Influence of Toll Collection Method on Motorways on Traffic Safety and Efficiency

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Abstract. The paper presents the results of the effectiveness analysis for various forms of toll collection on motorway gates and their impact on safety and efficiency of traffic. The results from field tests that were performed on the A1 motorway in Rusocin were used for the analysis. The research included the analysis of the video image of driver behaviour on the way to the toll booths and at toll booths. The PTV VISSIM tool was used to analyse the safety and efficiency of the traffic (microsimulation models of the Rusocin Toll Collection Plaza reflecting various forms of payment). The analysis of speed changes, delays, vehicle queues and driver service time has been made, including the method of toll collection (manual, automatic, hybrid). The analysis of traffic safety was carried out using surrogate measures used in the theory of traffic conflicts, taking into account the trajectory of vehicles movement.

Keywords: Intelligent transportation systems · Toll collection
Traffic safety

1 Introduction

The Federal Highway Administration in the 1990s began its activities to assess the benefits of toll collection. Four operational projects implemented under this program have been verified to assess the benefits (San Diego I-15 Express Lanes, Katy Freeway in Houston, TX, SR 91 Express Lane, Lee Way in Lee County, Florida). The study showed a number of benefits resulting from the toll collection, including [21]:

- Increased revenues - the generation of revenues provides financial incentives to implement investments to the extent that the value of revenues may cover investment costs and operating costs.
- Reduced traffic congestion - charging can potentially lead to maximized road capacity while maintaining a high level of service by changing the driving mode, increasing the number of persons in the vehicle and shifting travel times.
- Savings in travel time - saving time is not only for drivers using lanes with toll collection, but also for drivers on toll-free lanes who reach higher average speeds.

Based on the literature review, it appears that in the early years of introduction of intelligent toll collection systems on the roads, an increase in the number of accidents caused by the confusion of drivers and ignorance of these services was observed. Currently, due to the greater availability of these systems and greater awareness of

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drivers, intelligent toll collection systems lead to increased safety and reduction of accidents in places where they occur. However, the occurrence of tolls leads to the migration of part of the traffic to roads with a lower standard, which entails the risk of increasing the number of accidents on these roads [8]. An overview of regional toll collection programs on a toll road section developed by the National Center for Transit at the University of South Florida showed that the main advantage of Smart Card collection technology as the example of automatic toll collection is to reduce payment processing time. The average processing time using the Smart Card in the study was 2.27 s, compared to 3.07 s for traditional systems. Thus, the use of payment cards for travel allows drivers to save time by about 30% [9]. The implementation of an Open Road Toll system (ORT) can provide better performance in terms of toll collection than the conventional construction of a toll site. Automatic Vehicle Identification technology (AVI) for the Electronic Toll Collection system (ETC) is a concept that has revolutionized the way in which tolls are levied and the ever-increasing traffic on toll roads results in more frequent use of innovative methods such as ORTs. For example, after the introduction of ORT at the University Toll Plaza following results were estimated [10]:

– reduction of the average time losses for cash paying customers by 49.8%, while in case of customers using the automatic toll collection - by 55.3%;
– increase in the average speed of vehicles by 57%;
– decrease in the number of accidents by 22% at the place of tolling, and by 26% in the impact area.

A high-occupancy vehicle lane (HOV) is a lane reserved for vehicles carrying a driver and one or more passengers. HOV lanes have been designed to reduce road traffic when many persons travel in a single vehicle. Foreign experience (mostly from the USA) shows that HOV lanes do not always meet their objectives and do not fully use their potential, which is why more and more often HOV lanes are converted into High-Occupancy Toll (HOT) lanes, which are available both for vehicles with many number of passengers and not tolled, as well as other tolled vehicles [2]. The fees depend on the time of day and number of people in a vehicle. There are also differences in price depending on the day of the week. Pricing strategies are developed to improve traffic conditions in a given traffic corridor as much as possible [14].

Intelligent Transportation Systems services (ITS services) can be assessed on the basis of field tests or laboratory simulation models. Field research is extremely expensive and time-consuming. Simulation can help reduce fieldwork and is a useful way to evaluate ITS measures.

The microscopic approach means that every vehicle in the network is constantly modeled during the simulation while traveling through the designated road network. The movement of the vehicle from its origin to the destination is tracked as a result of its response to stimuli, such as traffic signals and the movements of other vehicles [1]. The main advantage of the microscopic simulation is that each driver is analyzed on an individual level. However, to obtain results at the microscopic level input data must also be provided at the microscopic level [3]. Therefore, it is important to recognize that the quality of the product obtained (regardless of the degree of program package advancement) is as good as the quality of the input data provided. The quality of input data not only takes into account the integrity of the data, but also adequate physical care when entering data into the system [17]. Microscopic traffic simulators aim to realistically emulate the flow of individual vehicles in the road network. They are capable of replicating complex dynamic traffic systems that are difficult or impossible to simulate using traditional mathematical models. A number of additional functions, such as individual vehicle route guidance systems [12] are available by enabling the formulation of a dynamic traffic network. Researchers are currently developing an option for dynamic target selection [2]. This adds an extra dimension to the microscopic traffic simulators.

Using VISSIM, a microscopic simulation package, the study enable to develope a model of the Rusocin Toll Collection Plaza at A1 motorway in Poland for the purpose of evaluating toll collection performance. Toll booth delay, driving time and volume data were collected in the field enabling the construction and calibration of a base model that closely resembled the current situation (manual toll collection). A number of scenarios were run aimed at quantifying the performance of different toll collection mechanisms and analyzing the impact fully automated toll collection system would have on future traffic parameters.

2 Impact of Toll Collection Methods on Traffic

Tolls are primarily a tool for collecting financial resources that enable the maintenance of road infrastructure and engineering structures existing on motorways and in their surroundings. However, the tolls are collected not only to increase the income, but also to be able to efficiently shape the transport policy of a given country through traffic management, and hence reduction of vehicle traffic. Tolls may affect traffic and environmental protection. Adaptation of tariffs for the use of road infrastructure can have a significant impact on reducing congestion on roads and on traffic disturbances for the environment. The reason for the occurrence of queues and delays on the entry toll booths to the motorway is primarily a manual toll collection system, which forces drivers to stop in order to pay tolls. There are various ways to collect fees, such as the aforementioned manual, electronic ones, which do not require stopping, but sometimes only a reduction of speed.

2.1 Toll Collection Methods

Due to the method of payment, toll collection systems can be divided into: manual, vignette and electronic The manual toll collection system is primarily characterized by the need to stop the vehicle at the toll collection point and pay tolls in cash or by using a payment card. After making the payment, the employee in the toll booth opens a barrier allowing to leave or enter the motorway. There are also toll booths where the driver has to handle himself using the terminal. Payments at the terminal can be made in cash or by credit card, debit card or special tokens used in some countries. In many places in the world a very popular method of payment is a pre-paid card for which before making a trip we pay a specific sum of money and when you use the toll road system, the appropriate amount is deducted from your account balance. Two variants can be distinguished depending on the current tariff system: open and closed. Manual open system is used when the tariff system is based on a toll for a specified section of a toll road (from the gate to the gate). The toll payment is only collected on toll plazas located across the roadway of the motorway. It is most often used on entrances to tunnels and bridges. A manual closed system is used when the tariff system is based on the fee for the actual number of kilometres travelled on a given section of a toll road. The toll plazas are located on the access roads to and from each motorway junction as well as on the motorway at the ends of the toll section. In the mentioned points, a driver entering a toll road section picks up a ticket, which he later pays at the toll collection points when leaving the motorway.

The vignette system is based on periodic fees for access to the infrastructure with validity for periods from one day to one year. Prices of vignettes depend primarily on the weight of the vehicle and the exhaust purity standards that the vehicle meets. The larger the vehicles or the more polluting the environment, the toll for the motorway is higher. The amount of the fee can also be linked to the time of day, e.g. higher during rush hour. The vignette can be purchased at border crossings, most gas stations, some stores, post offices, and in some countries also via the internet or by sending an SMS. Drivers attach a sticker to the windshield of the vehicle. The vignettes may differ from each other in colour or shape from year to year. In addition to stickers, there are also more advanced systems, such as magnetic identifiers or electronic vignettes, which are verified e.g. by devices recognizing vehicle license plates.

We can distinguish five main electronic toll collection systems [20]:

- automatic recognition of ANPR number plates (Automatic number plate recognition) by means of vehicles recording cameras
- VPS (Vehicle Positioning System) vehicle positioning systems based on GNSS satellite technology (Global Navigation Satellite System) and mobile GSM/GPRS telecommunications networks (Global System for Mobile Communications/General Packet Radio Service),
- DSRC microwave radio systems (Dedicated Short Range Communication) operating in the 5.8 GHz frequency band.
- "Radio Frequency Identification" (RFID) which refers to those technologies that use radio waves to identify devices automatically. In recent decades, RFID has been used mainly for Electronic Toll Collection in the United States (US). The performance and characteristics of RFID are, at least in practice, very similar to those of DSRC technology, as both are microwave-based approaches.
- Tachograph-based technology records the mileage of a user through an OBU (On-Board Unit) connected electronically to the vehicle´s odometer.

Open Road Tolling (ORT), with all-electronic toll collection, is now the preferred practice, being more efficient, environmentally friendly, and safer than open or closed manual toll collection [15].

Currently, there are two systems in Poland [11, 18]:

- manual toll collection system,
- electronic toll collection system.

In the manual toll collection system, vehicles operators pay a toll for toll roads at the toll booth. They are included in the toll collection area (MPO) and depending on the location, they are called:

– toll plaza (PPO), if it is located within the motorway,
– toll station (SOP), if it is located within the slip road.

There are two types of manual toll collection systems on Polish motorways - open and closed. There is also a possibility to pay a toll electronically with the use of the electronic toll collection system. It is possible due to the use of the OBU transponder placed in the vehicle. Then, the vehicle does not need to stop in order to pay. This system applies to the vehicles with a gross vehicle weight rating above 3.5 tonnes [18]. Electronic toll collection for vehicles with a total weight not exceeding 3.5 tonnes is possible in Poland on three sections of motorways: A2 (Konin - Stryków), A4 (Wrocław - Sośnica) and A4 (Kraków - Katowice).

2.2 Impact of Toll Collection Methods on Traffic Safety and Efficiency

Two benefits of open-road tolling are especially noteworthy [15]:

– Safety benefits: Generally, ORT facilities are nearly accident-free. ORT allows vehicles to travel at normal motorways speeds, avoiding dangerous stop-go traffic and sudden merges, and eliminating the danger of drivers jockeying for lane position. ORT can also cut down on the distractions toll payers face while driving, such as fumbling for change or having to slow down or stop to pay the toll.
– Economic Benefits (improving the efficiency of the transport system): Delays cause losses to both the driver and the overall economy. Drivers suffer direct costs of increased fuel consumption and vehicle wear and tear owing to idling and stop-and-go movement, as well as indirect costs of stress. Valuable time is spent in traffic instead of productive work. Delays also drive up the cost of shipping goods—a cost usually passed on to the consumer. ORT reduces delays and thus provides economic benefits.

The length of travel time and service time at toll booths depends primarily on the system that is used in a given place. This time is much longer when using the manual method of payment than in the electronic system. In the case of a manual toll collection system, the driver is forced to stop at gates where he must pay a toll. This generates a delay of 16 s on average, which can cause long queues. Considering the fact that on motorways the permissible speeds are relatively high, the driver must start braking much earlier, which may cause dangerous situations or collisions, because not everyone is able to assess the situation well and start to safely brake, In the case of an electronic toll collection system, the average travel delay (when the speed is reduced to 30 km/h when passing through the toll booths) is only 8 s, which is mainly due to the fact that vehicles do not have to stop to pay, but only slow down to legal speed. Some systems are so developed that vehicles do not even have to slow down when passing through toll booths. Thanks to this solution, the level of safety at toll plazas and within them is much higher and the queues being created are much shorter than in the manual system [16].

Common incidents types within toll plazas with a combination of ETC and manual toll lanes are rear-end or sideswipe incidents, fixed-object collisions, back-into crashes and pedestrian-related incidents. Rear-end incidents have the highest frequency. They are more frequent during peak hours and in the lanes that have queues. The most common reasons for sideswipe incidents and fixed-object collisions are merging movements and high-speed driving. Usually, pedestrian-related incidents have the lowest frequency at toll plazas [4].

Although the capacity of the plaza increases due to the increase of ETC lanes, changes in traffic lanes between ETC and manual lanes increase the probability of conflicts. To account for this effect, the "weaving ratio" parameter was introduced, which is the number of movements that change lines on ETC lanes compared to the total possible changes. With the increase in traffic, the risk of incident would increase for inbound traffic and would decrease for outbound traffic. The rate of increase in the number of road incidents will be lower than the growth rate of traffic. As a result, the risk of incident will decrease as traffic increases. This may be due to the average speed reduction in congested conditions [19].

Queues at the plaza, especially during peak hours, leads to more rear-end conflicts. One of the factors that increases rear-end collisions during congestion is the drivers' loss of forward attention to the decelerating front vehicle while they are under the lane-decision process. By increasing toll booth throughput capacity, ETC lanes can help reduce the number of rear-end conflicts. However, the first major problem is unfamiliarity among drivers who often stop at the plaza in an attempt to understand the payment methods. The other problem is the speed variation between manual and ETC lanes that increase the probability of conflicts. All things considered, the ETC system would decrease the level of safety at toll plazas [13]. The choice of the lane by driver can be determined by minimizing travel time, and even a short queue on toll collection would be an incentive for drivers to change lanes. The decision on the movement of drivers at toll booths is based on the relative time of transactions on automatic and manual toll lanes. In the case of lanes that serve both manual and ETC traffic, the driver instinctively weighs the time of waiting behind a not tolled driver and behind slower, heavy vehicles on the ETC lane. Such combo lanes can increase driver inattention while reducing capacity and increasing delays. Lane-searching process is the main cause of incidents [22] by analysing number of lane-changing manoeuvres and number of conflicts, situations in which a vehicle needs to brake or steer suddenly to avoid a collision, as surrogate measures of incident risk.

The type of toll lane, vehicle deceleration, speed, number of toll lanes and traffic intensity between the lanes would affect the location of conflict points at a plaza. The number of conflicts would decrease by increasing the number of ETC lanes at a plaza, because the ETC lanes lead to a more organized traffic flow through the toll plaza. Finding the optimal lane configuration is one of the most difficult tasks in the design of a toll plaza. Each configuration should provide services for all types of payments and not confuse drivers [13].

3 Methodology and Research Results at Toll Plaza in Rusocin

The research methodology enabled to determine the impact of the ITS service, which is electronic toll collection on the level of traffic safety and efficiency at motorway plaza (Fig. 1). At the beginning, it was necessary to identify the research object and collect data on the organization of traffic and the current system of manual toll collection for the plaza in Rusocin. Then, road traffic counts and analyses were carried out, which were used to determine the time of service at toll booths, vehicle speeds, queues length, delays and road lanes capacity. In the next step, the microsimulation model was developed, calibrated and verified based on the conducted field analyses. The model was the basis for simulation process in selected scenarios of drivers' service within the toll collection plaza.

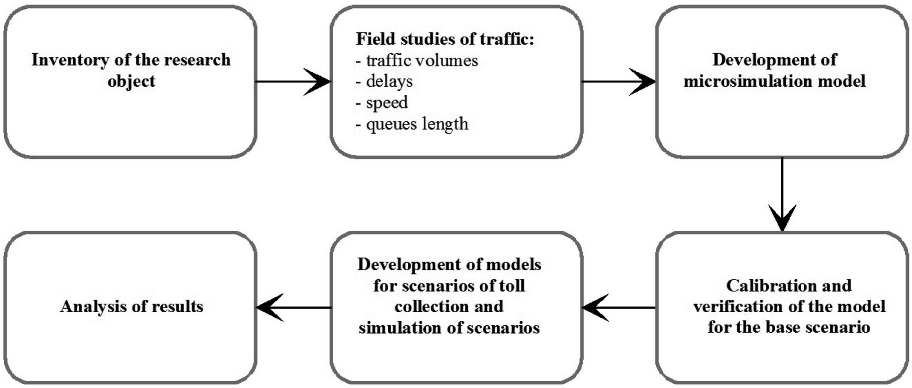

Fig. 1. Methodology for the research at Toll Plaza in Rusocin [own study]

3.1 Field Studies

The object of research and analysis is the Rusocin Toll Plaza (PPO). It is located in south of Gdańsk and in the north of Poland. This is the beginning of the concession section of the A1 Motorway. Drivers can use the 5 entry lanes and 10 exit lanes of the motorway. In addition, the two middle lanes can alternatively handle traffic in both directions. The 5 entry lanes are served by feeders that automatically issue tickets, without the need to press a button. It contributes to faster vehicle service. After taking the ticket, the barrier opens and the signal red light changes to green, which means that the vehicle can enter the motorway. 10 outbound lanes are equipped with toll booths where employees of PPO Rusocin are on duty 24 h a day for 7 days a week. The driver arriving at the toll booth must pay the fee in a manual form (credit cards or cash in PLN, EUR and USD are accepted). The amount of the fee depends on the vehicle category and the travelled distance.

In order to determine the traffic conditions on access to the PPO Rusocin, traffic volume measurements were carried out. There were 6 cameras recording vehicles within the motorway on the toll plaza. Data such as: traffic volumes, average time of vehicle service at toll booths and at ticket feeders, average queues appearing in individual traffic lanes as well as speeds on designated sections of the road on the access and within the toll plaza, were read from the recordings. The sample results are shown in Fig. 2. The share of heavy vehicles in outbound traffic was 10%. The level of service for the maximum outbound traffic after the toll plaza area is B, which means that there were very good traffic conditions on the motorway, traffic was fluent and vehicles were free to manoeuvre. The share of heavy vehicles in inbound traffic was also 10%. The level of service for the maximum inbound traffic before the toll plaza area was C, which means that there were relatively good traffic conditions on the motorway, the traffic was fluent, but the choice of speed and possibility of manoeuvring was limited.

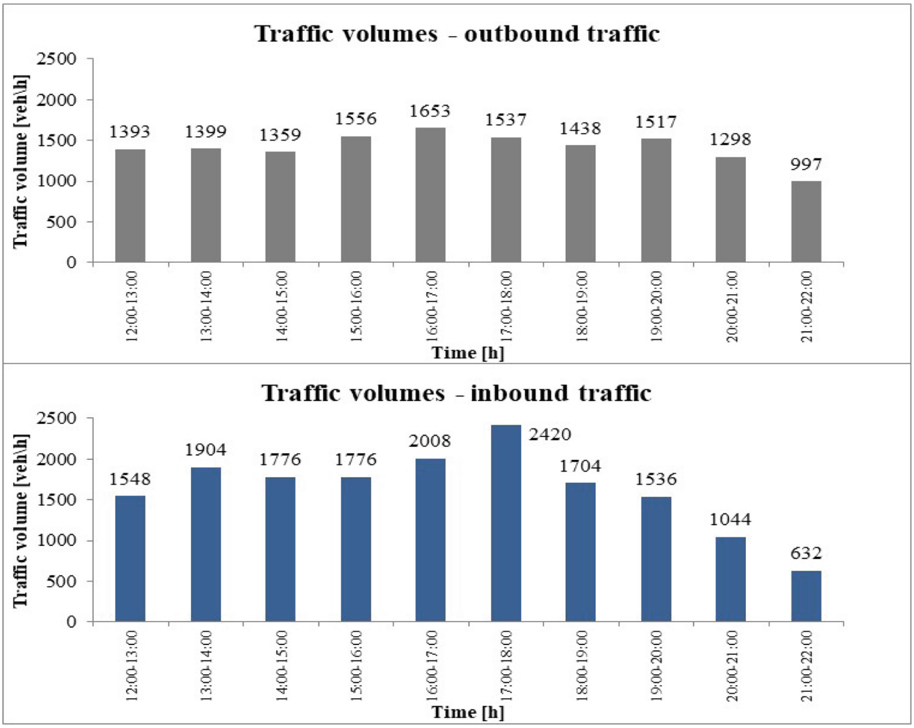

Fig. 2. Traffic volumes on access to the toll plaza [own study]

Time of servicing vehicles at toll booths or ticket feeders is a random variable and depends on many factors, including traffic volumes, time of day, weather conditions, number of available lanes and experience of the employee operating the toll booth. Vehicle service time includes the time needed for access to the toll booth or ticket terminal after leaving it by the previous vehicle, the time needed to pay the fee or take a ticket and the driver's reaction time from the moment of opening the barrier beam. The study made it possible to estimate the components of the vehicle service time. The average time of vehicle service at the toll booth was 21.8 s for private cars and 27.1 s for heavy vehicles. The average time of arrival to the control gate, after leaving it by another vehicle was 4.6 s for private cars and 7.1 s for heavy vehicles. The average toll collection time was 12.7 s for cars and 14 s for heavy vehicles. The average reaction time of the vehicle from the moment of raising the barrier was 4.5 s for private cars and 6 s for heavy vehicles. The cumulative distribution of the vehicle service time at the toll booth shows that 25% of vehicles do not exceed the service time of 18 s, half of the vehicles are within the service time up to 23 s, 75% of vehicles are serviced up to 26 s, and only 25% vehicles exceeds the service time of 26 s.

The average time of arrival to the ticket feeder after leaving it by another vehicle, was 4.4 s for private cars and 7.7 s for heavy vehicles. The average time of ticket collection from a feeder was 4.4 s for private cars and 6.4 s for heavy vehicles. The average response time of the vehicle from the moment of raising the barrier was 1.5 s for private cars and 2.1 s for heavy vehicles. The cumulative distribution of vehicle service time at the ticket feeder shows that 25% of vehicles do not exceed the service time of 9 s, half of the vehicles are within 10 s, 75% of vehicles are serviced for 14 s and only 25% of vehicles exceeds the service time of 14 s.

Capacity of the toll booth was estimated at 165 vehicles/hour for private cars and 133 vehicles/hour for heavy vehicles. Capacity of the lane with the ticket feeder was estimated at 350 vehicles/hour for private cars and 223 vehicles/hour for heavy vehicles. In the case lanes serving vehicles that pay tolls on the motorway, delays reach even up to 182 s. 25% of vehicles have a delay to 62 s, 50% vehicles to 77 s, and 75% to 86 s, 25% exceeds 86 s. In the case of lanes serving drivers taking a ticket delays reach up to 50 s. 25% of vehicles have delays to 35 s, 50% of vehicles to 38 s and 75% to 50 s, 25% exceeds 50 s.

The lanes located on the left side are much more often chosen by drivers, because the lanes on the right are occupied by heavy vehicles, which need more time to make a payment. Despite the speed limit within plaza up to 40 km/h, vehicles far exceed the permitted speed. Data obtained from field studies were used to develop a microsimulation model for base scenario.

3.2 Microsimulation Model

In order to develop the simulation model the Rusocin Toll Collection Plaza (Fig. 3) the PTV VISSIM program was used. VISSIM is a discrete, stochastic, time-based microscopic simulation tool that utilizes various models of driver behaviors and vehicle performance to accurately represent urban and inter-urban traffic. The flow of traffic in VISSIM is represented as the movement of individual driver/vehicle units. VISSIM contains a psycho-physical car following model for longitudinal vehicle movement and a rule based algorithm for lateral movements (lane changing). The user builds a network based on one or more aerial photographs or technical drawings, adding objects to the network exactly where they are needed and where they will have the desired effect on road users. The VISSIM simulation model has been validated based on data from various real situations [5]. The Rusocin Toll Plaza model was calibrated on the basis of data collected during the field studies and validated (with control group of data from the field studies) for the base scenario (existing traffic organisation and toll collection system). As part of research, models were developed which differ in the method of toll collection (manual, automatic, hybrid). Sample model view for hybrid toll collection method is presented at Fig. 4).

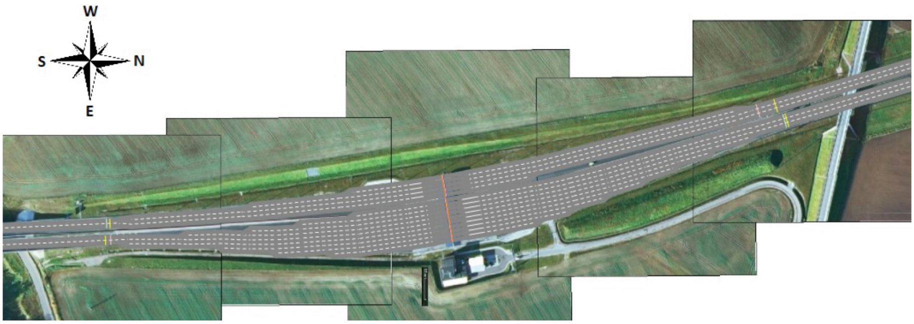

Fig. 3. The scheme of the analyzed Rusocin Toll Collection Plaza in VISSIM software [own study]

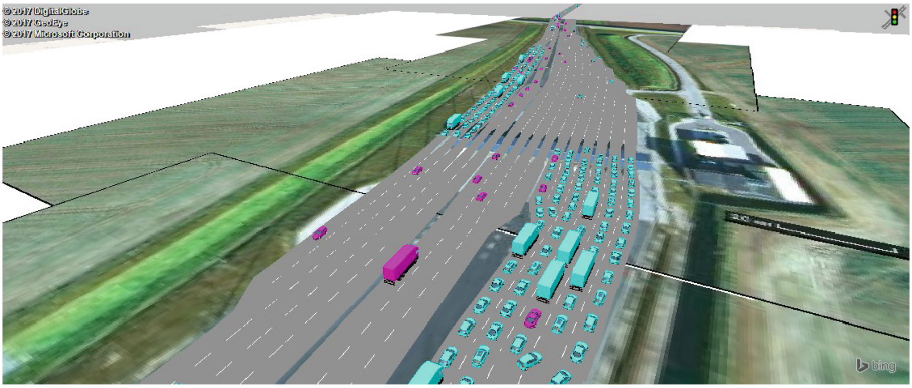

Fig. 4. An example of a microsimulation for the scenario that assumes manual and automatic toll collection software [own study]

3.3 Road Traffic Safety Analysis with Use of Surrogate Safety Measures

Parameters of road traffic and the behaviour of road users, which allow identification and assessment of changes affecting road safety are referred to as surrogate safety measures. Surrogate safety measures have their origin in traffic conflicts. The traffic conflicts technique is a methodology for field observers to identify conflict events at intersections by watching for strong braking and evasive manoeuvres. Surrogate safety measures can be also estimated with help of microsimulation techniques. The model developed in VISSIM enabled to obtain information on the trajectory of each vehicle in traffic flow. Data are stored in the form of x, y coordinates and a time marker. Trajectories analyses were carried out using the Surrogate Safety Assessment Model developed by New Global Systems Corporation [7].

The following surrogate safety measures were estimated (Fig. 5):

- Time to collision (TTC)
- Post-encroachment time (PET)

– Deceleration rate (DR)
– Maximum of the speeds of the two vehicles involved in the conflict event (MaxS)
– Maximum relative speed of the two vehicles involved in the conflict event (DeltaS)
– Conflict point or conflict line line location
– Vehicle speed difference - DeltaV (MaxDeltaV).

It has two main thresholds to define vehicle-to-vehicle conflicts. One is time-to-collision (TTC), with a default value of 1.5 s, and the other one is post-encroachment time (PET). The results would be displayed in a table representing number of conflicts.

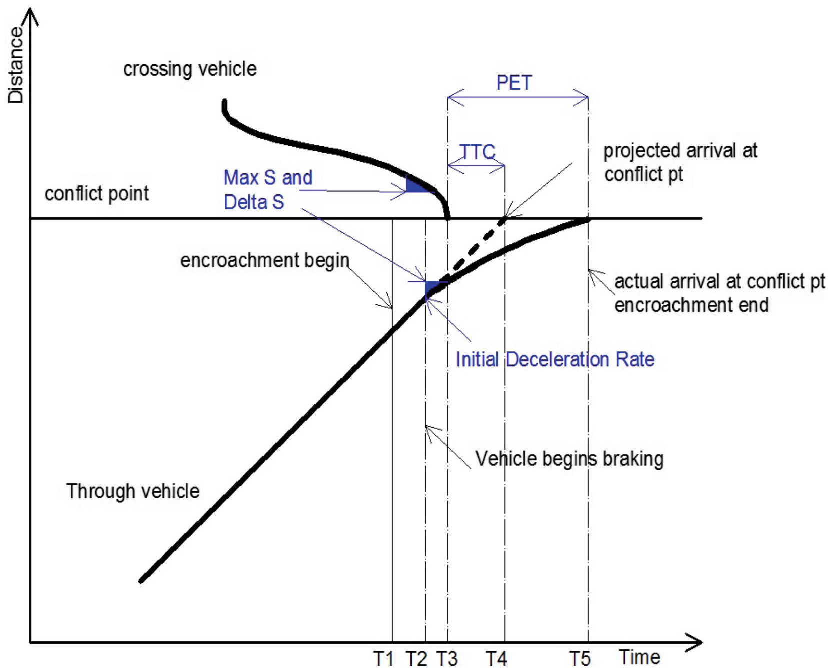

Fig. 5. Surrogate safety measures scheme [own study based on 6]

4 Results

As part of the research, the analyses of safety and efficiency of traffic for various scenarios of the application of toll collection at plaza were carried out. The analyses were carried out for the following scenarios:

– Scenario 0 (S0) – base scenario - existing manual toll collection (10 outbound lanes with toll booths/5 inbound lanes with ticket feeders)
– Scenario 1 (S1) – at inbound lanes: 4 lanes with manual toll collection/1 lane with automatic toll collection, at toll booth lanes: 8 lanes with manual and 2 lanes with automatic toll collection, it was assumed that 20% of drivers have the option to pay toll automatically

- Scenario 2 (S2) - at inbound lanes: 4 lanes with manual toll collection/1 lane with automatic toll collection, at toll booth lanes: 8 lanes with manual and 2 lanes with automatic toll collection, it was assumed that 40% of drivers have the option to pay toll automatically
- Scenario 3 (S3) – at inbound lanes: 3 lanes with manual toll collection/2 lanes with automatic toll collection, at toll booth lanes: 6 lanes with manual and 4 lanes with automatic toll collection, it was assumed that 40% of drivers have the option to pay toll automatically
- Scenario 4 (S4) – full automatic toll collection - no need to stop, 2 lanes for inbound traffic, 2 lanes for outbound traffic.

Examples of the results of simulation for traffic corresponding to the Level of Service “C” is shown in Table 1. The results concerning the performance indicators of the plaza (queue length, number of stops, delays) obtained using the VISSIM model and traffic safety indicators (number of conflicts) estimated with the help of Surrogate Safety Measures model. Indicators are presented for the area within toll booths for outbound traffic and ticket feeders for inbound traffic.

The introduction of automatic toll collection significantly improves traffic conditions. There are no traffic disturbances in the case of a fully automatic toll collection system. The efficiency of the hybrid system depends on the number of lanes used for toll and manual collection as well as the share of drivers who can pay automatically. At the same time, the number of available lanes for manual and automatic payments should correspond to the share of drivers who can make payments with one or other method (with too many manual toll booths in relation to the demand for manual payment traffic conditions get worse). In the case of hybrid systems, an increase in the capacity of both inbound and outbound direction has been observed, even up to 30% in the case of proper lanes division into automatic and manual toll collection (if the fully automatic system is used, capacity would increase more than 3 times in comparison to manual method). If a hybrid system is used, the number of conflicts increases. Deterioration of traffic safety results from increased conflicts related to the change of lanes by drivers looking for the right lane (sideswipe incidents), increased in speed variations between vehicles making payments in a manual and automatic manner (increase in the number of rear-end incidents) and mean speed increase resulting from improved traffic conditions.

Table 1. Traffic safety and efficiency indicators of Rusocin Toll Plaza [own study]

Indicator	Payment method	S0	S1	S2	S3	S4
Queue length at ticket feeders [m]	Manual	797	356	243	720	–
	Automatic	–	241	112	1	0
	Total	797	597	355	721	0
Max queue length at ticket feeders [m]	Manual	2097	426	728	1764	–
	Automatic	–	426	729	49	0
	Total	2097	852	1457	1813	0
Number of stops at ticket feeders	Manual	22520	8204	5793	11306	–
	Automatic	–	2239	1519	40	0
	Total	22520	10443	7312	11346	0

(*continued*)

Table 1. (*continued*)

Indicator	Payment method	S0	S1	S2	S3	S4
Delay at ticket feeders [s/veh]	Manual	344	229	132	201	–
	Automatic	–	28	26	10	0
	Total	344	257	159	211	0
Number of conflicts at ticket feeders	Manual	861	621	869	104	–
	Automatic	–	489	794	996	0
	Total	861	1110	1663	1100	0
Queue length at toll booths [m]	Manual	973	247	128	1558	–
	Automatic	–	8	1	0	0
	Total	973	255	129	1558	0
Max queue length at toll booths [m]	Manual	2948	429	732	4628	–
	Automatic	–	81	64	15	0
	Total	2948	510	796	4642	0
Number of stops at toll booths	Manual	21896	7736	3670	16132	–
	Automatic	–	97	25	10	0
	Total	21896	7833	3695	16142	0
Delay at toll booths [s/veh]	Manual	494	277	138	218	–
	Automatic	–	7	5	5	0
	Total	494	284	143	222	0
Number of conflicts at toll booths	Manual	1714	822	1112	906	–
	Automatic	–	317	636	660	0
	Total	1714	1139	1748	1566	0

5 Conclusion

Toll plazas are one of the most complex elements of the road system. Drivers are exposed to large amounts of information in a short period of time, in which they must make decisions about the choice of lane and speed reduction.

The study has showed the feasibility of modelling traffic at toll collection plaza and the possibility of assessing the safety and efficiency of traffic using VISSIM software and surrogate safety measures.

Field studies and conducted simulations allowed to draw conclusions about the impact of the toll collection method on traffic safety and efficiency. It should be noted that in addition to the method used to collect tolls, the organization of traffic within the toll plaza is of great importance.

The analysis of the impact of the methods used to toll collection on road traffic leads to the conclusion that it is justified to introduce a uniform solution for all drivers on the motorway resulting in lower speed variation between vehicles, homogenization of traffic and fewer lane changes). In the case of a fully automatic toll collection system, probability of conflicts occurrence and traffic disturbances are rare and capacity would increase more than 3 times in comparison to manual method.

In the case of hybrid systems - the area of access to toll booths or ticket feeders is important so that vehicles waiting in a queue in intensive traffic conditions do not block each other. In this case, the safety level should be increased by reducing the difference in speed between ETC lanes and cash lanes, and lanes with the same payment method should be clustered. The number of available lanes for manual and automatic payments should correspond to the share of drivers who can make payments with one or other method.

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References

1. Anderson, M.D., Souleyrette, R.R.: Pseudo-dynamic travel model application to assess traveler information. Transportation **29**(3), 307–319 (2002)
2. Bhatt, K.: Value Pricing Pilot Program: Lessons Learned. U.S. Department of Transportation, Federal Highway Administration, New Jersey (2008)
3. Chrobok, R., et al.: A microscopic simulator for freeway traffic. Netw. Spat. Econ.: Spec. Issue Reg. Transp. Models **2**(4), 371–387 (2002)
4. Ding, J., Ye, F., Lu, J.: Impact of ETC on traffic safety at toll plaza. plan, build, and manage transportation infrastructure in China. Presented at Seventh International Conference of Chinese Transportation Professionals Congress (ICCTP), Shanghai, China, pp. 695–701 (2007)
5. Fellendorf, M., Vortisch, P.: Validation of the microscopic traffic flow model VISSIM in different real-world situations. In: 79th Annual Meeting of Transportation Research Board, UK (2001)
6. FHWA: Surrogate Safety Measures From Traffic Simulation Models. Report nr. FHWA-RD-03-050, McLean, Virginia, USA (2003)
7. Gettman, D., et al.: Surrogate safety assessment model and validation: final report. FHWA-HRT-08-051, Federal Highway Administration, U.S. Department of Transportation (2008)
8. Hatcher, G., et al.: Intelligent transportation systems benefits, costs, and lessons. Publication Number: FHWA-JPO-14-159. U.S. Department of Transportation, Washington (2014)
9. Joslin, A.: Regional fare policy and fare allocation, innovations in fare equipment and data collection. National Center for Transit, Los Angeles (2010)
10. Klodzinski, J.: Evaluation of impacts from deployment of an open road tolling concept for a mainline toll plaza. Paper Presented at the 86th Annual Meeting of the Transportation Research Board, Orlando, USA (2007)
11. Kasprzyk, Z., Siergiejczyk, M.: Some problems of functional analysis of electronic toll collection system (ViaToll). In: Mikulski, J. (ed.) TST 2013. CCIS, vol. 395, pp. 426–432. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-41647-7_52
12. Mahmassani, H.S.: Dynamic network traffic assignment and simulation methodology for advanced system management applications. Netw. Spat. Econ. **1**(3–4), 267–292 (2001)
13. Mohamed, A.A., Abdel-Aty, M., Klodzinski, J.G.: Safety considerations in designing electronic toll plazas: case study. ITE J. **71**(3), 20–33 (2001)
14. Oskarbski, J., Marcinkowski, T., Zawisza, M.: Impact of intelligent transport systems services on the level of safety and improvement of traffic conditions. In: Mikulski, J. (ed.) TST 2017. CCIS, vol. 715, pp. 142–154. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-66251-0_12

15. Persad, K., Walton, M., Hussain, S.: Toll collection technology and best practices. Project 0-5217: Vehicle/License Plate Identification for Toll Collection Applications (2007)
16. Pickford, A.T.W., Blythe, P.T.: Road User Charging and Electronic Toll Collection, pp. 15–21. Artech House, Boston (2006)
17. Poon, N., Dia, H.: Evaluation of toll collection performance using traffic simulation. In: 27th Conference of Australian Institutes of Transport Research (CAITR 2005), Brisbane, 7–9 December 2005
18. Rosinski, A.: Modeling of exploitation process of highway toll collection system. Arch. Transp. Syst. Telematics **9**(1), 22–26 (2016)
19. Sze, N.N., Wong, S.C., Chan, W.F.: Traffic crashes at toll plazas in Hong Kong. In: Proceedings of the ICE-Transport, vol. 161, no. TR2, pp. 71–76, May 2008
20. Technology Options for the European Electronic Toll Service (2014). http://www.europarl.europa.eu/RegData/etudes/STUD/2014/529058/IPOL_STUD(2014)529058_EN.pdf. Accessed 22 Feb 2018
21. Ward, J.: Value Pricing: A Synthesis of Lessons Learned. University of Minnesota, Minneapolis (2003)
22. Wong, S.C., et al.: The effects of a traffic guidance scheme for auto-toll lanes on traffic safety at toll plazas. Saf. Sci. **44**(9), 753–770 (2006)