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Hybrid toll plaza capacity: Simulation modeling of traffic

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Abstract

In recent years, there has been a noticeable trend to move from barrier toll plazas (hereinafter referred to as TP) to free flow technology, which allows users to pay toll road tolls without stopping. Nevertheless, a large number of toll road projects have been implemented to date, where toll collection is carried out at barrier TPs. In the current situation, it is common for toll road projects with a barrier type of toll collection system to include hybrid-type TPs, which allow toll collection both in the barrier mode, which is usual for users, and in the free flow mode, subject to further transition of the road to a barrier-free type of toll collection. Taking into account the design features of the TP zone, the issue of providing capacity at the hybrid-type TP for vehicles with different types of payment is relevant. The purpose of this study is to develop a simulation model (hereinafter referred to as SM) of hybrid-type TP by discrete-event simulation modeling method in AnyLogic software environment, analyze its capacity in barrier and mixed tolling modes under different SM parameters, as well as to develop practical recommendations that can be applied at different stages of project implementation.

Keywords: Discrete-event simulation; toll road; toll plaza; hybrid toll plaza; hybrid main-line toll plaza; toll collection system; traffic congestion

1. Introduction

The prospects of a multi-lane free flow toll collection system (hereinafter referred to as TCS), which allows to collect tolls without stopping the vehicle on the expressway, are beyond doubt. This type of TCS is modern, provides a simple process of system maintenance, reduces capital and operating costs.

At the moment, ten toll road projects have been completed in Russia, implemented on the basis of barrier-type TCS, and only three projects have been implemented on the basis of barrier-free TCS, and the total number of functioning TCS is multiple higher than the number of toll gantries.

The main share of toll booths is accounted for by traditional barrier-mode TPs. Their design requires a vehicle to quickly reduce speed, navigate and rearrange between lanes with different types of tolls, perform toll payment actions with different types of tolls, and then accelerate and enter the flow of vehicles on the main course of the road. The number and complexity of actions performed by the user in the TP zone create additional traffic safety risks in the TP zone of a toll road. The relevance of this problem is emphasized in (Das et al., 2024; Xiang et al., 2022; Laksono and Moetriono, 2024; Xing et al., 2023).

One of the ways to solve the issues related to the improvement of road safety on the toll road, as well as to increase the threshold traffic intensity in the TP zone, is the transition to the barrier-free toll collection free flow (hereinafter referred to as FF) technology. This transition can be realized in stages. The intermediate stage can be the realization of hybrid TP, provided that its constructive and technological realization on the basis of barrier TP is possible. Such an approach allows the conversion of existing barrier-based TP lanes into express lanes with barrier-free tolling on the main runway and separate barrier-based toll lanes on the sides of the main runway, or barrier-based toll lanes on the main runway and separate barrier-free lanes on the sides of the road.

Within the framework of this study the authors will describe the main technological features of this type of TP, developed the SM of hybrid TP operating in two modes, conducted experiments on the SM, determining the features of this type of toll points. In the end of the study conclusions are made about the results of simulation experiments related to the features of hybrid TP, practical recommendations are given and further directions for further research are determined.

The objectives of the ongoing research are:

1. Development of an TP SM operating in the barrier mode;
2. Estimation of the ultimate capacity of the barrier TP under different traffic flow parameters;
3. Development of a TP SM operating in hybrid mode based on the configuration of the barrier TP;
4. Estimation of the ultimate capacity of the TP in hybrid mode under different traffic flow parameters.

2. Literature review

Despite the active spread of projects based on open road tolling, the research of barrier-type TP peculiarities does not stop. The study of user trajectories on barrier-type TPs, which allows to accelerate the understanding of behavioral aspects in complex interactive environments, is devoted to (Chouhan et al, 2024). A similar study (Qiaoqiao et al., 2024) concluded a higher crash risk for users of electronic toll collection (hereinafter referred to as ETC) compared to vehicles choosing to pay in cash, due to a higher initial speed. The study (Bari et al., 2023), performed by the method of simulation micro-modeling in VISSIM environment, is aimed at quantifying the system delay occurring for vehicles in the ETC lanes in mixed traffic conditions. In (Xie et al., 2024), a framework is proposed for personalized pricing at the TP that combines prediction, optimization and personalization elements to dynamically determine the displayed fare and personalized discounts for users based on their individual preferences. A model for determining the optimal number of barrier TPs at the exit of a highway in Istanbul considering mixed traffic conditions and tolling methods is presented in (Hermawan, 2023). The results of a comparison of barrier and barrier-free tolling systems, after gaining positive experience with open road tolling, are described in (Aksoy, 2023).

It can be said that the hybrid type of TP is not fully studied. It is possible to distinguish a number of works that touch upon this subject. Issues related to the analysis of road traffic safety, including in the hybrid TP zone, are considered in works (Abuzwidah and Abdel-Aty, 2014; Abuzwidah and Abdel-Aty, 2018; Saad et al., 2019; Xing et al., 2019; Mo et al., 2024; Collery and Gorecki, 2020). Separately, it is worth highlighting the study (Abuzwidah and Abdel-Aty, 2014), the authors of which note that the use of hybrid TP is an excellent solution for operational, environmental and economic issues. The results of this study proved that road safety is higher for those TPs that have been retrofitted into hybrid-type TPs.

3. A simulation model of a hybrid TP

In this section, we review the main technological features, capabilities, and limitations of providing toll collection on a hybrid TP.

3.1. Technological peculiarities of hybrid TP

Implementation of toll collection on the highway implies the presence of specially equipped TPs. All technological equipment and software designed for toll collection is a TCS.

Road projects with barrier-type TCS, but envisaging further transition to barrier-free TCS, envisage two phases of TP operation. The first phase involves an operational mode with barrier-type TCS at the TP. Barrier-type TCS provides for the restriction of vehicle traffic through the TP by means of entry and exit barriers in order to prevent violations of the rules of passage and to comply with the terms of use of the toll road.

The following barrier-type TCS technologies may be provided on the TP lanes:

1. Payment of toll on the highway by cash or bank card (manual payment) to a cashier-operator located in the toll booth. This type of payment involves stopping the vehicle at the toll lane to make the payment;
2. ETC payment is made by a special on-board electronic automatic payment device. The payment process takes place without stopping the vehicle in the toll lane, at a speed reduction of up to 30 km/h.

This study considers a TP consisting of 16 toll lanes, 8 lanes in each direction. The choice of the number of lanes is conditioned by the availability of operating TPs with a similar configuration, while calculating the configurations of which the maximum hourly traffic intensity achieved from the average annual daily traffic intensity, the uneven distribution of traffic intensity by direction, characteristic of "peak" intensity values, as well as the capacity of one toll lane were taken into account.

The scheme of the toll lanes of the first stage of operation of the TP operating in the barrier mode is presented in Figure 1.

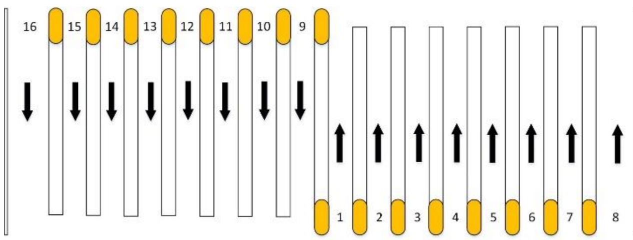

Figure 1. Schematic of TP toll lanes in barrier mode

The direction of traffic flows is shown by black arrow lines. Lanes 1-8 operate in the forward direction, lanes 9-16 in the reverse direction. There are no reversible lanes.

The second phase of TP operation in hybrid mode involves the use of the following types of TCSs:

1. For a number of side toll lanes on the TP, a manually operated barrier-type TCS is envisioned;
2. On the four central toll lanes (two lanes of each direction of traffic) a multi-lane FF toll collection system is envisaged at the TP.

The FF toll collection system does not provide for restrictions on the movement of vehicles through the TP when paying the toll. This system allows recording, charging and payment of tolls with a large number of vehicles passing through the communication zone at the same time without stopping the traffic on the road section, as the processing of data on vehicle passages is carried out in ETC mode. Fare payment is envisaged with the use of ETC, provided that the on-board unit is located inside the vehicle.

The reconstruction of the TP during the transition between the first and second stages of operation provides for the dismantling of two safety islands between lanes 1-2, 9-10, the dismantling of the peripheral equipment of the barrier-type TCS and the reconstruction of the TP safety island in the dividing strip, and the installation of FF TCS on lanes 1-2, 9-10.

The scheme of toll lanes of the second stage of operation of the TP operating in hybrid mode is presented in Figure 2.

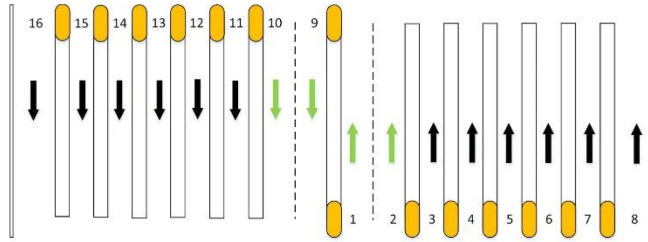

Figure 2. Schematic of TP toll lanes in hybrid mode

The direction of traffic flows is shown by lines with arrows. Arrows of black color show movement on barrier lanes for lanes 3-8 in forward direction, for lanes 11-16 – in reverse direction. Green arrows show traffic on lanes operating in FF mode for lanes 1-2 in the forward direction, for lanes 9-10 in the reverse direction.

3.2. Development of the SM of the TP in the barrier mode

To conduct simulation experiments, an TP SM was developed, operating in both barrier and hybrid modes. It should be noted that the parameters of the TP SM correspond to the parameters of the designed TP in terms of geometric dimensions, zones of access and entry from the toll zone, as well as modes of operation of the toll lanes, which allows to carry out preliminary simulation calculations at the stages of design surveys and design. Since the hybrid-type TP has a symmetrical structure (8 lanes in each direction), an SM implementation with 8 physical lanes designed for a single direction of travel was sufficient for analysis.

The TP area is connected to a two-lane section of the main course of the roadway. There are no additional interchanges upstream or downstream of the TP.

The developed TP model allows visual observations of the passing traffic in 3D mode from any point of view, which allows to improve the quality of experiments and to reveal the hidden features of traffic flows when studying the modeled processes.

In order to estimate the ultimate capacity of the TP operating in the barrier mode under different traffic flow parameters, an SM was developed corresponding to the lane layout shown in Figure 1.

Figures 3 and 4 show the general view and top view of the developed TP SM operating in the barrier mode.

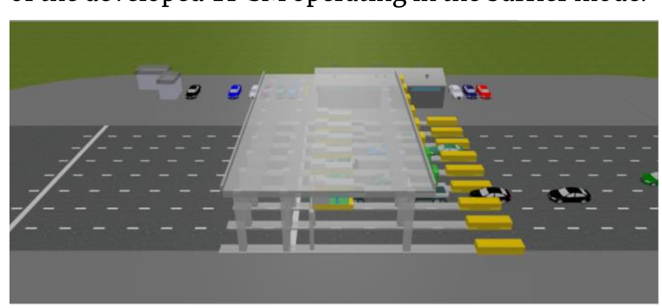

Figure 3. Simulation model of TP in barrier mode. General view

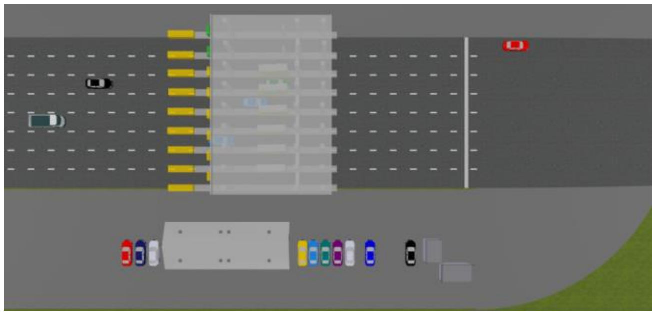

Figure 4. Simulation model of TP in barrier mode. Top view

The developed SM allows modeling the operation of the TCS, the toll lanes of which function in manual and ETC tolling modes, as well as taking into account the different ratio of lanes in the TCS configuration.

The following restriction on the minimum number of lanes in the TCS configuration should be taken into account: the configuration should have at least two ETC lanes; the configuration should have at least two manual toll lanes. The need for a minimum of two toll lanes of each type is because if one lane fails for technical reasons or in the event of an accident, the second lane will continue to operate, ensuring uninterrupted acceptance of all types of tolls at the TP. For a given TP SM in barrier mode, which includes 8 toll lanes, the following TP configurations will be the limit: 2 ETC and 6 manual toll lanes; 6 ETC and 2 manual toll lanes.

The developed TP SM in barrier mode allows to take into account the following parameters:

1. Traffic intensity at the TP;
2. Traffic composition;
3. Share of ETC users;
4. Number of lanes in operation;
5. Modes of lane operation;
6. ETC lane maintenance time;
7. Maintenance time of manual lane;
8. Additional parameters (User behavior).

A detailed description of the TP SM parameters used in this study can be found in (Talavirya et al. 2023).

3.3. Study of the SM of the TP in the barrier mode

As part of the TP SM study in barrier mode, we will examine under which traffic flow parameters and in which configuration of the TCS the highest throughput at the toll plaza is achieved.

The following SM parameters, listed in Section 3.2, will be held constant in the barrier mode TP study:

- Traffic composition. The following distribution of vehicles by class is assumed: cars - 75%, vans - 5%, trucks - 20%;
- Number of functioning lanes. It is assumed that all 8 toll lanes are functioning;
- Automatic lane maintenance time. The value is a random variable with a symmetrical triangular distribution ranging from 7 to 60 seconds;
- Manual lane service time. The value is a random variable with a symmetrical triangular distribution in the range of 7 to 45 seconds;
- Additional Parameters (User Behavior). The user influence coefficient is 5%.

When studying the TP in barrier mode, we will consider the following SM parameters listed in Section 3.2 as variables:

- Traffic intensity at the TP. The input traffic flow is Poisson with intensity in the range of 250 to 4000 veh./h;
- Share of ETC users. Values in the range of 50 to 95% of the proportion of ETC users are considered;
- Modes of lane operation. Configurations with different ratios of manual lanes ranging from 2 to 6 are considered. The remaining lanes operate in ETC mode.

In order to evaluate the limits of the capacity of the TP in the barrier mode in different TCS configurations, 50 groups of experiments were conducted to identify the threshold traffic flow intensity at which congestion starts to form on the TP. This intensity is considered to be the threshold intensity for the TP configuration 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 veh./h to 4000 veh./h in 10 veh./h increments. The duration of observations for each experiment was 1 hour.

The results of groups of experiments 1-50 to evaluate the ultimate throughput of the TP in barrier mode are summarized in Table 1.

Table 1. Maximum throughput capacity of the TP in barrier mode

Experiment group №	Number of ETC lanes	Number of manual lanes	Share of ETC users									
			50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
1-10	2	6	530	590	680	790	910	1080	1590	No congestion occurs	No congestion occurs	No congestion occurs
11-20	3	5	510	570	670	760	830	1080	1230	A short-term congestion	No congestion	No congestion

										occurs	occurs	occurs
21-30	4	4	460	510	610	680	790	940	1210	A short-term congestion occurs	No congestion occurs	No congestion occurs
31-40	5	3	440	520	570	620	740	920	1340	A short-term congestion occurs	No congestion occurs	No congestion occurs
41-50	6	2	420	480	540	610	690	940	1210	A short-term congestion occurs	No congestion occurs	No congestion occurs

Based on the results of the experiments, it can be noted that at a minimum throughput of 250 veh./h, congestion never occurs at the TP. At the same time, congestion is stably formed at intensity values 450-500 veh./h higher than the threshold value indicated in Table 1.

As can be seen from Table 1, when the ETC users share is between 50 and 70%, the threshold intensity does not exceed 1000 veh./h. When the ETC users share is between 50 and 80%, as the number of manual lanes decreases, the threshold intensity decreases from 13.0 to 23.9%. The minimum throughput obtained was 420 veh./h and the maximum was 1590 veh./h. Reducing the number of manual lanes in the TP configuration decreases the throughput of the TP. At the same time, increasing the ETC users share within the same configuration increases throughput.

At 85% ETC users share in the 3/5, 4/4, 5/3, 6/2 TCS configurations, short-term congestion may occur and disappear within a short time. We do not consider such congestions as static, as their permanent presence in SM is not observed. When the ETC users share is from 90 and 95%, no congestion is observed in all configurations of the TCS.

The obtained result has shown that for the TP operating in the barrier mode, in the considered configuration, the ETC users share over 85% in the vehicle flow will avoid the formation of congestion at the TP.

3.4. Development of the SM of the TP in the hybrid mode

In order to evaluate the ultimate capacity of the hybrid TP under different traffic flow parameters, an SM has been developed corresponding to the lane layout shown in Figure 2.

Figures 5 and 6 show the overall and top views of the developed hybrid TP SM.

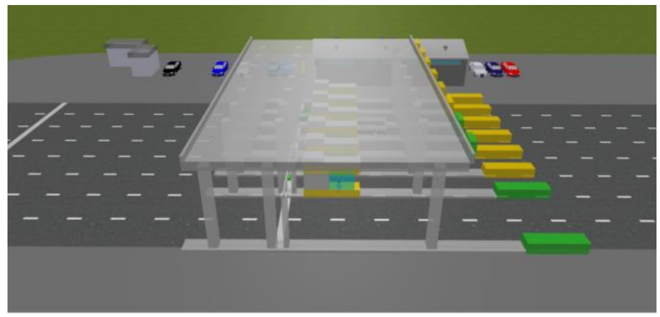

Figure 5. Simulation model of the TP in hybrid mode. General view

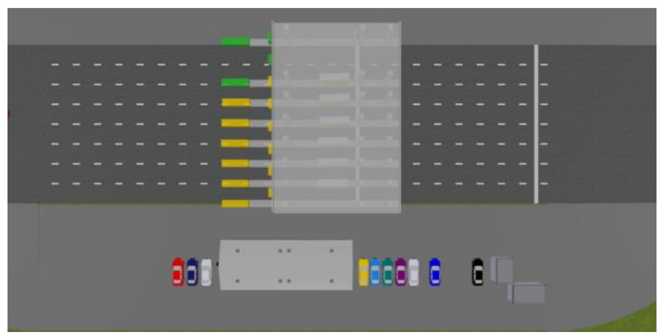

Figure 6. Simulation model of the TP in hybrid mode. Top view

The developed SM allows to simulate the operation of the TP, two lanes of which operate in the FF mode, which allows vehicles to freely pass through the zone of the TP without stopping, as well as from 2 to 6 lanes operating in manual mode, depending on the adopted configuration of the TP.

The developed TP SM in hybrid mode allows taking into account the following parameters:

1. Traffic intensity at the TP;
2. Traffic composition;
3. Share of ETC users;
4. Number of lanes in operation;
5. Maintenance time of manual lane;
6. Speed of passing through the FF lanes.

Unlike the barrier-based TP SM, the hybrid TP SM will have a number of differences, in particular, the User Behavior parameter will not be applicable for the FF lanes. Also, in the barrier TP SM it was considered that vehicles could pass through the ETC lanes at a speed not exceeding 30 km/h. Taking into account that there are no obstacles in the form of an exit barrier on the FF lanes, 60 km/h will be considered as the permissible speed of passing through them.

3.5. Study of the SM of the TP in the hybrid mode

As part of the hybrid mode TP SM study, we will consider at which traffic flow parameters and TCS configuration specified in the hybrid TP SM the highest throughput at the toll booth is achieved, and consider whether the number of manual toll lanes can be optimized for the hybrid TP.

When investigating the hybrid mode TP, we will assume the following SM parameters listed in Section 3.2 to be constant:

- Traffic composition. The parameters used in Section 3.3 are assumed;
- Manual lane service time. The parameters used in Section 3.3 are assumed;
- Speed of passing through FF lanes. A speed of 60 km/h is adopted as the speed considered safe when passing through barrier-free lanes.

Variable parameters:

- Traffic intensity at the TP. Values in the range of 250 to 4000 veh./h are considered;
- Share of ETC users. Values in the range of values used in Section 3.3 are considered;
- Number of lanes in operation. Configurations with different numbers of manual lanes ranging from 2 to 6 are considered. The remaining lanes (except for the two lanes operating in FF mode are considered non-functioning).

In order to evaluate the capacity limits of the TP in the hybrid mode in different TCS configurations, 50 groups of experiments were also conducted to identify the threshold traffic flow rate at increasing traffic flow rates ranging of 250 veh./h to 4000 veh./h with a step of 10 veh./h and the observation duration of each experiment equal to 1 hour.

The results of the groups of experiments 51-100 for estimating the ultimate capacity of the TP in the barrier mode are presented in Table 2.

Table 2. Maximum throughput capacity of the TP in hybrid mode

Experiment group №	Number of FF lanes	Number of manual lanes	Share of ETC users									
			50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
51-60	2	6	530	570	680	780	950	1080	1440	A short-term congestion occurs	No congestion occurs	No congestion occurs
61-70	2	5	510	550	670	750	860	1060	1220	A short-term congestion occurs	No congestion occurs	No congestion occurs
71-80	2	4	460	510	590	710	800	900	1230	A short-term congestion occurs	No congestion occurs	No congestion occurs
81-90	2	3	450	510	560	620	730	940	1220	A short-term congestion occurs	No congestion occurs	No congestion occurs
91-100	2	2	420	490	530	600	720	920	1210	1470	No congestion occurs	No congestion occurs

Experimental results showed that at a minimum throughput of 250 veh./h, no congestion occurred at the TP, stable congestion formation was observed at an intensity 500 veh./h higher than the threshold value shown in Table 2.

As can be seen in Table 2, when the share of ETC users is from 50 to 70%, the threshold intensity does not exceed 1000 veh./h. Reducing the number of operating manual lanes results in a minimal reduction in the throughput of the TP (up to 110 veh./h) at a share of ETC users of 50%, and contributes to an increasing reduction in throughput as the share of ETC users increases.

For share of ETC users from 50 to 80%, as the number of operating manual lanes decreases, the threshold intensity decreases from 14.0 to 24.2%. The minimum throughput obtained was 420 veh./h and the maximum was 1440 veh./h. Reducing the number of manual lanes in the TP configuration reduces the throughput of the TP, similar to the barrier-mode TP. Increasing the share of ETC users also increases the throughput at the TP.

At the 85% share of ETC users, short-term congestion may occur in the 2/6, 2/5, 2/4, 2/3 TCS configurations, which disappears within a short time. In the 2/2 TCS configuration, when only 4 toll lanes are in operation, congestion occurs at intensities above 1470 veh./h. Thus, with 85 % share of ETC users, it is possible to reduce manual lanes from 6 to 3, provided that the occurrence of short-term congestion on the TP is not critical for the road operator.

At the share of ETC users from 90 to 95% in all the TP configurations, no congestion formation is observed, which shows the feasibility of using the hybrid mode.

Having analyzed the results of the experiments performed on simulation models of TPs operating in the barrier and hybrid modes, three main conclusions were made.

Conclusion 1. At a low share of ETC users of up to 75%, the capacity of the manual lanes at TPs operating in barrier and hybrid mode is approximately the same. Optimization of the number of operating manual lanes is possible if the traffic intensity at the TP does not reach the obtained capacity thresholds.

Conclusion 2. When the share of ETC users exceeds 85%, the transition to a hybrid mode of operation at the TP can be considered reasonable, as the capacity of 2 to 6 ETC lanes is comparable to the capacity of two lanes operating in the FF mode. Thus, it is possible to reduce the maintenance costs of operating four toll lanes.

Conclusion 3. At a low share of ETC users below 80%, in order to operate the TP in hybrid mode with high traffic intensity, the operator should increase the share of ETC users, because at low share of ETC users the queue of vehicles on manual lanes will extend beyond the approach to the TP zone and block access to the FF lanes. An example of the described traffic jam formed at the PR SM in hybrid mode in a configuration with 2 FF lanes and 6 manual lanes at an intensity of 1500 veh./h and an share of ETC users of 70% is shown in Figure 7.

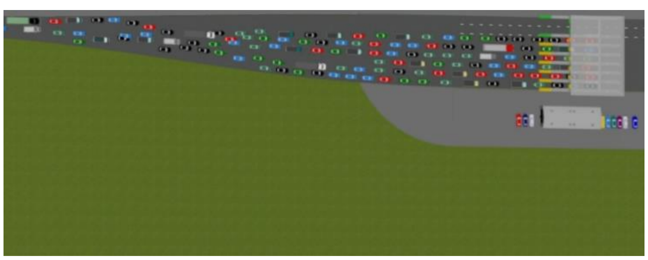

Figure 7. Formation of congestion on manual toll lanes at TP in hybrid mode

As can be seen in Figure 7, the FF lanes remain free as the accumulated queue in the manual lanes blocks free passage from the main run of the two-lane roadway.

4. Conclusions

The study presented an analysis of the performance of a hybrid type TP operating in two different modes. Section 2 reviewed the current scientific literature, highlighting the level of development of this issue. The technological features of the hybrid TP have been taken into account in the development of the SM, which were reported in Section 3.1. The following sections summarized the SM and traffic flow parameters used and applied in the simulation experiments.

The results of the simulation experiments on the SM showed comparable performance of the TP in barrier and hybrid modes, provided that the vehicle flow contains no more than 75% share of ETC users. When the share of ETC users is more than 85%, the transition to the hybrid mode may be more reasonable, as there is an opportunity to reduce the operational costs of the toll road operator. If the share of ETC users is low, not exceeding 75%, in conditions of high intensity, congestion may form at the hybrid tolling station, when the queue at the manual toll lanes will block the access to the FF lanes, making the operation of this type of tolling station ineffective.

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 simulation model for each crossing point, taking into account the peculiarities of its geographical location, 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-logical districts 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 under different conditions, taking into account daily, weekly and seasonal irregularity of the flow, may be required.

The described approach of estimating the ultimate capacity for hybrid-type TP, as well as any other types, can be applied at various stages of toll road projects, from design surveys to the stage of its operation. The greatest practical value from the use of the proposed simulation models can be achieved during the direct operation of the toll station, since the toll road operator, having the most accurate data on the composition and specifics of traffic, can use the available data to solve predictive and optimization problems.

Further work of the authors, developing and continuing the theme of this study, is aimed at analyzing and identifying additional dependencies affecting the throughput of the hybrid TP, as well as refining the SM, improving its accuracy by adding new parameters to it.

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