Simulation Modeling of the Operation of the Toll Plaza with Reversible Lanes

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Abstract: - The construction of toll roads depends on the available territory. The limited area often does not allow the construction of a full-fledged toll plaza (hereinafter referred to as TP) with high capacity and many lanes. In such cases, the configuration of TP is linked with the configuration of reversible lanes. Reversible lanes carry traffic and help optimize traffic flow. The challenge is to choose the optimal configuration of a TP that provides the highest capacity (traffic flow increases in both directions) and helps control operators' errors resulting in traffic congestion problems. The present study estimates TP with reversible lanes throughput capacity in different configurations and traffic flow parameters. The study employs discrete-event simulation modeling in the AnyLogic software environment. Our results show the optimal configuration of the reversible lanes and explain what traffic flow parameters affect their capacity. The paper concludes with practical recommendations on how to effectively apply simulation modeling to a TP operation and optimize it.

Key-Words: - discrete-event simulation, toll road, toll plaza, reversible toll plaza lanes, reversible lanes, toll collection system, traffic congestion.

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1 Introduction

The toll road construction in Russia has over a 15-year history. A large network of high-speed and inner-city sections of toll roads has been developed. Technical solutions for toll collection vary and include adapting generally accepted standard solutions to the transport, climatic, and socio-geographical specifics of the regions. During this time, Toll Plaza's engineering facilities (TP) complexes have changed significantly. Despite the development of free-flow toll collection technology, road projects with the use of classical barrier TPs continue to be widespread, which confirms the relevance of this article.

This paper completes the authors' series of studies on the throughput capacity of TP with barrier-type tolling systems published by the authors in 2020 – 2023 (the main results are collected in the book, [1]). In those articles, authors have previously reviewed several types of intra-city toll road TPs. Our first simulation model has been created for the TP at the exit from the intra-urban toll road. We considered the specifics of traffic flows and user behavior in this selected area. We have considered different types of service time distributions and estimated the parameters of the gamma laws of service time distributions. We estimated the emerging queue using the following parameters: the number of vehicles in the queue, queue length, waiting time of vehicles in the queue, and vehicle flow density.

Similarly, we estimated throughput capacity, possible risks of congestion, and its parameters for the TP on the main course and exit from the intra-city toll road in our second simulation model.

In our third simulation model, we considered a separate case of the location of the TP on the exit from the intra-urban toll road before the regulated intersection. We estimated possible traffic situations that led to traffic congestion problems. We studied the throughput capacity of the TP and determined the values of threshold traffic intensities affecting the traffic situation. Our optimization experiments aimed at adjusting the phases of the traffic lights to increase the speed of exit from the toll road. A detailed summary of the research results from these three studies is described and published in [1].

The types of TPs considered in our earlier studies [1] had a fixed number of lanes. This fact limits the number of possible configurations of the toll collection system (hereinafter referred to as TCS). In this paper, we consider a different type of TP, a reversible-type barrier TP. This type of TP can be used in cramped urban environments, and in the regions where it is not possible to accommodate a full-fledged TP due to land allocation constraints (both in urban areas and outside the city on express toll highways).

The objectives of this study are:

- To develop a simulation model (hereinafter referred to as SM) of a TP with reversible TCS;
- To estimate the capacity of a reversible TP with different numbers of active lanes and different configurations of the TCS;
- To estimate the share of electronic toll collection (hereinafter referred to as ETC) users that will allow traffic to pass through the TP without congestion.

2 Literature Review

A large number of studies have assessed how well toll road infrastructure functions. This fact demonstrates the increasing research interest in how to assess the quality of the TP management process.

Studies have explored various factors that impact TP operation. The study [2], explored performance indicators of the services provided at the TP in one project in India. The results of this study, based on exploring user perceptions, showed that factors such as driver behavior, infrastructure and traffic characteristics, trip characteristics, and the behavior of the TP operators had a positive impact on the quality of service at the TP. The importance of driver behavior as a factor affecting the capacity of the TP was explored in [1]. The application of ETC as a means of improving the efficiency of the TP operation is considered for toll road projects in Taiwan [3], Korea [4], and India [5]. Separate studies focused on the factors that affect the efficiency of the traffic flow in a TP. The study [6] explored the service time at the TP with the manual toll payment method, using the example of the TP project in India. The authors of the study [7] explored the traffic flow for a two-lane toll road with a TP and manual and automatic toll lanes. Separately, it is necessary to mention the study [8], devoted to the study of the traffic flow passing through a TP as a hydrodynamic model, which is able to describe its density and its evolution when passing several TPs.

An important part of the tolling process is the management of TCS configurations at the TP. The study [9] introduced a control method based on the configuration of TP lanes and variable speed limit control. This study demonstrated, through simulation experiments, an improvement in the saving of traffic flow time through the TP and an improvement in driving safety. A new methodology for optimal toll management that combines recurrent neural networks, mass service theory, and metaheuristics was introduced in [10]. This methodology was experimentally tested on real data from a toll road project in Serbia.

The most acute problem related to the efficiency of toll collection at the barrier-type TPs is the problem of traffic congestion in the zone.

The main problem related to the efficiency of toll collection at the barrier-type TPs is traffic congestion. The study [11] employed a stochastic model to explore congestion increase in the TP front zone and how the number of toll lanes impacts it. The study [12] investigated how congestion grows in the TP exit zone, and developed a method of combining the traffic flow patterns after the passage of manual and automatic toll lanes. A queuing model to estimate the profiles of waiting time and queue length using closed-form equations was presented in the study [13]. A quantitative assessment of the total delay of the traffic flow of vehicles passing through the TP zone, produced by simulation modeling, was presented in studies, [14], [15].

There are few works devoted to the study of reversible TPs. There are only a few works devoted to the study of reversible TPs. The most relevant study is [16] as it explores different values of forward and reverse traffic flow through the TP. They concluded that the toll lanes for the direction with lower intensity usually remain unused. The traffic flows were estimated using the M/M/1 queuing model, [16]. They applied the reversible TP concept and it led to the reduction of congestion and the optimization of the parameters of the resulting congestion. Further study of the reversible TP using the simulation method will make it possible to expand the set of used parameters involved in the creation of the model, increasing the efficiency of optimization processes of selecting the configuration of the TCS at the TP.

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3 Simulation Model Construction of the TP

In this section we consider supervisory controller design to enforce boundedness, reversibility, and liveness in a system modeled by a TP.

3.1 Technological Peculiarities of the TP

Let us consider the technological features of a reversible TP. A reversible TP has one or more central toll lanes that can collect tolls in both directions of motorway traffic. Thus, the reversible TP allows the number of lanes to be adjusted in response to varying traffic volumes.

Reversible toll lanes, as well as stationary (non-reversible) lanes, can operate in one or more toll collection modes such as automatic (ETC), manual, or mixed.

An example of a reversible TP lane arrangement scheme is shown in Figure 1. This figure shows a reversible TP that allows traffic to flow in two directions. In one direction, the lanes pass through lanes 1-6, while in the reverse direction, the lanes pass through lanes 7-12.

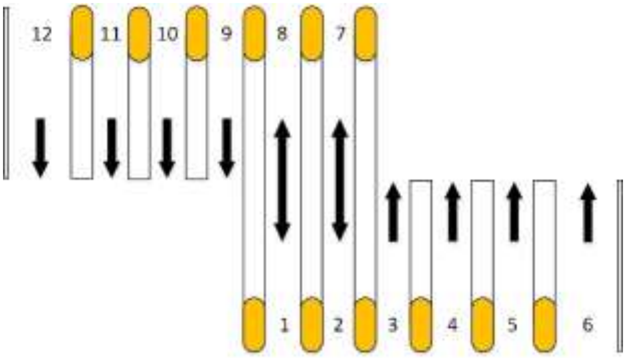

Fig. 1: An example of a reversible TP lane arrangement scheme with 12 lanes

The direction of traffic flows is shown by lines with arrows. As can be seen in Figure 1, lanes 1 and 8, 2 and 7 are reversible, where the lines have arrows in two directions. Non-reversible lanes have lines with arrows in only one direction. Thus, between 4 and 6 lanes, lanes can operate in each direction. In the case of four-lane operation, there will be operation from lane 3 to lane 6 in one direction, and from lane 9 to lane 12 in the opposite direction. In the case of six lanes, there will be operation from lane 1 to lane 6 in one direction, and from lane 7 to lane 12 in the opposite direction.

The advantage of reversible TPs is that we can regulate the number of functioning lanes in line with the changes in the intensity of traffic flows, which allows the most efficient use of the largest number of lanes at pendulum intensity, which is possible when carrying out various types of correspondence: labor, recreational, and seasonal. Reversible TP mode allows for more efficient use of engineering and technical support of the TP and ensures minimum downtime of the TP equipment.

Nevertheless, constructing a reversible TP has one core limitation. The TP cannot function effectively at a high intensity of traffic flow passing through the TP in forward and reverse directions in one period.

The above-mentioned technological peculiarities of TP lead us to the problem of how to select the optimal number of functioning toll lanes and to configure the TCS for each direction of traffic at the TP and thus ensure the maximum intensity of traffic flow with the given parameters through the TP in both directions.

3.2 Selecting the TP Configuration

To build the simulation model and conduct our experiments, we selected a TP configuration consisting of 18 physical toll lanes where 6 central physical lanes are reversible. Thus, the modeled TP has 24 logical toll lanes. The lane arrangement scheme of the reversible TP of the simulation model is shown in Figure 2.

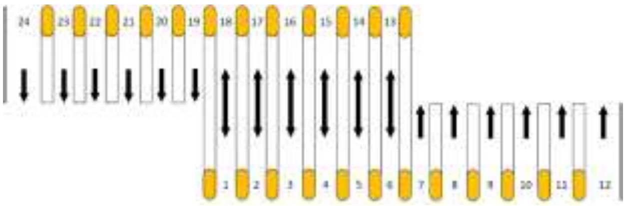

Fig. 2: Reversible TP simulation model. Lanes arrangement schemes

The direction of movement of vehicles is shown by lines with arrows. As can be seen in Figure 2, lanes 1, 2, 3, 4, 5, 6, 13, 14, 15, 16, 17, 18 are reversible, and these lines have arrows in two directions. Non-reversible lanes have lines with arrows in only one direction. Thus, between 6 and 12 lanes can operate in each direction. In the case of a six-lane operation, there will be operation from lane 7 to lane 12 in one direction, and from lane 19 to lane 24 in the opposite direction. In the case of twelve lanes, there will be operation from lane 1 to lane 12 in one direction, and from lane 13 to lane 24 in the opposite direction.

3.3 Creation of the TP Simulation Model

To conduct simulation experiments, a simulation model (SM) with 18 physical and 24 logical toll lanes was developed. Of these, 6 central physical lanes are reversible, which equals 12 logical lanes.

Earlier in the book, the SM of the TP on the main course of the intra-city toll road [1] with 18 physical lanes were radiated. The SM with this number of physical lanes on the TP has shown efficient operation with high throughput in both intra-urban and motorway conditions.

Since the same configuration can be applied for each direction of the TP, taking into account the number and mode of operation of the toll lanes, it will be sufficient to analyze the performance of the TP in one direction of traffic.

Figure 3 and Figure 4 show the general view and top view of the developed SM of the reversible TP.

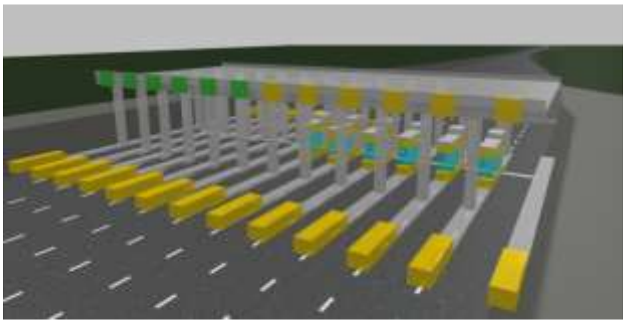

Fig. 3: Simulation model of the reversible TP. General view

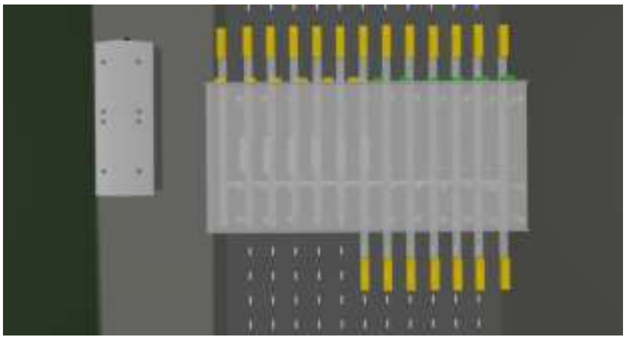

Fig. 4: Simulation model of a reversible TP. Top view.

As shown in Figure 3 and Figure 4, the parameters of the simulation model of the reversible TP correspond to the parameters and proportions of the designed TP in terms of geometric dimensions, enter and exit zones, as well as modes of operation. This allows preliminary simulation calculations to be carried out at the design survey and design stages. Depending on the obtained parameters and results of simulation modeling, design solutions can be timely adjusted to improve the transport characteristics of the TP.

If there are transport nodes in close proximity to the TP that affect the traffic flow behavior in the TP area, they can also be added to the SM.

The SM allows observing potential traffic in 3D at different angles and spatial orientations of the model. This improves the quality of visual observations of the experiments and helps to identify hidden features of traffic flows in the simulated processes.

The TP zone is connected to the main road sections with 2 lanes located upstream and downstream. There are no additional transportation nodes before or after the TP.

3.4 Estimation of Capacity Limits of the Reversible TP

The developed SM of the reversible TP allows taking into account the following parameters:

1. Traffic intensity on the TP;
2. Traffic composition;
3. Distribution of vehicles by payment mode;
4. Number of toll lanes in operation;
5. Modes of operation of the lanes;
6. Automatic lane service time;
7. Manual lane service time;
8. Additional parameters (user behavior).

A detailed description of the SM parameters is outlined within the study, [1].

In order to conduct simulation experiments for this type of TP, the values of SM parameters № 2, 3, 6, 7, 8 were fixed, corresponding to the parameters of TP operation on the main course of a toll road outside a large urban agglomeration (distribution of vehicles by class: Car - 75%, Lorry - 5%, Truck - 20%; share of ETC users: 70%; impact of user behavior: 5%). The choice of the 70% ETC usage share is based on the assumption that the TP under study is located in a suburban area, outside the urban agglomeration within a radius of ≥ 200 km from its center, which corresponds to real examples of this type of TPs. If the assumption of closer or farther away from the city is adopted, the parameter of the share of ETC use will increase or decrease accordingly, which may affect the results of the study and will require additional analysis.

To solve the set research problems, we assumed that for both directions, traffic flow would have the same values. Accordingly, the values of parameters № 1, 4, and 5, were changed during the simulation experiments.

The configuration of the TP is set by the number of toll lanes and their operation mode. The developed SM allows to consideration of all possible configurations both at minimum and maximum possible number of operating lanes in one direction of motorway traffic. The SM also takes into account that the TP should operate with a minimum of two manual lanes to ensure uninterrupted acceptance of cash and bank cards by users and to provide redundancy in case of failure of one of the lanes.

Table 1, Table 2, Table 3, Table 4, Table 5, Table 6 and Table 7 summarize all reversible TP configurations in one direction of the motorway. These configurations may differ in the number of lanes and the ratio of manual to ETC lanes. The tables show possible configurations with corresponding numbers, for which the number of manual and ETC lanes (in the "Number of lanes" rows) and lane numbers (in the "Lane №." rows) are shown. The lane numbers in the "Lane №" column correspond to the lane numbers in Figure 2.

Table 1. One-way reversible TP configurations with 6 lanes in one direction

Configurations		Manual lanes	ETC lanes
Configuration 1	Number of lanes	2	4
	Lane №	11-12	7-10
Configuration 2	Number of lanes	3	3
	Lane №	10-12	7-9

Table 2. One-way reversible TP configurations with 7 lanes in one direction

Configurations		Manual lanes	ETC lanes
Configuration 1	Number of lanes	2	5
	Lane №	11-12	6-10
Configuration 2	Number of lanes	3	4
	Lane №	10-12	6-9

Table 3. One-way reversible TP configurations with 8 lanes in one direction

Configurations		Manual lanes	ETC lanes
Configuration 1	Number of lanes	2	6
	Lane №	11-12	5-10
Configuration 2	Number of lanes	3	5
	Lane №	10-12	5-9
Configuration 3	Number of lanes	4	4
	Lane №	9-12	5-8

Table 4. One-way reversible TP configurations with 9 lanes in one direction

Configurations		Manual lanes	ETC lanes
Configuration 1	Number of lanes	2	7
	Lane №	11-12	4-10
Configuration 2	Number of lanes	3	6
	Lane №	10-12	4-9
Configuration 3	Number of lanes	4	5
	Lane №	9-12	4-8

Table 5. One-way reversible TP configurations with 10 lanes in one direction

Configurations		Manual lanes	ETC lanes
Configuration 1	Number of lanes	2	8
	Lane №	11-12	3-10
Configuration 2	Number of lanes	3	7
	Lane №	10-12	3-9
Configuration 3	Number of lanes	4	6
	Lane №	9-12	3-8
Configuration 4	Number of lanes	5	5
	Lane №	8-12	3-7

Table 6. One-way reversible TP configurations with 11 lanes in one direction

Configurations		Manual lanes	ETC lanes
Configuration 1	Number of lanes	2	9
	Lane №	11-12	2-10
Configuration 2	Number of lanes	3	8
	Lane №	10-12	2-9
Configuration 3	Number of lanes	4	7
	Lane №	9-12	2-8
Configuration 4	Number of lanes	5	6
	Lane №	8-12	2-7

Table 7. One-way reversible TP configurations with 12 lanes in one direction

Configurations		Manual lanes	ETC lanes
Configuration 1	Number of lanes	2	10
	Lane №	11-12	1-10
Configuration 2	Number of lanes	3	9
	Lane №	10-12	1-9
Configuration 3	Number of lanes	4	8
	Lane №	9-12	1-8
Configuration 4	Number of lanes	5	7
	Lane №	8-12	1-7
Configuration 5	Number of lanes	6	6
	Lane №	7-12	1-6

As shown in Table 1, Table 2, Table 3, Table 4, Table 5, Table 6 and Table 7, the reversible TP can operate in a range of 6 to 12 toll lanes, with the number of manual lanes ranging from 2 to 6 units and the number of automatic lanes ranging from 3 to 12 units.

To evaluate the capacity limits of a reversible TP with different numbers of active lanes and different configurations of the TP, 23 groups of experiments were conducted to identify the threshold traffic flow intensity at which congestion starts to form on the TP. This intensity can be considered as the threshold intensity for the configuration of the TP and the corresponding set of recorded SM parameters. Each group of experiments included the analysis of the operation of the TP configuration at increasing traffic flow intensity in the range from 250 vehicles/h to 3500 vehicles/h, with a step of 10 vehicles/h. The duration of observations for each experiment was 1 hour.

The results of the experiments to evaluate the ultimate capacity of the reversible TP are presented in Table 8.

In the TP configuration column, the "ETC" indicates the number of automatic lanes, and the "M" indicates the number of manual toll lanes.

As shown in Table 2, the threshold intensity for each TP configuration ranged from 710 to 1070 vehicles/h.

Our experimental results show that when the share of ETC users in the flow is not high enough, congestion forms at the TPs due to the accumulation of queues at the manual toll lanes. An example of queuing at manual toll lanes is shown in Figure 5 and Figure 6.

Table 8. Experimental results for estimating the ultimate throughput of the reversible TP

Experiment group №	Number of lanes	TP configuration	Threshold intensity
23	12	6 ETC; 6 M	1070
22	12	7 ETC; 5 M	1010
21	12	8 ETC; 4 M	930
20	12	9 ETC; 3 M	830
19	12	10 ETC; 2 M	780
18	11	6 ETC; 5 M	980
17	11	7 ETC; 4 M	910
16	11	8 ETC; 3 M	840
15	11	9 ETC; 2 M	750
14	10	5 ETC; 5 M	970
13	10	6 ETC; 4 M	860
12	10	7 ETC; 3 M	830
11	10	8 ETC; 2 M	750
10	9	5 ETC; 4 M	950
9	9	6 ETC; 3 M	820
8	9	7 ETC; 2 M	710
7	8	4 ETC; 4 M	860
6	8	5 ETC; 3 M	800
5	8	6 ETC; 2 M	700
4	7	4 ETC; 3 M	810
3	7	5 ETC; 2 M	710
2	6	3 ETC; 3 M	800
1	6	4 ETC; 2 M	710

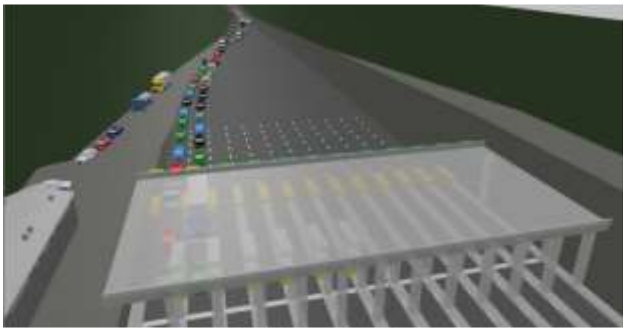
Fig. 5: Formation of congestion on manual toll lanes of a reversible TP. General view

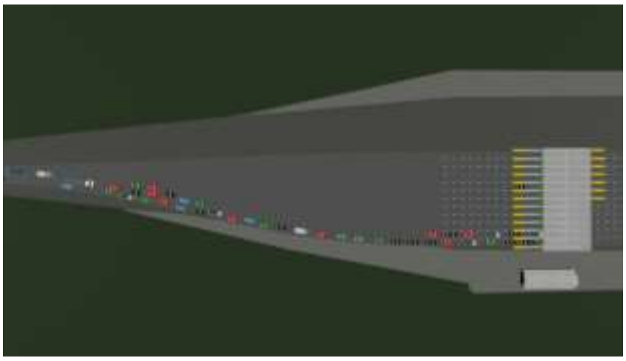
Fig. 6: Formation of congestion on manual toll lanes of a reversible TP. Top view

In addition, we conducted 5 groups of experiments to evaluate the influence of the parameter of ETC users' share on congestion formation in front of the reversible TP. For the experiment, the configuration of the TP with the maximum (12 units) number of functioning lanes was selected, 10 of which operate in ETC mode and 2 – in manual mode. The results are shown in Table 9.

When developing an SM of the TP, two target indicators are key: the length of the queue formed and the waiting time in the queue. To calculate the time of queue length and waiting time in the queue, classical methods of mass service theory can be applied, taking into account the peculiarities of the modeled TP. The derivation of the necessary formulas, the applied mathematical apparatus, and numerical methods are described in detail by the authors of this paper in [1].

In complex cases, for example, when building a simulation model that includes several transportation objects, such as a TP and a regulated traffic light object directly following the TP, machine learning (ML) methods as an application of artificial intelligence (AI) can be used. An example of such an object is considered in detail by the authors in [1].

Table 9. Estimation of the fraction of ETC that allows vehicles to pass through the TP without causing congestion. Experimental results

Experiment group №	Number of lanes	TP configuration	Intensity without congestion	Threshold intensity	Intensity with congestion	Share of ETC users
29	12	10 ETC; 2 M	250	No congestion	No congestion	95%
28	12	10 ETC; 2 M	250	No congestion	No congestion	90%
27	12	10 ETC; 2 M	250	1690	3500	85%
26	12	10 ETC; 2 M	250	1040	1500	80%
25	12	10 ETC; 2 M	250	880	1500	75%
24	12	10 ETC; 2 M	250	780	1500	70%

As it can be seen from Table 8 and Table 9, with 70% ETC share, at any configuration of the reversible TP, a stable congestion is formed at a flow rate of 1500 vehicles/h and higher. Table 3 shows that increasing the ETC share to 75-80% does not solve the problem of congestion formation at flow rates of 1500 vehicles/h and above. At ETC share equal to 85%, stable congestion is formed at flow rates of 3500 vehicles/h and above. Only at values of 90-95% of ETC share, traffic congestion will not occur for the considered configuration of the reversible TP. This means that the remaining 5-10% of vehicles in the flow are not equipped with ETC on-board units and are not enough to form congestion due to queuing on the manual lanes shown in Figure 5 and Figure 6.

4 Conclusion

The reversible TP simulation model considered in this study shows that the ways to increase capacity for one direction of traffic flow are:

- Increasing the number of functioning lanes;
- Changing the configuration of the TP by changing the combination of ETC and manual toll lanes;
- Increasing the proportion of ETC users in the traffic flow.

It should be noted that in order to assess the risks of a toll road and the TPs located on it, it is advisable to apply an individual SM for each charging point, taking into account the peculiarities of its geographical location, remoteness from urban agglomerations, the composition of traffic at the facility, the regularity of user correspondence, as well as the impact of the surrounding transport, logistics, and social infrastructure. When the TP is located in pronounced industrial and logical areas of the city, as well as in the border zones between the city and the region, in order to analyze the capacity of the TP, an additional assessment of traffic intensity in different conditions, taking into account the daily, weekly and seasonal irregularity of the flow, may be required.

Further work on the development of the SM of the reversible TP, which is beyond the scope of the described study, should focus on identifying the parameter set to improve its accuracy, as well as analyzing and identifying the following dependencies that affect toll plaza capacity:

- TP configurations and ETC user shares;
- TP configurations and the "Tag failure" parameter;
- TP configurations and traffic composition.

Further research direction for us is to study the ratio of flow density and flow speed on free flow sections of toll roads because as follows from the results of [17], the decrease in flow speed due to the increase in flow density can also lead to the formation of congestion at the TP.

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References:

[1] Talavirya, A., Laskin, M., and Dubgorn, A., Application of Simulation Modeling to Assess the Operation of Urban Toll Plazas, *Simulation Modeling - Recent Advances, New*

Perspectives, and Applications, 2023, https://doi.org/10.5772/intechopen.1002003.
[2] Yogeshwar V. Navandar, D.A. Patel, Ashish Dhamaniya, S. Velmurugan, Chintaman Bari, Users perception based service quality analysis at toll plazas using structural equation modeling, *Case Studies on Transport Policy*, Vol.13, 2023, 101053.
[3] Tseng, P.-H. & Pilcher, N., Political and technical complexities of Electronic Toll Collection: Lessons from Taiwan, *Case Studies on Transport Policy*, Vol.10, No.1, 2022, pp. 444-453.
[4] Chang, M.-S. & Kang, K.-W., Evaluations and improvements of the Korean highway electronic toll system. *IATSS Research*, Vol.26, No.1, 2002, pp. 37-44.
[5] Chintaman B., Ashish D., Satish C., Drivers' willingness to shift towards electronic toll collection system in India, *Case Studies on Transport Policy*, Vol.13, 2023, 101046.
[6] Chintaman S. Bari, Satish Chandra, Ashish Dhamaniya, Shriniwas Arkatkar, Yogeshwar V. Navandar, Service time variability at manual operated tollbooths under mixed traffic environment: Towards level-of-service thresholds, *Transport Policy*, Vol.106, 2021, pp. 11-24.
[7] Komada, K. & Masukura, S. & Nagatani, T., Traffic flow on a toll highway with electronic and traditional tollgates, *Physica A-statistical Mechanics and Its Applications - PHYSICA A*, Vol.388, No.24, 2009, pp. 4979-4990.
[8] Marasco, A., Nonlinear hydrodynamic models of traffic flow in the presence of tollgates, *Mathematical and Computer Modelling*, Vol.35, No.5–6, 2002, pp. 549-559.
[9] Naitong Y., Minghui M., Shidong L., Wenjie W., Hu Z., Optimal control method of freeway based on tollbooths lane configuration and variable speed limit control, *Physica A: Statistical Mechanics and its Applications*, Vol.603, 2022, 127801.
[10] Petrovic, A., Delibašić, B., Nikolić, M., Bugaric, U., Lio, P., Controlling highway toll stations using deep learning, queuing theory, and differential evolution, *Engineering Applications of Artificial Intelligence*, Vol.119, 2023, 105683.
[11] Takashi N., Traffic jam at adjustable tollgates controlled by line length, *Physica A: Statistical Mechanics and its Applications*, Vol.442, 2016, pp. 131-136.
[12] Binbin C., Wei Li, Improving highway traffic performance: Merging pattern design of a departure zone after tollbooths or ETC, *Physica A: Statistical Mechanics and its Applications*, Vol.608, Part 1, 2022, 128251.
[13] Andrea P., Raffaele M., A multi-class time-dependent model for the analysis of waiting phenomena at a motorway tollgate, *Journal of Traffic and Transportation Engineering (English Edition)*, Vol.8, No.2, 2021, pp. 237-256.
[14] Chintaman B. & Yogeshwar N. & Ashish D., Delay modelling at manually operated toll plazas under mixed traffic conditions, *International Journal of Transportation Science and Technology*, Vol.11, No.1, 2020, pp. 17-31.
[15] Chintaman B., Satish C., Ashish D., Estimation of system delay based toll equivalency factors at toll plazas using simulation, *International Journal of Transportation Science and Technology*, Vol.12, No.3, 2023, pp. 822-835.
[16] Kumar, A., Thakare, A., Tawalare, A., Strategy to Reduce Queuing Time at Toll Plaza, *Transportation Research. Lecture Notes in Civil Engineering*, Vol.45, 2020, pp. 453-464.
[17] Gasnikov A.V., Klenov S.L., Nurminsky E.A., Kholodov Ya.A., Shamray N.B. *Introduction to Mathematical Modeling of Traffic Flows: tutorial. 2nd ed*, MCCME, Moscow, 2013.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.