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Impact of the manual toll collection system on the traffic flow of vehicles on the highway

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ABSTRACT
The article presents the negative impact of manual toll collection system on the traffic flow of vehicles on the highway. This problem applies in particular to manual toll collection systems at bottlenecks highways, especially near large urban areas where a large proportion of induced traffic. This paper presents the basic limitations of the system and demonstrated the need for its modernization.

KEYWORDS: highway traffic flow, manual toll collection systems

1. Introduction

The system that is used for collecting toll on the Polish highways concerns personal cars is the manual system [1, 2]. This system operates by collecting toll in the form of cash or allows for non-cash transactions using card payment. The biggest disadvantage of the manual toll collection is the need to stop the car at the collection booth in order to issue the payment, which may result in a situation that severely restricts the vehicle traffic flow on the highway. From the point of view of the road user, the need to stop the vehicle in order to issue the payment in the manual toll collection system is a nuisance which should occur as rarely as possible or should be eliminated altogether. The majority of toll roads in Poland uses the open toll collection system for passenger vehicles. The configuration of the open toll collection system allows collecting the toll for the passage through the route based on the given section, without taking into consideration the distance travelled by the vehicle and based on the vehicle category. Therefore, the importance of effective organisation of the manual toll collection system by its modernisation is becoming vital. However, in order to solve the problem it is firs required to identify the factors, which influence the effectiveness of the system and the traffic flow of vehicles on the highway.

2. Manual toll collection system as a mass service system

The vehicle traffic process on the highway and the service in the manual toll collection system may be described using the classical notions of the so called theory of mass service i.e. queuing systems. The various toll collection stations in the manual toll collection system may be described as a service station network at which the customers arrive. The stations in the queuing system are equivalent of the toll collection stations and the customers arrive at this cluster of stations in their vehicles. The queue of tasks to be performed, which is created at the approach to the station is a set number of vehicles which are waiting to issue the toll at the manual toll collection station. The description of the toll collection system using the theory of mass service is a valid tool supporting the design of such systems.

Due to the fact that references on mass service systems, to which group the manual toll collection systems belong, contain numerous definitions of notions related to the queuing theory, this paper uses the uniform definitions listed below. According to the applied naming practice the following notions are used in the mass service systems such as the toll collection system:

- arrival time, which is the time at which the vehicle arrives at the toll collection station cluster and takes place in the queue to issue the payment at a collection booth,

- service starting time, which is the time at which the vehicle drives to the toll collection station and the toll collection process starts;
- service end time, which is the time when the toll collection is complete and the vehicle leaves the station, at the same time leaving the manual toll collection station cluster, which is a part of the manual toll collection system,
- service (transaction) time, which is a difference between the service end time and the service starting time,
- waiting time (for the service), which is a difference between the service starting time and the arrival time,
- stay time, which is a difference between the end time and the arrival time or the sum of the service time and the waiting time,
- the service waiting time of highway users includes both the waiting time for transaction and the time during which the transaction is concluded.

The description of the manual toll collection system functioning assumes that the arrival of vehicles are random and the times between vehicle arrival are entered as variables which are subject to exponential distribution of vehicle arrival time λ_{poj} and the service time μ_{poj} as well as $\rho = \frac{\lambda_{poj}}{\mu_{poj}}$. The manual toll collection system may be described as a queuing system with waiting time for m-toll collection stations and j-vehicle arrivals. Assuming that $\frac{\rho}{m} \geq 1$ and the number of vehicles is infinite $j \to \infty$ then the addend of the sum $\sum_{j=m}^{\infty}\left(\frac{\rho}{m}\right)^{j-m}$ is divergent. Assuming that the addend of the sum has an infinite threshold and $\frac{\rho}{m} < 1$ a probability results that there will be no vehicles at the toll collection station:

$$p_0 = \frac{1}{\sum_{i=0}^{m-1}\frac{\rho^i}{i!} + \frac{\rho^m}{(m-1)!\,(m-\rho)}}, \quad \frac{\rho}{m} < 1 \qquad (1)$$

It is assumed that a vehicle arrives at a manual toll collection station cluster using a manual toll collection system and all toll collection stations m are occupied and there is no queue; in this case the user must wait for an average of $\frac{1}{m\mu_{poj}}$. If another vehicle arrives at the toll collection area, assuming that it encounters one previously arriving vehicle, then the average vehicle waiting time is $\frac{2}{m\mu_{poj}}$.

It might be then stated that the average vehicle waiting time in the queue to the toll collection station in the manual toll collection system, where r is the size of the vehicle queue, is:

$$\bar{t} = \frac{1}{m\mu_{poj}}p_m + \frac{2}{m\mu_{poj}}p_{m+1} + \ldots + \frac{(r-1)}{m\mu_{poj}}p_{m+r} + \ldots \qquad (2)$$

Finally, after transformations, the average vehicle waiting time in the queue to the toll collection station in the manual toll collection system is [3], [4]:

$$\bar{t} = \frac{\rho^{m+1}}{\lambda_{poj}(m-1)!(m-\rho)^2}p_0 = \frac{\left(\frac{\lambda_{poj}}{\mu_{poj}}\right)^{m+1}}{\lambda_{poj}(m-1)!\left(m-\frac{\lambda_{poj}}{\mu_{poj}}\right)^2}p_0 \qquad (3)$$

The size of the vehicle queue waiting at the toll collection station r is described by formula [3], [4]:

$$p_{m+r} = \frac{\rho^{m+1}}{m!m^r}p_0 = \frac{\frac{\rho^{m+r}}{m!m^r}}{\sum_{i=0}^{m-1}\frac{\rho^i}{i!} + \frac{\rho^m}{(m-1)!(m-\rho)}}, \qquad r \geq 0, \quad \rho < m \qquad (4)$$

The probability that all toll collection stations in the system in the collection area are occupied and that there is no queue (r=0) is described by the formula [3, 4]:

$$p_m = \frac{\rho^{m+1}}{m!}p_0 = \frac{\frac{\rho^m}{m!}}{\sum_{i=0}^{m-1}\frac{\rho^i}{i!} + \frac{\rho^m}{(m-1)!(m-\rho)}}, \qquad r \geq 0, \quad \rho < m \qquad (5)$$

Therefore the average number of vehicles waiting in a queue to the toll collection station may be calculated using the relationship [3, 4]:

$$\bar{v} = \frac{\rho^{k+1}}{\lambda_{poj}(k-1)!(k-\rho)^2}p_0, \quad 1 \leq k \leq m-1, \ \rho < m \qquad (6)$$

The presented characteristics describing the manual toll collection system as a mass service system have been applied in the operation of original software tool used to analyse the impact of the manual toll collection system on the service waiting time of highway users.

3. Impact of the manual toll collection system on the traffic flow of vehicles on the highway

in order to provide a valid evaluation of the impact of the manual toll collection system on the highway user waiting time a proprietary software toolkit was used (figure 1) in addition to the data obtained from the GDDKiA (General Directorate for National Roads and Highways) related to automatic continuous measurement of traffic [5]. The software capabilities allow completing the verification process using any method and from any given place, using live streaming video data as well as previously recorded, archive data from video surveillance systems. In order to verify not only the toll collection process but also the capabilities of the discussed system, a toll collection station and a time period were selected, for which the verification has already been performed using traditional methods. In both cases the goal is to establish the waiting time of all vehicles arriving at the toll collection station.

Fig. 1. View of the toolkit during operation [own work]

In order to maximise the precision of the measurement results and to meet the requirement of attaching a single video frame to each of the events (arrival at the toll collection station, beginning and end of service at the toll collection station) a key procedure was used to support the software, that is the automatic OCR character recognition, which allowed for the synchronisation of the system date and time with the data from the video surveillance system. Additionally, in some application, it allows for entering the data acquired during the so called vehicle categorisation, which is their identification and positioning in a certain group into the system. For each manual toll collection station the following parameters are recorded and established using the relationships described in chapter 2:

- arrival time at a given station,
- service starting time for a given vehicle at a given station,
- service end time for a given vehicle at a given station,
- current size of the queue of vehicles at a given station,
- average waiting time for a vehicle in a queue to issue the payment,
- average size of the queue of vehicles waiting to issue the payment,
- average number of vehicles waiting in queue in the toll collection area.

The collection of this information allows establishing:

- the waiting time for the service,
- the size of the vehicle queue,
- the time of vehicle service.

The above parameters allowed for the analysis of the influence of the manual toll collection system on the highway user waiting time for the service.

In the first phase the periods of vehicle traffic intensification were identified. The second phase is the measurement of waiting time of users of the manual toll collection system based on the results from phase one. In the first phase of measurements the software toolkit allowed for the identification of congestions. The software recorded times reflecting the start and end of periods where the size of the queue at any station exceeded the threshold value of five vehicles, which is assumed as critical from the point of view of service waiting time.

In the second phase, the periods selected based on the results of congestion period measurements performed in phase one were subject to detailed analysis. In order to obtain reliable and precise data from the measurements this principal phase, using the software toolkit, has been divided into two phases.

In the first phase service times at individual toll collection stations were measured. To do so, the service starting time for each vehicle at the toll collection station i.e. its arrival at the cashier's booth was recorded. Then the service end time for each vehicle was recorded i.e. the moment it left passing the automatic barrier line. Establishing those two times (toll collection start and end) automatically allowed establishing the service time at the toll collection station per vehicle.

In the second phase of the measurement, each vehicle for which the service starting and end times have been established was found in the recorded video using the OCR function at the moment it has arrived in the toll collection station cluster and took its place in the queue to the toll collection station. The time of its arrival has been recorded as the arrival time in the manual toll collection system. The difference between the service end time at the toll collection station and the arrival time was used to establish the sought time the vehicle spends in the system, which is the total vehicle waiting time. The measurements were conducted for a real toll collection area with 7 toll collection stations.

Table 1. Vehicle service time at toll collection stations and the percentage of the number of vehicles

Day	Time	0 - 10 s	11 - 20 s	21 - 30 s	31 - 60 s	> 60 s	Average
11.04.2012	16:00 - 19:00	837 (38%)	1046 (47%)	188 (8%)	137 (6%)	11 (0%)	14.3
25.04.2012	16:00 - 19:00	1011 (44%)	966 (43%)	177 (8%)	106 (5%)	10 (0%)	13.3
10.05.2012	17:00 - 20:00	819 (44%)	712 (38%)	198 (11%)	133 (7%)	16 (1%)	14.6
22.05.2012	16:00 - 19:00	906 (44%)	815 (40%)	179 (9%)	143 (7%)	20 (1%)	14.6

Table 1 presents the percentage of cars being serviced at the toll collection station in the specified period of time.

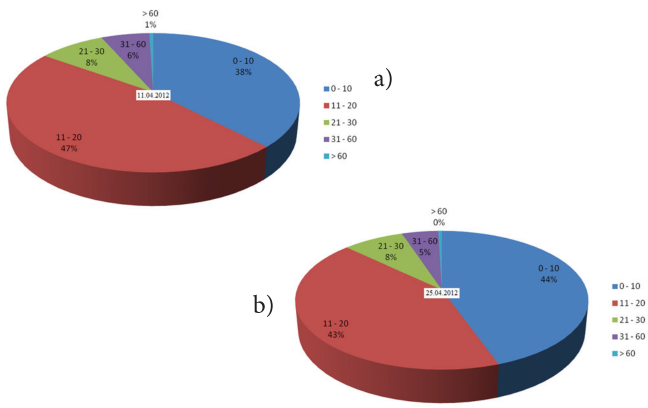

Fig. 2. Percentage distribution of service times (transaction completion times) for the toll collection area [own work]

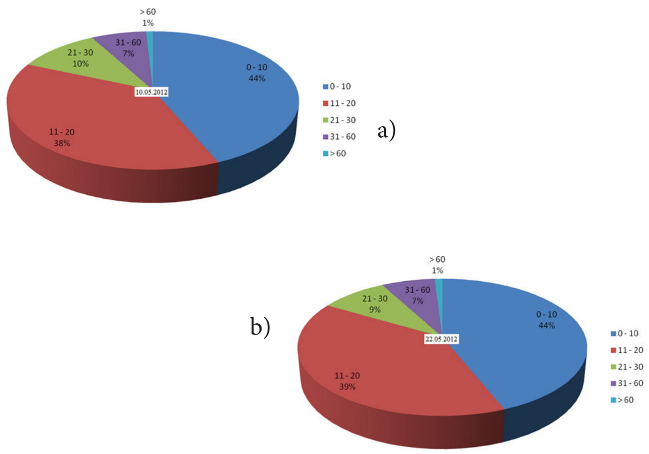

Fig. 3. Percentage distribution of service times (transaction completion times) for the toll collection area [own work]

Establishing the service time (transaction completion time) allowed establishing the service waiting time of highway users including both the waiting time for transaction and the time during which the transaction is concluded. Table 2 shows average service waiting times of highway users in the toll collection area subject to the experiment.

Table 2. Average waiting time of vehicles for service in the toll collection area

Day	Time	Service waiting time periods in the toll collection area		
		0 - 90 s	**90 - 180 s**	**< 180 s**
11.04.2012	16:00 - 19:00	0 s	134 min	96 min
25.04.2012	16:00 - 19:00	0 s	124 min	67 min
10.05.2012	17:00 - 20:00	0 s	26 min	179 min
22.05.2012	16:00 - 19:00	0 s	46 min	136 min

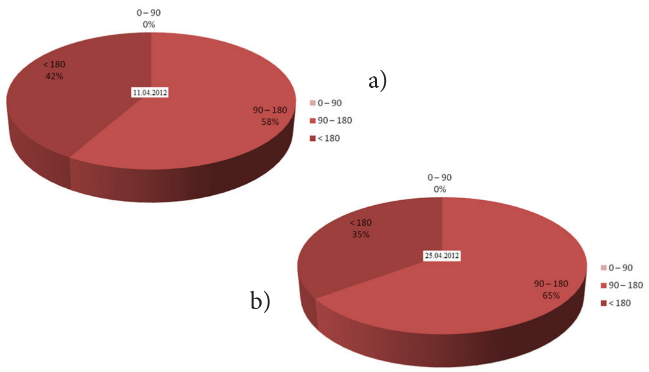

Fig. 4. Percentage distribution of service waiting times for the toll collection area [own work]

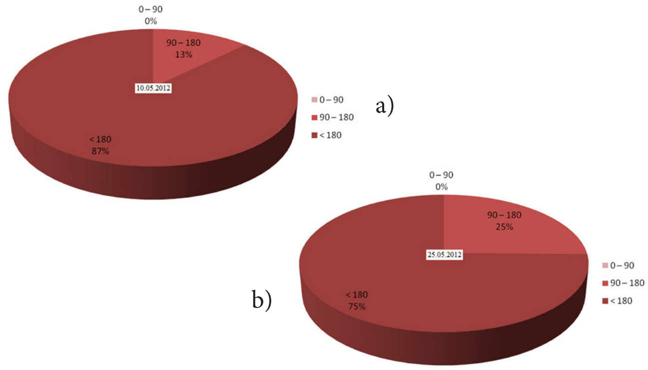

Fig. 5. Percentage distribution of service waiting times for the toll collection area [own work]

The analysis of the service waiting times brings the conclusion that in the tested toll collection area using the manual toll collection system, the waiting time was longer than 180 seconds for more than 60 minutes in any given period. This shows the negative impact of the sole use of the manual toll collection system on the traffic flow of vehicles on the highway by considerably extending the system users' service waiting time.

4. Conclusion

Taking into consideration the acquired results of measurements action must be taken to shorten the waiting time in the toll collection area using the manual toll collection system. The toll collection area is a typical example of a mass service system with several independent, parallel service stations. In case of congestions in the systems of this type there are three methods of conduct to improve their performance: limiting the number of vehicles, shortening the service type and changing the number/type of the toll collection stations. Limiting the number of vehicles is possible by legal or administrative action. It seems however to be an unreasonable solution due to the public right of drivers to access the highway and the resulting decrease in the income from road tolls. The reduction of vehicle traffic may also be achieved by increasing the tolls, however, practice shows that this is a short term solution and is always badly received by highway users. Shortening the service time seems to be the best solution from the point of view of the highway users and the operator. In practice, this will be very difficult to implement as there exist limits and this time may not be shortened below them. Those limits are the result of delays of vehicles in the queues, bad habits of drivers and the toll collection process itself. Increasing the number of stations is by far the most costly solution, which is the result of not only the expansion of the toll collection area but also of the need for additional employees for the toll collection stations. Based on the results and the conclusions presented above it might be assumed that there exists a considerable negative impact of using solely manual toll collection systems on the traffic flow of vehicles on the highway. Action should be taken for the modernisation of such systems to the free-flow standard, which will allow collecting toll without the need to stop the vehicles.

Bibliography

[1] Ustawa z dnia 27 października 1994 r. o autostradach płatnych oraz o Krajowym Funduszu Drogowym, Tekst jednolity Dz. U. 2004.256.2571

[2] Ustawa z dnia 7 listopada 2008 r. o zmianie ustawy o drogach publicznych oraz niektórych innych ustaw, Tekst jednolity Dz.U. 2008 nr 218 poz. 1391,

[3] CZACHÓRSKI, T.: Analityczne modele kolejkowe w ocenie efektywności pracy systemów i sieci kolejkowych. Pro Dialog, 2003 nr 16,

[4] FILIPOWICZ, B.: Modele stochastyczne w badaniach operacyjnych. WNT, Warszawa 1996,

[5] Generalna Dyrekcja Dróg Krajowych i Autostrad: Archiwizacja i analiza danych ze stacji ciągłych pomiarów ruchu w roku 2010 – 2011. Warszawa 2011.