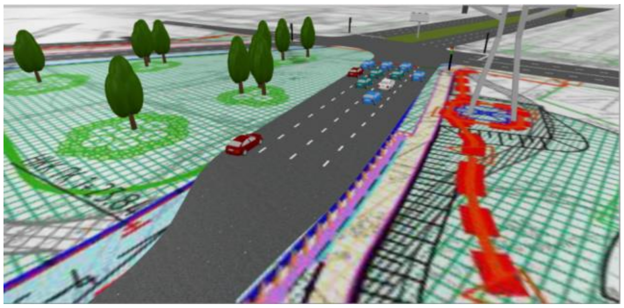

Figure 3. General view of the simulation model of the controlled intersection at the exit from the toll road

The simulation model of a signal controlled intersection is aimed at evaluating the effectiveness of setting up traffic light phases that ensure the exit of traffic at the exit from the toll plaza. Thus, the signal control of communication at this traffic light object in the directions of movement "Toll plaza – Shuvalovsky" and "Toll plaza – Planernaya Street" is reproduced. Note that the control of these directions is carried out separately, since the right turn from the right lane is controlled by an additional section of the traffic light.

The sequential arrangement of the toll plaza and the traffic light object can lead to the following traffic situations:

1. Traffic congestions may occur at the entrance to the toll plaza in case of insufficient capacity of the toll plaza and high traffic intensity through the toll plaza;
2. There may be a risk of traffic congestion at the entrance to the intersection if there is insufficient time for the traffic light to exit from the toll plaza.

The following measures will be accomplished with the help of the developed simulation model of the traffic intersection:

- Analysis of the throughput capacity of the toll plaza at the exit from the toll road;
- Analysis of the throughput capacity of the traffic intersection, including an operating toll plaza and signal controlled traffic light object;
- Assessment of the possibility of optimizing the operation of a traffic light object to increase the throughput capacity of a traffic intersection.

5. Results of the research

5.1. Estimation of the throughput capacity

Simulation experiments were carried out aimed at studying the functioning of the toll plaza at various traffic intensities to determine the maximum throughput capacity of the toll plaza at the exit on Shuvalovsky Prospect. The limiting capacity was considered to be the capacity at which vehicles, when passing through the toll lanes, lined up outside the toll plaza entrance zone that is the line beyond which the expansion of the highway section from 2 to 6 lanes begins. The operation of the traffic light behind the toll plaza was not taken into account to estimate the throughput of the toll plaza.

A number of simulation experiments were carried out with traffic intensities in the range from 100 to 4000 vehicles/hour in increments of 50 vehicles/hour, which allow estimating the maximum load on the toll plaza. As a result of the simulation experiments, it was found that the throughput capacity for the developed toll plaza simulation model and the set traffic environment parameters corresponds to the intensity value of 1700 vehicles/hour. At higher intensities, at which a queue is formed outside the toll plaza entrance area, the distributions of the vehicle passage time through the automatic and manual toll lanes of the toll plaza form an inseparable mixture of distributions, which is well approximated by the gamma distribution law. At high intensity values (1700 – 4000 vehicles/hour), the distribution law has an especially strong right-sided asymmetry. An indirect characteristic of this asymmetry is a significant difference between the average value of the passage time of the toll plaza zone and its most probable value.

5.2. Analysis of the throughput capacity of the traffic intersection

To analyze the throughput capacity of the traffic intersection, simulation experiments were carried out aimed at studying the time of passage of the traffic flow through the toll plaza and signal controlled intersection with the actual parameters of the duration of the phases of the traffic light that provides exit from the toll plaza.

A number of simulation experiments were carried out with traffic intensities in the range from 100 to 4000 vehicles/hour in increments of 50 vehicles/hour, which make it possible to evaluate the functioning of the intersection under different traffic loads.

As a result of the simulation experiments, it was found that with the existing parameters of the phases of the traffic light, with intensity above a value of 900 vehicles/hour, formation of the traffic congestion begins at the entrance to the intersection. If the vehicle queue exceeds a distance of more than 475 meters, traffic congestion occurs in the toll plaza exit area, which results in a decrease of the service time on the toll lanes and the occurrence of a second traffic congestion at the entrance to the toll plaza area. The distribution of service time at toll plaza with a traffic intensity of 900 vehicles/hour is shown in Figure 4.

With an incoming traffic intensity of 900 vehicles per hour, a separable mixture of distributions of the vehicles passage time through the toll plaza zone is no longer observed, however, the observed empirical distribution is well approximated by an exponential law (a special case of the gamma distribution).

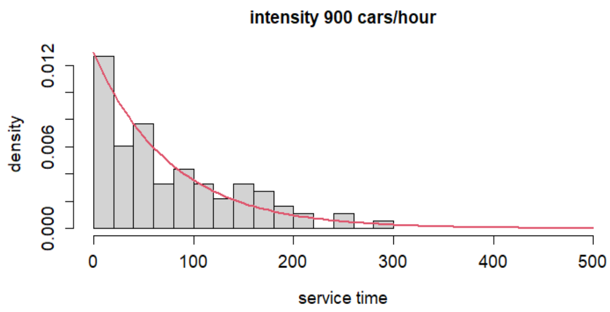

Figure.4. Distribution of service time at the toll plaza when incoming traffic intensity is 900 vehicles/hour

5.3. Optimization of traffic intersection throughput capacity

With an incoming traffic intensity of 900 vehicles per hour, a separable mixture of distributions of the vehicles passage time through the toll plaza zone is no longer observed, however, the observed empirical distribution (Figure 4) is well approximated by the exponential law.

Our goal is to find an optimal mode of operation of the traffic light cycle with the distribution density of the value Z – the number of vehicles in the traffic congestion on the road section, that can be written as:

$$\begin{cases} P(Z=0) = e^{-(\lambda T + \int_0^{\tau} \mu(t)dt)} \sum_{k=0}^{-\infty} \left(\frac{\lambda T}{\int_0^{\tau} \mu(t)dt} \right)^{\frac{k}{2}} I_{|k|}(2\sqrt{\lambda T \int_0^{\tau} \mu(t)dt}), at\ k \le 0, k \in Z \\ P(V^{*}=k) = e^{-(\lambda T + \int_0^{\tau} \mu(t)dt)} \left(\frac{\lambda T}{\int_0^{\tau} \mu(t)dt} \right)^{\frac{k}{2}} I_k\left(2\sqrt{\lambda T \int_0^{\tau} \mu(t)dt}\right), at\ k > 0, k \in Z \end{cases} \quad (1)$$

where, $\mu(t)$ is a variable intensity within the green phase of the traffic light from 0 to τ;

T – variable, the full time cycle of the traffic light;

$T-\tau$ – time duration of the red traffic light phase;

$I_{|k|}(x)$ – modified Bessel function of the first kind, for $k=0, \pm 1, \pm 2, \ldots, \pm\infty$.

The derivation of equation (1) is described in detail in the study (Talavirya and Laskin, 2021).

To find the appropriate solution, the OptQest optimizer built into AnyLogic was used. The OptQest optimizer automatically finds the best values for the model parameters, taking into account the given constraints, and provides a convenient graphical interface for configuring and monitoring the progress of the problem solution. OptQest is a trademark of OptTek Systems, see website for details: *www.opttek.com*. Constantly changing the model parameters within the given constraints, OptQest performs a set number of iterations by combining heuristic methods, optimization methods and neural networks. The minimum value of the objective function is determined at each iteration. In our case, the objective function is the minimum time that the vehicle spends in the traffic intersection zone from the moment of crossing the entry line to the toll plaza zone, until the moment of crossing the line on which the traffic light is installed.

Table 1 presents the search conditions for the optimal parameters of the traffic light time phases, including the maximum and minimum values, as well as the increment of the selected parameter, within which the OptQest optimizer was used. As a result of the optimization experiment, the parameters of the time phases of the traffic light at the exit from the toll plaza were set, which made it possible to reduce the time for the vehicle to leave the toll road. Optimization results are shown in Figure 5 and Table 1.

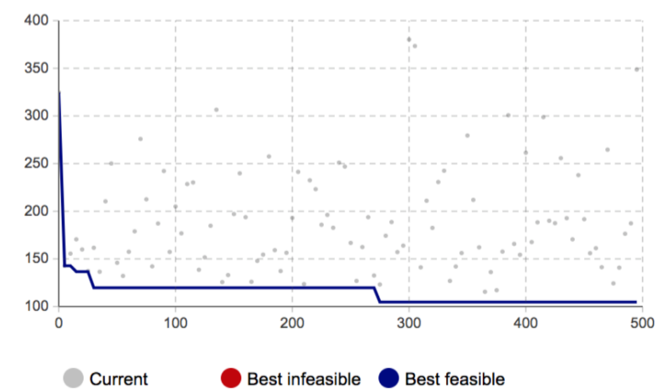

Figure.5. The average time for the traffic environment to pass through the road section in the iterative process (Number of iterations - 500 units, experiment duration - 1800 s.)

Figure 5 shows the iteration number on the horizontal axes. The corresponding point on the graph is the minimum average time the vehicle is located in the intersection zone. A solid line indicates the best result obtained by the corresponding iteration. In particular, in Figure 5 you can see that the best result was achieved at iteration number 275, the minimum average time the vehicle was located in the intersection zone is ~ 105 seconds. Table 1 shows the parameters of the traffic light object, in which the best result was obtained.

Table 1. The best parameters of traffic light phases at the exit from the toll plaza.

	Current	Best
Iteration completed	500	272
Objective	295	104
Parameters		
parSG	49	120
parSR	66	40
parRG	95	16
parRR	72	13

As can be seen from Table 1, the minimum time of agents' location in the simulation model, equal to 104.665 seconds, is possible when using the parameters of the traffic light phases at the exit from the toll plaza, equal to 120 (parSG) and 40 (parSR) seconds for the green and red phases of the traffic light, respectively, in the forward direction, and 16 (parRG) and 13 (parRR) seconds for the green and red phases, respectively, in the right turn section of the traffic light.

A number of simulation experiments were carried out to assess the throughput capacity of the traffic intersection after optimizing the phase parameters of the traffic light at the exit from the toll plaza. The simulation results showed that when the phases of the traffic lights indicated in Table 1 are established, the throughput capacity of the entire intersection coincides with the throughput capacity of the toll plaza - 1700 vehicles/hour. In other words, under such traffic light modes, all vehicles outgoing from the toll plaza have time to leave the intersection zone (cross the traffic light line) without the formation of an intermediate congestion between the toll plaza and the traffic light.

At any intensity of the traffic environment exceeding the value of 1700 vehicles/hour, there is no traffic congestion at the entrance to the signal controlled intersection, because the phases of the traffic lights are set so that the outgoing traffic for a sufficiently long period of time corresponds to the traffic with an intensity of 1700 vehicles/hour - the maximum intensity of the traffic outgoing from the toll plaza zone. The traffic congestion in this case will be formed only at the entrance to the toll plaza.

6. Conclusions

In this study, on the example of the WHSD project, the simulation method was used to analyze the connection of the toll plaza at the exit of the interurban toll road to the street-road network. Being in a cramped urban environment, toll plazas may be located in close proximity to the urban transport network. This imposes increased requirements for the organization of traffic for such intersection.

The authors have made an assessment of traffic situations that can lead to the formation of traffic congestions both at the entrance to the toll plaza and at the entrance to the signal controlled intersection. In the course of the study the following results have been achieved:

- The throughput capacity of the toll plaza was analyzed;
- The throughput capacity of the traffic intersection was analyzed;
- The parameters of the phases of the traffic light of the traffic intersection, which ensured exit from the toll road, were optimized.

The results of the study made it possible to reduce the risk of congestion at the investigated transport intersection.

This research, however, is subject to several limitations. The simulation model does not include oncoming and intersecting traffic directions at regulated intersections, which can be an additional obstacle that impedes the movement of traffic flow from the toll plaza.

The output of the present research will be useful for to direct market participants: governmental customers, concessionaires, toll road operators, design institutes and developers of transport systems, and can be used at various stages of the transport projects implementation of toll plazas.

With the emergence of new road exits and traffic directions at the traffic interchange, the role of new elements in changing the transport environment and their impact on traffic congestion should be examined.

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