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Using of discrete-event modeling in throughput capacity analysis of a toll plaza at the exit of the interurban toll road

Alexander Talavirya [1,*], and Michael Laskin [2]

[1] Higher School of Economics, Souyuza Pechatnikov 16, Saint-Petersburg, 190121, Russia
2 St. Petersburg Institute for Informatics and Automation of the Russian Academy of Sciences, 14 Line, 39, St. Petersburg, 199178, Russia

[*]Corresponding author. Email address: a.talavirya@yandex.ru

Abstract

Despite the development of multilane free flow (MLFF) tolling solutions, a large number of toll road projects with a barrier toll collection system (TCS) are currently being implemented in Russia. Therefore, studies of toll plazas (TP), as a transport infrastructure element of barrier TCS, are still relevant. Ignoring issues of assessing current and predicted intensity on TPs can cause regular traffic congestions on toll roads. This study addresses the issue of TP assessment throughput capacity during toll road operational stage. We use discrete-event simulation of TP. As a methodology for transport micro-modeling Western High Speed Diameter toll road TP in St. Petersburg, Russia, was considered as a case for our study. The simulation model of TP at the exit of toll road was developed with the help of AnyLogic software. We accounted for the specifics of traffic composition and user behavior in the selected urban district. Traffic intensity value of forming traffic congestion at TP was established experimentally. We analyzed two cases of service time distribution with low and high traffic intensity. In the first case, our results show a splitting of total service time distribution into two distributions for different toll lane operating modes. In the second case, influence of user behavior on nature of the TP service time distribution was revealed. For both cases we determined parameters of gamma laws for service time distribution. Our findings indicate that when TP throughput capacity is insufficient, TP performance becomes low, and service time distribution increases, regardless of the type of fare payment. Implications for toll road operators and useful insights are discussed.

Keywords: discrete-event simulation; toll road; toll plaza

1. Introduction

Today in Russia there is an active development of road transportation network in line with the goals and objectives of the national program “Safe and high-quality roads”. Toll roads play a special role in the development of transportation industry since they create internal transport corridors and significantly improve safety and comfort while driving. At present, barrier type of toll roads prevails in Russia, where fare is paid after vehicle slows down or stops at the TP. Despite the use of the promising TCS technologies, such as MLFF, in a number of ongoing projects barrier TCS are still actively used.

The managing issue for existing TPs, which are carried out by operating organizations – toll road operators, remains relevant. Toll road operators manage traffic flow, using TCS and traffic management system (TMS), ensuring the efficient use of toll road and providing quality of user services.

While managing traffic flow on toll roads, operators have to evaluate and predict traffic intensity on TP on a regular base. Also, to provide the necessary and sufficient throughput capacity of TP with increasing traffic intensity, operators can carry out technical measures to increase the throughput capacity of the TP. Such measures can include:

1. implementation modern TCS technologies, for example, a switch from a barrier based TCS to MLFF;
2. increase of the number of TP lanes;
3. construction of reversible toll lanes. This option can be used only in case, when TP zones in two directions of road are combined;
4. optimization of operational modes of toll lanes. This method is carried out by changing ratio of toll lanes on TP, that are operating in different modes, and receiving different types of payment means;
5. modernization of TCS on TP. Modernization can be carried out by introducing new means of payment, as well as new methods of payment acceptance on toll lanes.

While increasing throughput capacity by implementing modern fare payment technologies is considered to be the most effective way, such an approach has two significant limitations. The first limitation is a long transition period to new system and high cost of the project. Another significant limitation is the need to implement technology for the entire toll road which does not allow to solve the problem locally for one TP.

Increasing TP throughput capacity by expanding the existing TP boundaries and adding toll lanes is common, but it also has limitations. In most cases, existing engineering infrastructure in boarders of TP area impedes to such approach. The infrastructure includes engineering buildings and structures, necessary to operate TP. Additional restrictions to this measure may also appear due to the inability to reconstruct the TP canopy. Reconstructing TP located in urban area is a most difficult objective. If constrained by the surrounding urban infrastructure, TP can be located on flyovers or tunnels which leads to a significant increase in the reconstruction works cost.

The most common measures to increase the throughput capacity of the TP are technical optimization and modernization of hardware and software components of TCS. It can be made both within the framework of a single toll lane; the entire TP; or the entire toll road. The solution to this problem by toll road operator will begin with an analysis of current throughput capacity of the TP.

Our study employs discrete-event simulation method for TP traffic flow analysis. Simulation model allows to:

1. reproduce TCS logic accurately;
2. add additional parameters to simulation model, such as user behavior;
3. conduct experiments to analyze the current state of TCS and quality of its work;
4. manage all the metrics necessary for TP operation and conduct their statistical analysis;
5. predict the operation of an optimized or modernized TCS.

Based on the results of this study, the operator can evaluate traffic load of TP, and carry out timely planning of measures to optimize and modernize the TCS.

2. Literature review

As noted by Serova E.G. (2007), methods of computer simulation are currently considered as a mandatory step in making responsible management decisions in companies that actively use modern information technologies in their activities. We can evaluate toll road functioning with the help of the simulation method (microsimulations or macrosimulations depending on the level of system abstraction).

The use of macrosimulation models can be used to estimate toll fare and thus help optimize distribution of traffic flow on TP during daily use of the toll road (Kaddoura & Nagel, 2019), as well as during major national events (Lin et al., 2018). The use of macrosimulations is common for solving both transport, and economic problems. For example, they are used for general economic assessment of toll roads as an object of transport infrastructure (Anas et al., 2017); economic assessment of hazardous materials transportation risks when developing double tariffs for toll roads (Kim et al., 2013); assessing effectiveness of electronic toll collection (ETC) implementation in modernization of TCS within toll road (Soares et al., 2016); determining the most economical time for concluding public private partnership contract (Feng et al., 2019).

Microsimulation transport models are used to solve a wide range of problems, related to operational tasks of toll roads. In particular, such tasks may include:

- Verification of calculated data on the current and forecast throughput capacity of TP;
- Simulation of various modes of operation of TP;
- Optimization of TP operation modes;
- Justification of the need to modernize the TP in order to increase throughput capacity.

As it was confirmed is study by Punitha (2018), TP can be considered as a queuing system, as well as discrete-time modeling approach is completely applicable for it. Aksoy et al. (2014) used an example of the TP simulation model functioning at Fatih Sultan Mehmet Bridge toll. Using the VISSIM software, a number of experiments were conducted to change the

TP intensity for a different number of open payment lanes, which allowed to improve the quality of service. Another effective methodology for assessing the TP performance using the GENTOPS simulation model was proposed by Aycin (2006). Similar problems of optimizing the operation modes of toll lanes by simulation methods were solved by Izuhara et al. (2001) and Levinson & Chang (2003). The evaluation of TP modernization effectiveness was studied by Yosritzal et al. (2018). In the study, it was noted that the most appropriate increase in throughput capacity on TP may be implementing of ETC and MLFF, instead of increasing in the number of existing manual lanes on TP.

The use of microsimulation is also common for solving the problems of forecasting TP traffic flow. Predicting the average queue length on the TP using the short-term memory model and particle swarm algorithm used by Peng et at. (2020). Munawar & Andriyanto (2013) also demonstrated a possibility of using simulation model to solve queuing time prediction problems with a case study of Cililitan Toll Plaza, Jakarta. In their study of Zhang et al. (2018), authors use the VISSIM simulation software to determine the optimal ratio of the number of the manual and ETC lanes. The results of the study indicate that we can optimize the TP operation performance without increasing the number of lanes. However, the specific traffic conditions of different TPs were not taken into account by authors.

In addition, the use of simulation can be used for issues related to improving the safety of vehicles on TP. Thus, the study by Jehad et al. (2018) considers possibility of VISSIM simulation model for simulating TP configuration scenarios and improving the quality of TP design solutions.

3. Toll plaza simulation model

The use of TP discrete-event simulation model is proposed as a methodology for analyzing traffic flow. In contrast to the generalized TP modeling methodology, which is used at toll road design stage, using of simulation modeling methods at operation stage allows to take into account and reflect a number of special conditions that could be formed during TP operation. Such conditions can be formed due to peculiarities of its geographical location, traffic composition, regularity of user correspondence, and impact of surrounding transport, logistics and social infrastructure.

As a case, analysis and simulation model of the TP "Bogatyrsky str./Planernaya str.", located at the exit of the Western High-Speed Diameter (WHSD) toll road in Primorsky district of St. Petersburg was made (see Figure 1).

Figure 1. TP "Bogatyrsky str./Planernaya str." general view

The toll road uses an open-type barrier TCS. Primorsky district ranks first in terms of population in St. Petersburg, and also has a pronounced daily labor correspondence. Since the launch of the neighboring section of the WHSD in 2016, frequent cases of congestion have been observed at the TP due to the insufficient throughput capacity of TP toll lanes. The configuration of this TP provides six toll lanes, four of which operates in automatic mode and provide ETC payment via the on-board unit (OBU). This payment mode provides non-stop passage through the lanes, the speed limit is 30 km/h. The remaining two lanes operate in the manual mode and allow to provide payments to cashier in cash or by contact/contactless credit cards. The developed traffic model only affects TP at the exit to Primorsky district, and does not affect main direction of toll road and return entrance to highway from the district.

The simulation model was developed using the AnyLogic software with the help of the road traffic library (see Figures 2 and 3).

Figure 2. TP "Bogatyrsky str./Planernaya str." simulation model

Figure 3. TP "Bogatyrsky str./Planernaya str." simulation model

4. Data input

The TP simulation model allows us to take into account the following parameters of transport flow:

- Traffic intensity on TP;
- Traffic composition;
- Distribution of vehicles by payment methods;
- Service time on automatic lane;
- Service time on manual lane;
- Additional parameters (user behavior and tag failure).

4.1. Queuing analysis

The TP data for simulation model, including intensity, traffic composition, distribution of payment methods and service time, was obtained from video data on Northern Highway LLC website (2019). As there are no large logistics centers in Primorsky district, heavy vehicles are not allowed on this TP. This allows us to use only light vehicles in our TP simulation model. The specified length of the light vehicle in the model is 5 meters. The distribution of the vehicles by payment methods for this TP is 80% of ETC, and 20% manual toll collection. It is assumed that manual toll lanes service time is triangularly distributed with mean value of 20 (for contactless bank cards payments), min of 7 (for ETC) and max value of 45 (for contact bank cards and cash payments) seconds.

In addition to the parameters mentioned above, an additional parameter of user behavior and tag failure was added into our model, thus affecting the throughput capacity of the ETC lanes. The "Tag failure" parameter takes into account the probability of the OBU failure (5%). When driving through the ETC lane "Tag failure" can be caused, if the OBU isn't read on the entry antenna, is incorrectly fixed, or due to the negative OBU balance and it is not accepted for payment. It is assumed that tag failure time is also triangularly distributed with the mean value of 7 (in case of wrong Tag fixing), min of 3 (in case of second antenna reading) and max value of 60 (in case of negative balance) seconds.

An additional feature of the studied TP is the presence of a bottleneck at the exit of main road direction with only two lanes before TP, six toll lanes, and connection of six lanes into two lanes after passing through the TP. This feature allows to consider the entire TP zone as a certain "obstacle" that slows down the speed of movement and evaluate its transit time as time required to travel the section from the exit from main road direction to six lanes, and again in two lanes.

Analysis of the daily traffic intensity of the TP will allow to determine user service time distribution on toll lanes, as well as to assess the possibility of congestion during the day in a weekly cycle.

4.2. Traffic intensity

Figure 4 shows a graph of the observed traffic intensity at the Bogatyrsky str./Planernaya str., TP by days of week from 0:00 to 24:00. The intensity was calculated in number of vehicles per hour.

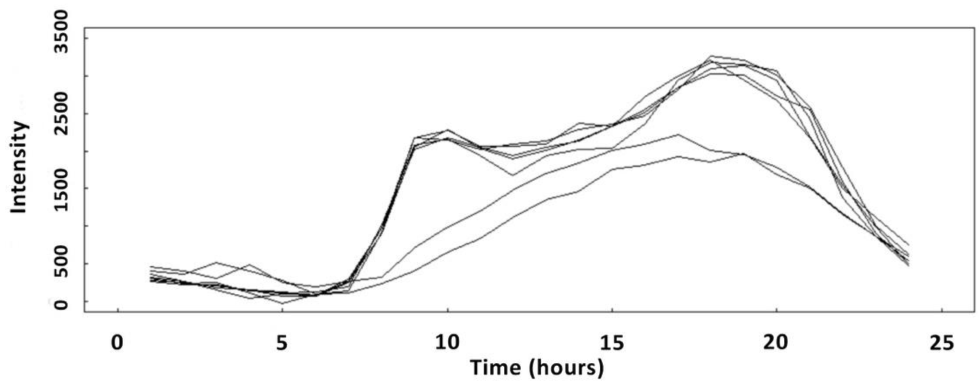

Figure 4. Observed traffic intensity on TP "Bogatyrsky str./Planernaya str." during the week from 0:00 to 24:00 (intensity - in the number of vehicles per hour)

Figure 4 shows seven lines (five for working days and two for the weekend days). Working days are more intense than weekends. The lines in the graph of traffic intensity on working days are similar. Peak intensities on the weekdays for the TP are in evening rush hour, when drivers travel home.

5. Analysis of toll plaza simulation model

As we can see in Figure 4, the traffic intensity on TP varies in the range from 60 to 3140 vehicles per hour, depending on the day of the week and time of day. We will be interested in the answers to the questions:

- At what traffic intensity traffic congestion will be formed in arrival zone of TP?
- How input stream intensity affects the vehicle service time distribution on TP?

Unlike the classical queuing theory schemes, by service time we mean time required for vehicle to pass TP from the exit point from main road direction (exit has only two lanes) to point after TP, in which six TP lanes are again connected into a two-lane road (see Figure 2).

A number of experiments were performed on our TP simulation model. Service time distribution was studied, with an input flow rate of 250 to 3250 vehicles per hour, in increments of 250. The appearance of congestion is considered as a queue of vehicles that goes beyond the entrance zone of TP, connected to two entrance lanes. As a result of the experiments, it was established that the congestion starts with the traffic intensity above 1010 vehicles per hour.

Consider the service time distribution at low and high traffic intensities obtained as a result of simulation. Figure 5 shows service time distribution at an input flow rate of 250 vehicles per hour.

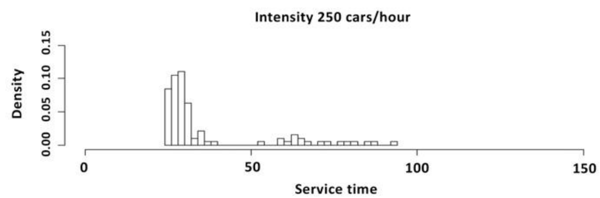

Figure 5. Empirical service time distribution at an input flow rate of 250 vehicles per hour

Distribution mentioned above is a mixture of two distributions, each of which is service time distribution of vehicle passing the entire described section either through the ETC or manual lane. At this intensity, the user behavior (OBU was not read on the entry antenna, was incorrectly fixed, or has a negative OBU balance) has practically no effect on service time distribution. Each of the distributions shown in Figure 5 is well approximated by the density of the gamma distribution, each with its own parameters. In classical scheme of queuing system with parallel servicing, one would expect that service time obeys the Erlang distribution law (a special case of gamma distribution). Since disturbing influences are added to the model in form of the user behavior effect, gamma law of service time distribution seems quite expected, as more general, regarding to the Erlang distribution.

Figure 6 shows service time distribution (TP passage) for vehicles passing through ETC lanes, and in Figure 7 for vehicles passing through manual lane.

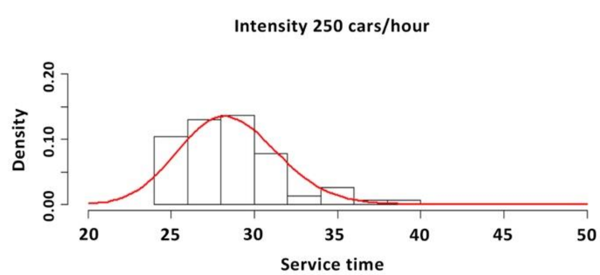

Figure 6. Empirical service time distribution at an input flow rate of 250 vehicles per hour. Vehicle passage through ETC lanes.

Parameters of the gamma distribution law are: shape = 92.5561, rate = 3.2438. The result of empirical distribution correspondence check to the model with the specified parameters by the Kolmogorov-Smirnov test: p-value = 0.7561.

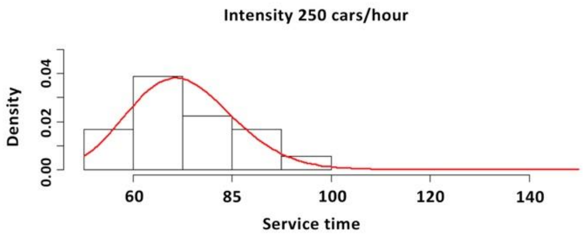

Figure 7. Empirical service time distribution at an input flow rate of 250 vehicles per hour. Vehicle passage through manual lane.

Parameters gamma distribution law are: shape = 43.9366, rate = 0.6265. The result of empirical distribution correspondence check to the model with the specified parameters by the Kolmogorov-Smirnov test: p-value = 0.5406.

Figure 8 shows service time distribution (TP passage) at a traffic intensity of 3000 vehicles per hour.

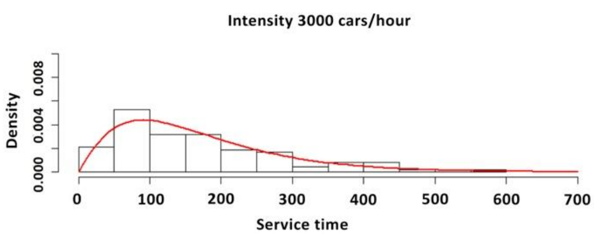

Figure 8. Empirical service time distribution at an input flow rate of 3000 vehicles per hour

Parameters gamma distribution law are: shape = 2.1510, rate = 0.0126. The result of empirical distribution correspondence meet to the model with the specified parameters by the Kolmogorov-Smirnov test: p-value = 0.7748. With such traffic intensity, "tag failure" effect is manifested: due to the large number of vehicles, the user behavior and tag failures affect the TP passage time of other vehicles. As a result, the entire TP begins to work as a single queuing device, with a mixture of service time distributions, where different payment methods are inseparable. Thus, with low intensity, service time distribution is a mixture of two separable gamma distributions, depending on the payment method.

With high intensity, the service time distribution obeys gamma distribution law with parameters for which distribution has significant left-side asymmetry. Table 1 presents gamma law service time distribution parameters at low intensities and the passage of vehicle through ETC lane. Table 2 presents gamma law service time distribution parameters at high intensities and the passage of the vehicle through manual lane. Tables 1 and 2 show mathematical expectations and most probable values of the service time (TP passage) at low input flow intensities (in seconds). Gamma law distribution parameters in these tables have such values, that asymmetry of distributions is not large and mathematical expectation and most probable value differ slightly from each other. This situation persists until the mix of distributions for different payment methods is separable and there is no congestion on TP. As mentioned above, congestion on the TP appears when the intensity becomes above the value 1010 vehicles per hour. Table 3 presents gamma laws service time distribution parameters at high intensities of the input flow.

At high intensities of the input flow, under the conditions of emerging queue, expectation of service time differs significantly from most probable service time.

Table 1. Gamma law service time distribution parameters at low intensities and the passage of vehicle through ETC lane

	Gamma law service time distribution parameters				
Intensity	shape	rate	p-value	Mathematical expectation	Most probable value
250 veh. per hour	92,5561	3,2438	0,7561	29	28
500 veh. per hour	110,5992	3,3190	0,3967	33	33
750 veh. per hour	29,0106	0,8016	0,1619	36	35
1000 veh. per hour	12,3898	0,3214	0,0741	39	35

Table 2. Gamma law service time distribution parameters at low intensities and the passage of vehicle through manual lane

	Gamma law service time distribution parameters				
Intensity	shape	rate	p-value	Mathematical expectation	Most probable value
250 veh. per hour	43,9366	0,6265	0,5406	70	69
500 veh. per hour	36,3945	0,4700	0,9730	77	75
750 veh. per hour	20,0014	0,2253	0,9352	89	84
1000 veh. per hour	16,4466	0,1342	0,8955	123	115

Table 3. Gamma laws service time distribution parameters at high intensities of the input flow

	Gamma law service time distribution parameters				
Intensity	shape	rate	p-value	Mathematical expectation	Most probable value
1250 veh. per hour	1,5210	0,0132	0,0617	115	39
1500 veh. per hour	2,0381	0,0127	0,3758	161	82
1750 veh. per hour	1,9516	0,0137	0,3035	142	69
2000 veh. per hour	2,5330	0,0149	0,1739	170	103
2250 veh. per hour	2,5919	0,0135	0,8186	192	118
2500 veh. per hour	2,2586	0,0109	0,6657	207	115
2750 veh. per hour	2,2658	0,0147	0,7156	154	86
3000 veh. per hour	2,1511	0,0126	0,7748	170	91
3250 veh. per hour	2,2402	0,0133	0,2608	169	93

6. Conclusions

Using the case of the TP on the WHSD toll road in St. Petersburg, Russia, simulation model was developed. The model possesses both parameters of generalized modeling technique and additional parameters that affect the intensity, and are determined during the operation stage of the toll road.

As a result of our experiments, the traffic intensity when congestion starts to form on TP was established. Regarding the established value, two cases of service time distribution with low and high traffic intensities were considered. The results of the analysis showed that at low intensity the total service time distribution is a combination of two vehicle service time distributions in different lane operating. At high traffic intensity, that is close to a peak, mixed TP service time distribution was determined, and the influence of user behavior at high traffic intensity was also noted. For each case, gamma laws service time distribution parameters were determined.

The results of the case study show that with insufficient throughput capacity, the TP ceases to operate efficiently, and the user service time increases, regardless of type of payment methods.

The described methods and the simulation model can be used to assess the existing and predicted throughput capacity of TP for toll road operator. Possessing throughput capacity data and model parameters obtained under TP operating conditions, toll road operator can estimate parameters of current TP throughput capacity with sufficient accuracy. If the obtained simulation results show insufficient values of TCS operation, the operator may conclude that the TCS needs to be optimized or modernized. To check the operability of selected upgrading measures of the TCS, the operator can also use a modified TP simulation model.

The described methodology is applicable for intracity TP on the exit from main direction of toll road, located in a balanced residential area, and large volume of pendulum migrations. It is also noted, that when placing TP in clearly defined industrial and logical areas of the city, as well as in border areas between the city and suburb, TP throughput capacity analyze may require an additional assessment of traffic intensity under various conditions, taking into account daily, weekly and seasonal and irregular traffic flow.

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