Some Problems of Functional Analysis of Electronic Toll Collection System (ViaToll)

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Abstract. The article presents the issues of transport telematics systems. Presented toll collection systems, which are used in Poland. Particular attention was paid to the electronic toll collection system, which utilizes transponder OBU mounted on the vehicle. Through its use is not required to stop the vehicle in order to pay the tolls. Analysis of the situation occurring now makes it necessary to make a functional analysis of electronic toll collection systems.

Keywords: transport telematics, toll collection systems, electronic devices.

1 Introduction

The issue of transport telematics appeared in Polish literature in the mid-nineties. Even then, attempts were made to determine the extent of the conceptual and the area of transport telematics applications [1 - 2], which is defined as a field of knowledge and technical activities integrating information technology with telecommunications as applied to the needs of the transport systems.

Motorway telematics combines the use of intelligent transport systems on motorways in order to significantly increase travel and transportation security, increased reliability of transport, improve the use of road infrastructure and achieve better economic performance by reducing environmental degradation. Transport telematics systems are particularly useful in the following areas:

- control and monitoring of the use of motor vehicles,
- fleet management,
- toll collection vehicles
- information on the methods and conditions of travel.

An important system in the area of telematics is highway toll collection system. Autonomous decision on driver's of choosing route of travel, determines the payment of tolls on toll roads or the continuing traveling without paying the legal tolls. This decision starts, in the structure of the motorway telematics processing, the collection of the information used for further applications for the intelligent transportation on highways and toll roads. The proper functioning of the toll collection system contributes significantly to the increase in travel safety. The toll motorway sections during the entire transport process follows a two-way transmission of data (information).

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This is necessary due to the nature of the installed devices and their use. These devices communicate each other by the way of question and answer using actuators and sensors. In addition to the flow of information on the layout of a telematics system, the data are distributed partly outside the system to GSM, GPS and the Internet. This is to contact the user with a charging system before you travel and monitoring of vehicle tracking user in order to determine its position, and determine the moment since entering the paid section. Toll collection system is significantly involved in the supply and processing of information within the telematics motorway.

2 Electronic Toll Collection System (ViaToll)

Figure 1 shows the types of electronic toll collection systems used in the world.

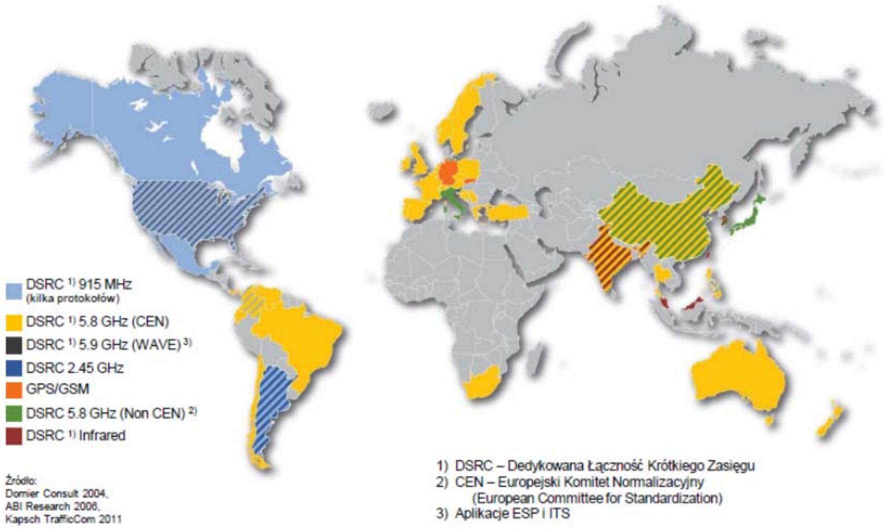

Fig. 1. Electronic toll collection systems used in the world [4]

According to the law on main public roads [3], all users of motor vehicles are obligated to pay a fee for toll roads. The introducing, since the 1st of July 2011, the National Toll Collection System has enabled the payment of tolls electronically for users of vehicles with a maximum mass exceeding 3.5 tones. Users of other types of vehicles still have to use the manual toll collection systems. Therefore, on the toll roads, there are two basic types of toll systems: manual toll system and an electronic toll collection system.

In Poland, within the framework of ViaToll electronic toll collection system in the 5.8 GHz DSRC technology (CEN) (Figure 1) was introduced. DSRC technology is used as a tool for automatic toll collection for passing a toll motorways, expressways and selected roads. This is done with the cooperation of sensors placed on gateways and transponders in the vehicle for which the fee is charged for the journey. The principle of DSRC technology functioning is as follows (Figure 2).

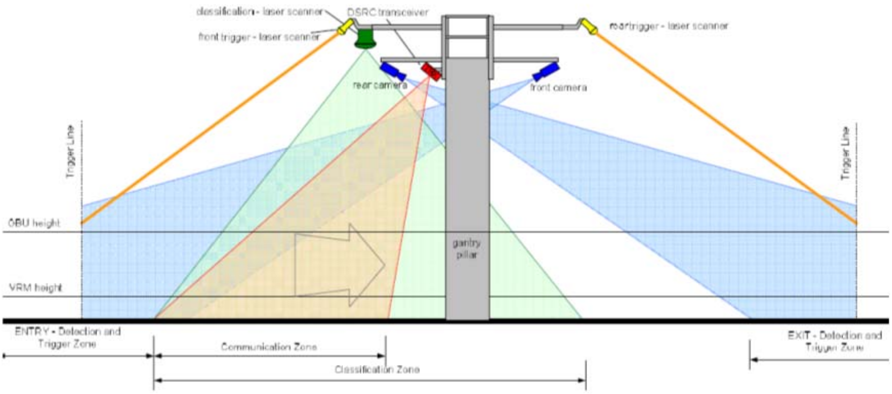

Fig. 2. Diagram of the gantry pillar operating in the 5.8 GHz DSRC technology [4]

Transponder mounted on the windscreen, at the time of entering a detection zone, sends a signal to the sensor with information about the vehicle (radio at 5.8 GHz microwave frequency at speeds of up to 500 kb/s). The laser scanner classifies the type of vehicle. Additionally vehicle journey is recorded by CCTV cameras installed on the control gantry. Similarly, an exit point detection zone is recorded by CCTV installed on the gantry. The data recorded by the gantry are sent to the central tolling, where after the processing of vehicle parameters data, the settlement of payment takes place.

Electronic Toll Collection System in Poland operates as an open system or a closed system, depending on the type of the motorway.

Closed toll system always has a point of entry to the toll road and the point of exit from the toll road. In this system, the user has no possibility to exit from the toll road between the point of entry and the point of exit. Depending on traffic volume, Toll Plazas consist of a belt entry or exit lanes located on Toll Stations. In a closed system toll roads the payment is carried out basing on the distance traveled by the vehicle and the vehicle category. The length of the the toll road section, covered by the distance, is based on the information contained in the transponder, which is read by the detector DSRC located on the gantry.

Open toll system has Toll Plazas with exit lanes, where payment is made for the journey. The number of lanes in each direction, in an open system, is defined in such a way that ensured the maximum throughput of the system. All entry and exit lanes are controlled by an automatic toll collection system in the form of an Electronic Toll Collection System with the system manual (mixed system). In an open system toll road the payment is made basing of the current section of the toll road without taking into account the distance traveled by the vehicle and on the vehicle category. The most toll roads in Poland actually operates and in the coming years will operate in an open system.

3 Functional Analysis of the Electronic Toll Collection System

In analyzing the functional elements of a gantry carrying out their functions in the 5.8 GHz DSRC system (Figure 2), we can conclude that the relationship in terms of reliability can be illustrated as shown in Figure 3.

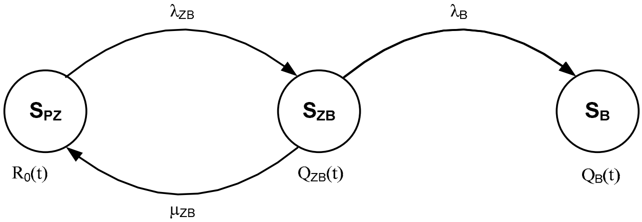

Fig. 3. Relations in the DSRC system using transponder and CCTV cameras

Symbols in Figure 3:

$R_0(t)$ – probability function of the system staying in complete capability,
$Q_{ZB}(t)$ – probability function of the system staying in a state of emergency safety,
$Q_B(t)$ – probability function of the system staying in a state of safety failure,
λ_{ZB} – intensity go from complete capability to the state of emergency safety,
λ_B – intensity go from emergency safety to the state of safety failure,
μ_{ZB} – intensity go from emergency safety to the state of complete capability.

State of complete capability S_{PZ} is a state in which all components are functioning properly performing the function of gantry payment. State of emergency safety S_{ZB1} is a state in which the fault is one of the equipment on the gantry. State of safety failure S_B is a state in which the elements of the gantry are faulty and there is no possibility to take the electronic toll from the users of the toll road.

The system shown in Figure 3 can be described by the following equations Kolmogorov-Chapman:

$$\begin{aligned} R_0'(t) &= -\lambda_{ZB} \cdot R_0(t) + \mu_{ZB} \cdot Q_{ZB}(t) \\ Q_{ZB}'(t) &= \lambda_{ZB} \cdot R_0(t) - \mu_{ZB} \cdot Q_{ZB}(t) - \lambda_B \cdot Q_{ZB}(t) \\ Q_B'(t) &= \lambda_B \cdot Q_{ZB}(t) \end{aligned} \tag{1}$$

Assuming the initial conditions:

$$\begin{aligned} R_0(0) &= 1 \\ Q_{ZB}(0) &= Q_B(0) = 0 \end{aligned} \tag{2}$$

and applying the Laplace transform to give the following equations:

$$
\begin{aligned}
& s \cdot R_0^*(s) - 1 = -\lambda_{ZB} \cdot R_0^*(s) + \mu_{ZB} \cdot Q_{ZB1}^*(s) \\
& s \cdot Q_{ZB}^*(s) = \lambda_{ZB} \cdot R_0^*(s) - \mu_{ZB} \cdot Q_{ZB}^*(s) - \lambda_B \cdot Q_{ZB}^*(s) \\
& Q_B^*(s) = \lambda_B \cdot Q_{ZB}^*(s)
\end{aligned}
\tag{3}
$$

Using the reverse transformation, were obtained:

$$
R_0(t) = \frac{\exp\left[-\frac{t \cdot (\lambda_B + \lambda_{ZB} + \mu_{ZB})}{2} \right] \cdot \left[\begin{array}{l} \lambda_B \cdot \sinh\left[\frac{t \cdot \sqrt{A}}{2}\right] - \lambda_{ZB} \cdot \sinh\left[\frac{t \cdot \sqrt{A}}{2}\right] + \\ \mu_{ZB} \cdot \sinh\left[\frac{t \cdot \sqrt{A}}{2}\right] + \cosh\left[\frac{t \cdot \sqrt{A}}{2}\right] \cdot \sqrt{A} \end{array} \right]}{\sqrt{A}}
\tag{4}
$$

$$
Q_{ZB}(t) = \frac{2 \cdot \lambda_{ZB} \cdot \exp\left[-\frac{t \cdot (\lambda_B + \lambda_{ZB} + \mu_{ZB})}{2} \right] \cdot \sinh\left(\frac{t \cdot \sqrt{B}}{2} \right)}{\sqrt{B}}
\tag{5}
$$

$$
Q_B(t) = \frac{2 \cdot \lambda_B \cdot \lambda_{ZB} \cdot \exp\left[-\frac{t \cdot (\lambda_B + \lambda_{ZB} + \mu_{ZB})}{2} \right] \cdot \sinh\left(\frac{t \cdot \sqrt{B}}{2} \right)}{\sqrt{B}}
\tag{6}
$$

where:

$$
A = \left(4 \cdot \left(\frac{\lambda_B}{2} + \frac{\lambda_{ZB}}{2} + \frac{\mu_{ZB}}{2} \right)^2 - 4 \cdot \lambda_B \cdot \lambda_{ZB} \right)
$$

$$
B = \left(\lambda_B^2 - 2 \cdot \lambda_B \cdot \lambda_{ZB} + 2 \cdot \lambda_B \cdot \mu_{ZB} + \lambda_{ZB}^2 + 2 \cdot \lambda_{ZB} \cdot \mu_{ZB} + \mu_{ZB}^2 \right)
$$

The obtained relations allow to determine the probabilities of staying DSRC system in states of complete capability R_0, emergency safety Q_{ZB} and safety failure Q_B.

Computer simulation method makes it possible to determine the impact of changes in indicators of reliability of system components on the reliability of the system under test. Adopted the following values for the system analyzed:

– research time one year:

$$t = 8760 \text{ [h]},$$

– intensity go from complete capability for the state of emergency safety:

$$\lambda_{ZB} = 0{,}000005 = 5 \cdot 10^{-6} \left[\frac{1}{h}\right]$$

– intensity go from emergency safety for the state of safety failure:

$$\lambda_{ZB} = 0{,}000003 = 3 \cdot 10^{-6} \left[\frac{1}{h}\right]$$

Intensity go from emergency safety to the state of complete capability μ_{ZB} is the inverse of the exponential distribution repair time t_{ZB} :

$$\mu_{ZB} = \frac{1}{t_{ZB}} \left[\frac{1}{h}\right] \quad (7)$$

Probability stay in complete capability as a function of intensity repair of the analyzed system shown in Figure 4.

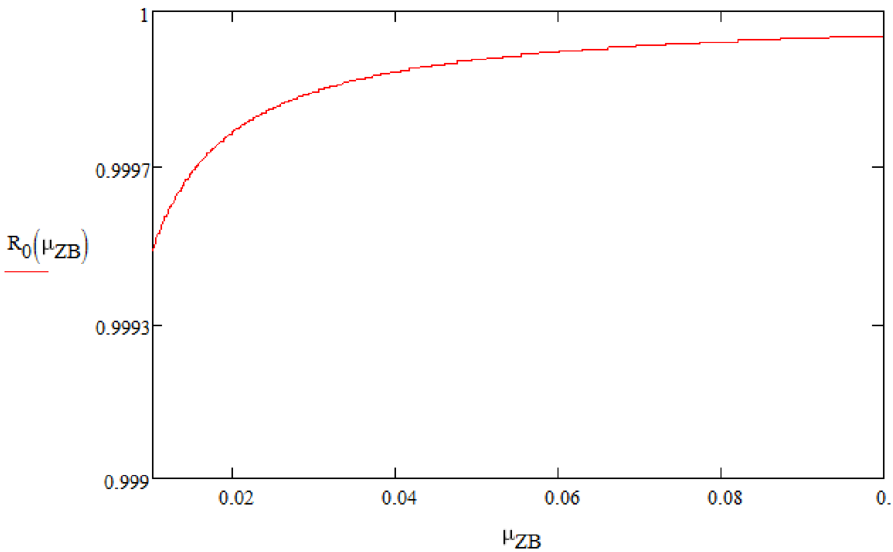

Fig. 4. Dependence of probability stay in complete capability R_0 as a function of intensity repair of the analyzed system

Functional analysis of the electronic toll collection system allowed the determination of probabilities DSRC system staying in different states. Determination and analysis of the probabilities of these relationships as a function of repair system revealed that:

– the value of the probability of the system staying in complete capability R_0 is the maximum for the minimum of time t_{ZB},
– function $R_0 = f(\mu_{ZB})$ is an increasing function and has a non-linear character.

4 Conclusion

This paper presents the types of electronic toll collection systems in Poland and the world. The analysis of functional and reliability gantry electronic toll collection system in the 5.8 GHz DSRC technology was made. Assuming three analyzed states reliability of electronic toll collection system and the transition between them, there were determined the equations, allowing the determination of the probability of the system staying in those states. Determined relations enabled to define the influence of the intensity of the effect of possible repairs on the value of the probability of the system staying in complete capability.

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